Energy and Resource Quality: The Ecology of the Economic Process

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Summary. A series of hypotheses is presented about the relation of national energy use to national economic activity (both time series and cross-sectional) which offer a different perspective from standard economics for the assessment of historical and current economic events. The analysis incorporates nearly 100 years of time series data and 3 years of cross-sectional data on 87 sectors of the United States economy. Gross national product, labor productivity, and price levels are all correlated closely with various aspects of energy use, and these correlations are improved when corrections are made for energy quality. A large portion of the apparent increase in U.S. energy efficiency has been due to our ability to expand the relative use of high-quality fuels such as petroleum and electricity, and also to relative shifts in fuel use between sectors of the economy. The concept of energy return on investment is introduced as a major driving force in our economy, and data are provided which show a marked decline in energy return on investment for all our principal fuels in recent decades. Future economic growth will depend largely on the net energy yield of alternative fuel sources, and some standard economic models may need to be modified to account for the biophysical constraints on human economic activity.

Stable consumer prices, full employment, and increasing per capita wealth have been economic and political goals in the United States since at least the 1930's. Aggregate economic growth has been the principal means for realizing these goals. On average, these goals were met from the mid-1940's to the early 1970's, when the U.S. economy grew at an average annual rate of 4 percent, recessions were relatively short and mild, and inflation rates rarely exceeded 4 percent. Since 1973, however, the United States and other Western nations have experienced irregular and even negative economic growth rates together with high unemployment, unprecedented inflation and budget deficits, and declining productivity rates.

These events seem to defy explanation by or even to contradict some of the most fundamental economic models that guided the prosperity of the preceding 40 years. A number of analysts have commented on the difficulties these models now encounter. Drucker (*1*) stated that "both as economic theory and as economic policy Keynesian economics is in disarray." Leontief (*2*) described many economic models as unable "to advance, in any perceptible way, a systematic understanding of the structure and the operations of a real economic system." Instead, they are based on "sets of more or less plausible but entirely arbitrary assumptions" leading to "precisely stated but irrelevant theoretical conclusions." Bailey and others (*3*) chronicled the failure, mutual conflicts, and frustrations of a number of economic models.

Glassman (*4*), responding to Leontief, suggested that greater diversity in economic theory is needed to supplement the conditioned expectations of formal theory. We agree, and present a different theoretical perspective for analyzing economic production based on relatively simple models that begin with the importance of natural resources, and fuel energy in particular. Our intent is not to replace standard economic models, nor do our models offer solutions for all the economic problems described above. Rather, our perspective, which in part has been presented by others (*5*), shows how some economic problems can be understood more clearly by explicitly accounting for the physical constraints imposed on economic production.

We examine the historical record of the last 90 years to test the hypotheses generated by our model. Empirical testing of economic theories is a difficult but essential procedure which is too frequently ignored. Simultaneous changes in variables make controlled observations difficult if not impossible. The empirical analyses of time series and cross-sectional data presented below cannot be used to prove hypotheses unequivocally, nor do they assure that the parameters will not change in new ways in the future. Empirical assessments, however, can be used to identify hypotheses that are consistent with reality and to reject hypotheses that are not.

Statement of Hypotheses

We approach macroeconomics from a thermodynamic perspective that emphasizes the production of goods, rather than the neoclassical perspective that emphasizes the exchange of goods according to subjective human preferences. Production is the economic process that upgrades the organizational state of matter into lower entropy goods and services. Those commodities are allocated according to human wants, needs, and ability to pay. Upgrading matter during the production process involves a unidirectional, one-time throughput of low entropy fuel that is eventually lost (for economic purposes) as waste heat. Production is explicitly a work process during which materials are concentrated, refined, and otherwise transformed. Like any work process, production uses and depends on the availability of free energy. The laws of energy and matter control the availability, rate, and efficiency of energy and matter use in the economy and therefore are essential to a comprehensive and accurate analysis of economic production.

Changes in natural resource quality affect the ease and cost of fuel and matter throughput in human economies because lower quality resources nearly always require more work directly and indirectly to upgrade them into goods and services. Technological change can counter changes in natural resource quality to varying degrees, but historically, many technical advances that have lowered unit labor costs have been realized by

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increasing the quantity of fuel used directly and indirectly to perform a specific task. The degree to which technological change can offset declining resource quality as some basic natural resources are depleted (for example, fuel and metal ores) and/or mismanaged (some biotic resources) is an empirical question and cannot be easily predicted. Nevertheless, such resource changes have important implications for what is and is not possible in the economy. Economic theory and policy must incorporate the physical properties of resources if economic predictions are to be accurate and economic policies effective.

In the section below we present a series of specific hypotheses derived from our biophysical perspective, accompanied by an alternative example of a more traditional hypothesis. In our empirical assessments of how changes in fuel quantity and quality have affected the U.S. economy, we examine (i) various relations between fuel use, economic output, productivity, and inflation over the past 90 years and (ii) cross-sectional relations between direct and indirect fuel use and economic value for 1963, 1967, and 1972. We use real gross national product (GNP) as a measure of aggregate output in the time series analysis, while acknowledging some of the inadequacies of GNP as a measure of output and social welfare. As a measure of fuel use we sum the quantities of fossil, nuclear, and hydropower fuels used in the economy and analyze the effects of changing fuel mix by adjusting caloric heat measures for fuel quality. Except as indicated, nuclear and hydropower fuels are converted to heat equivalents based on the prevailing heat rate at fossil steam electric plants.

1) A strong link between fuel use and economic output exists and will continue to exist, both temporally and cross sectionally. The correlation is strengthened when adjustments are made for fuel quality and the sector in which fuel is combusted. Alternative hypotheses are that such a link never existed, or that it can be and has been substantially decoupled, especially as the price of fuel increases (*6*).

2) A large component of increased labor productivity over the past 70 years resulted from increasing the ability of human labor to do physical work by empowering workers with increasing quantities of fuel, both directly and as embodied in our industrial capital equipment and technologies. One alternative hypothesis views productivity as an exogenous technical driving force that has increased the productivity of capital and labor (*7*).

3) Changes in the general price level have been correlated with changes in the money supply relative to the physical supply of energy. This suggests that the rising real physical cost of obtaining energy and other resources from the environment is one important factor in inflation. Various economic models emphasize either monetary or fiscal measures for explaining inflation (*8*).

4) Energy costs of locating, extracting, and refining fuel and other resources from the environment have increased and will continue to increase despite technical improvements in the extractive sector. This reduces the supply of nonenergy goods producible from a given quantity of energy. One alternative hypothesis is that resource-augmenting technical change and/or the development of inexhaustible fuel supply systems will mitigate any foreseeable natural resource scarcity (*9*).

Our hypotheses are not necessarily inimical to standard economics. Rather, we believe such an approach provides a physical basis for some macroeconomic

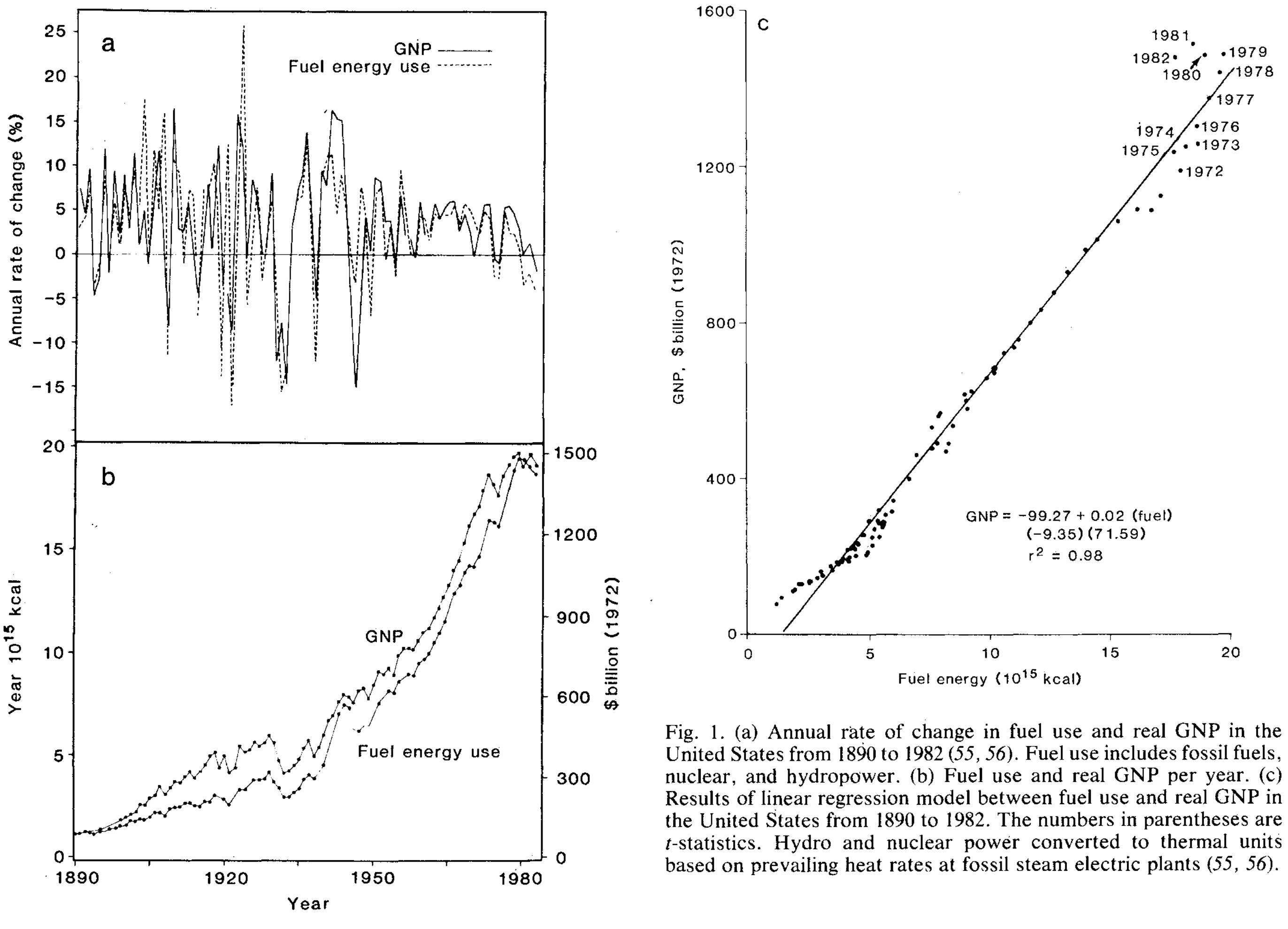


Fig. 1. (a) Annual rate of change in fuel use and real GNP in the United States from 1890 to 1982 (*55*, *56*). Fuel use includes fossil fuels, nuclear, and hydropower. (b) Fuel use and real GNP per year. (c) Results of linear regression model between fuel use and real GNP in the United States from 1890 to 1982. The numbers in parentheses are *t*-statistics. Hydro and nuclear power converted to thermal units based on prevailing heat rates at fossil steam electric plants (*55*, *56*).

phenomena. Such an analysis leads neither to an unrealistic cornucopian view of our future material condition, nor to one of "gloom and doom." We believe a physical analysis of economic production provides realistic assessments of the problems we face and some of the needed characteristics of any plausible solution.

Energy and Economic Production

The economic process is frequently depicted in basic economic texts as a closed system in which the flow of output is "circular, self-feeding, and self-renewing" (*10*). This model is seriously incomplete. In reality, the human economy is an open system embedded in a global environment that depends on a continuous throughput of solar energy. The global system produces the environmental services, foodstuffs, fossil and atomic fuels derived from solar and radiation energies, and various other resources that are essential inputs to the human economy. The human economy uses fossil and other fuels to support and empower labor and to produce capital. Fuel, capital, and labor are then combined to upgrade natural resources to useful goods and services. Economic production can therefore be viewed as the process of upgrading matter into highly ordered (thermodynamically improbable) structures, both physical structures and information. Where one speaks of "adding value" at successive stages of production, one may also speak of "adding order" to matter through the use of free energy (*11*).

Fuel quality as well as quantity limits economic production because fuels differ in the amount of economic work they can do per unit heat equivalent (kilocalorie). Petroleum, for example, can perform a more versatile array of tasks and do many of them more efficiently than coal (*12*). Per kilocalorie, petroleum is estimated to be 1.3 to 2.45 times as valuable as coal (*13*). Similarly, electricity can be converted to mechanical and heat energy at the point of application and can be controlled precisely, reducing the heat equivalents required to perform many tasks (*14*). One measure of the quality of electrical energy is the opportunity cost of transforming fossil fuels to electricity (3 to 4 kilocalories of fossil fuel per kilocalorie of electricity in 1983).

Another important quality of fuels is the amount of energy required to locate, extract, and refine them to a socially useful state. This aspect of fuel quality is measured by a fuel's energy return on investment (EROI), which is the ratio of gross fuel extracted to economic energy required directly and indirectly to deliver the fuel to society in a useful form. As the EROI for fuel declines, the energy opportunity costs of securing additional amounts increase, and increasing amounts of already extracted energy must be diverted from the production of nonenergy goods to extract a given quantity of new fuel. Net energy is a more relevant measure of fuel supply than gross energy because it represents the energy available to produce final-demand goods and services. At an absolute minimum, the aggregate EROI for fuels must be greater than 1 for an economic system to function, and probably much greater for it to grow. *Ceteris paribus*, economies with access to higher quality natural resources, particularly fuels with higher EROI, can do more economic work than those with lower EROI fuel resources.

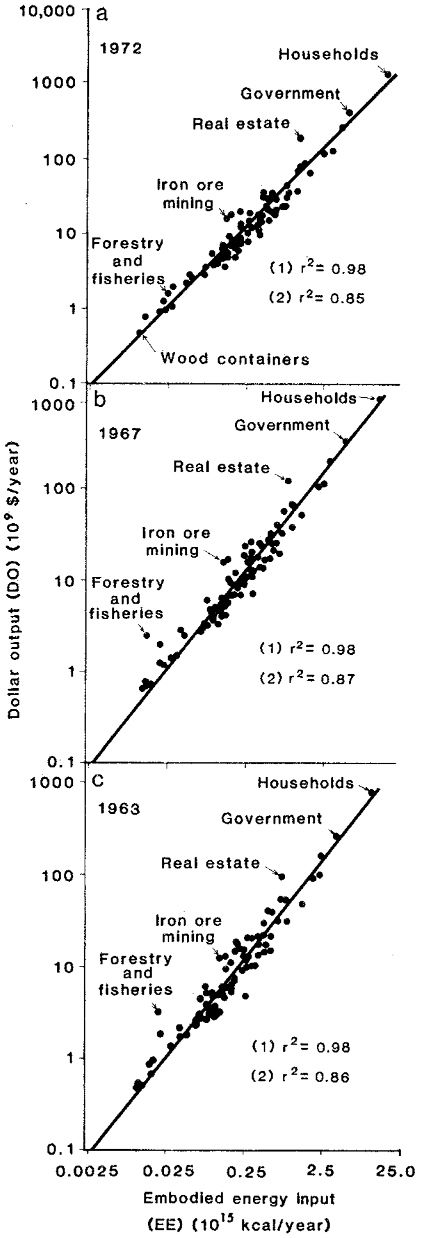


Fig. 2. Cross-sectional analysis of embodied energy inputs and dollar output for the U.S. economy in 1963, 1967, and 1972. Energy input includes direct fuel measured at the point of combustion and embodied in intermediate goods, labor, and government services purchased by each sector. For all three years $r^2 = 0.98$ if all points shown are included in the regression (option 1). Because households and government are relatively large sectors, including them in the regression may yield misleadingly high correlations. Excluding households and government from the regression yields r^2 values of about 0.86 (option 2). Excluding households and government from energy intensity calculations yields r^2 values of about 0.55 (*18, 24*).

Energy costs of capital and labor. Fuels, nonfuel minerals, capital, and labor are all necessary to produce economic output. Most standard models of production consider fuel and other natural resources to be qualitatively no different from other factors of production. As a result, many believe that natural resource inputs to production are "small potatoes compared to labor, or even to capital," and that "reproducible capital is a near perfect substitute for land and other exhaustible resources" (*15*). This view is inaccurate because free energy is required to upgrade and maintain all organized structures, including capital and laborers, against the ravages of entropy. It ignores the physical interdependence of capital, labor, and natural resources.

All goods and services (both economic and environmental) have quantifiable direct and indirect energy costs of production, termed their embodied energy. The embodied energy of a good or service can be calculated with input-output techniques developed by Herendeen and Bullard and by Hannon *et al.* (*16*), which were based on the pioneering economic work of Leontief (*17*). Early attempts to quantify the embodied energy of goods ignored the energy costs of labor, capital, and government services. These factors do have substantial energy costs. Labor consumes energy directly in the form of fuel and food, and indirectly as fuel energy embodied in shelter, clothing, education, and social services, and other commodities. These energy costs can be incorporated directly in calculations of embodied energy (*18*), or can be thought of as an energy opportunity cost (*19*) for labor, which is the amount of fuel that would have to be diverted from other uses to substitute for labor at the margin.

Standard production functions do not account for the important physical interdependence between energy and all other factors: the availability of all factors created by humans depends on the existence of free energy in the natural environment. Capital and labor are combined to extract energy from the environment, but they cannot create in a physical sense the free energy and matter from which they are derived. Thus, elasticities of substitution between natural resources and capital and labor calculated at the level of the firm or industry do not necessarily reflect true substitution possibilities over the economy as a whole. Including the direct and indirect energy costs of producing capital and labor reduces the degree to which capital and labor can be substituted for fuel in production (*20*).

Fuel use and economic output. Fuel use and economic output in the United States have been highly correlated for at least the past 90 years (*21*). This relation is shown in various ways in Figs. 1 and 2. The high coefficient of determination of Fig. 1c is consistent with the hypothesis that, at least in the past, economic output and fuel use have been tightly linked. While a causal relation from fuel use to GNP or vice versa cannot be verified, a strong contemporaneous link between the two variables is supported (*22*).

The results of statistical analyses of long time series of economic variables often are dominated by trends rather than correlations between annual variations in the variables. The validity of the statistical correlation of Fig. 1 was analyzed further with a Box-Jenkins transfer function analysis, a procedure that can remove the nonstationary components of the two time series. When this analysis is applied to the first differenced time series of real GNP and fuel use in the United States from 1900 to 1980, the results support a significant interrelation between the annual rates of change of GNP and fuel use (*23*).

Cross-sectional analysis of direct plus indirect fuel use and economic output in the United States reinforces the results of the time series analysis. Regression analysis of embodied fossil fuel, hydro, and nuclear energy use and dollar value of output across 87 sectors of the U.S. economy indicates a strong correlation between the two variables if the energy costs of labor and government services are included (*18*, *24*) (Fig. 2). This relation holds true for all the years for which the requisite national input-output tables are available.

Fuel efficiency. Despite problems inherent in measuring fuel quality, fuel use, and GNP as a measure of welfare (*25*), the fuel use/real GNP (E/GNP) ratio remains a popular and not inappropriate measure of fuel efficiency (*26*). The U.S. E/GNP ratio has declined 42 percent since 1929, about half of this since 1973 (Fig. 3a). This decline has been interpreted by some as meaning that factor substitution and conservation measures have decreased substantially the quantity of fuel used per unit of economic output and that similar improvements are possible in the future (*6*). We believe this interpretation of changes in the E/GNP ratio overestimates past improvements and potential future gains in actual energy efficiency.

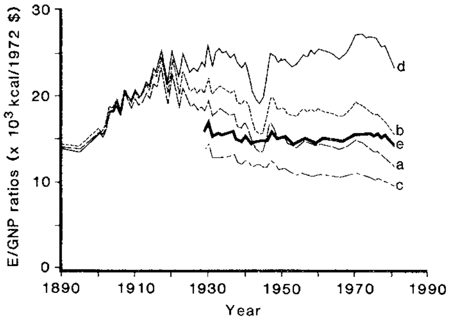


Fig. 3. Fuel/real GNP ratio for the United States. (a) No fuel or GNP modifications. (b) Fuel quality factors of 1.3 for petroleum, 1.0 for coal, and 4.0 for primary electricity and no GNP modifications for changes in household fuel use. (c) Fuel quality factors in (b) and GNP modified for effects of changes in household fuel use (*27*). (d) Fuel quality factors of 1.74 for petroleum, 0.92 for coal, 16.8 for electricity, and no GNP modifications. (e) Fuel quality factors as in (d) and GNP modified for changes in household fuel use (*27*).

Figure 3 shows the sensitivity of the E/GNP ratio to corrections made for fuel quality and to GNP modifications to account for relative shifts in fuel use between sectors of the economy. Between 1929 and 1981, a period when the ratio was declining, three factors which are not normally considered as contributing to improved fuel efficiency account for 96 percent of the annual variation in the E/GNP ratio (*27*). The factors are (i) the proportion of total fuel use accounted for by petroleum, (ii) the proportion of total fuel use accounted for by primary electricity (hydro and nuclear), and (iii) the proportion of direct fuel use in final demand (that is, gasoline or electricity used by households) versus intermediate demand sectors (oil or electricity used in manufacturing).

An empirical examination of the relation between these factors indicates that 69 percent of the variation in the E/GNP ratio since 1929 can be attributed to changes in the type of fuel used. As the percentage of high-quality fuels such as petroleum and primary electricity increased, more economic work was done (more GNP produced) per heat equivalent burned, and the E/GNP ratio declined. Correcting fuel use data for changing fuel quality produces a smaller overall decline in the E/GNP ratio (Fig. 3, lines a, b, and d) and even a slight increase in the ratio if the quality factors derived from our regression analysis (*27*) are used (Fig. 3, line d). Thus, much of the decline in the E/GNP ratio has been due to our ability to expand the use of higher quality fuels.

A relative shift in direct fuel use from final demand sectors to intermediate sectors, or vice versa, also changes the E/GNP ratio. For example, a dollar's worth of fuel purchased by households represented 145,000 kilocalories in 1972, whereas a dollar's worth of *nonfuel* good or service purchased by households represented only 5,600 to 11,800 kilocalories (*28*). Thus, the E/GNP ratio is sensitive to the partitioning of fuel between direct household use and fuel use to produce goods consumed by households. Such relative shifts in the point of fuel combustion account for 27 percent of the variation in the ratio since 1929; they were most important during World War II, when petroleum use was rationed, and since 1973, when the high price of fuel has discouraged its direct use by households. Eighty-eight percent of the decline in the E/GNP ratio since 1973 can be explained by the declining proportion of GNP spent on fuel by households. Lines c and e in Fig. 3 show the effects on the ratio of including corrections for fuel quality and for relative shifts in fuel use between households and intermediate sectors. When these effects are accounted for, the corrected E/GNP ratio shows little or no long-term trend since 1929 (Fig. 3, line e).

We do not argue that there have been no energy efficiency improvements during this period. Even with corrections, the E/GNP ratio does show a modest decline since 1973, indicating that higher fuel prices have led to real efficiency improvements, as other analysts have suggested (*29*). The fuel quality and GNP modifications are an attempt to include important attributes of fuel use and social welfare not accounted for in uncorrected fuel use and GNP statistics. The E/GNP ratio is sensitive to such modifications. Our regression analysis suggests that technological change which has led to a decline in the E/GNP ratio has often relied on intensified use of higher quality fuels. Our analysis does not support the hypothesis that the shift toward a service-oriented economy, such as the United States has undergone since World War II, is a significant factor in the decline in the E/GNP ratio.

Labor Productivity and Technical Change

In many economic models, technological advance is presented as an exogenous driving force powered by advances in human knowledge that increase labor and capital productivity. Denison (*7*) states that advances in "human knowledge of how to produce things at low cost" are the most important causes of the increase in per capita national income observed between 1948 and 1973. In this and other analyses, technological change is not measured directly, but rather is assigned the residual of increases in per capita income after all "tangible" factors have been accounted for. Because energy and natural resources are not considered tangible factors by most analysts, a large residual remains. Griliches and Jorgenson (*30*) stated that relabeling changes in factor productivity as 'technical progress" or "advance in knowledge leaves the problem of explaining growth in total output unresolved."

From an energy perspective, productivity gains are facilitated by technical advances that enable laborers to empower their efforts with greater quantities of high-quality fuel embodied in and used by capital structures. As Cottrell (*5*) observed, "productivity increases with the per capita increase in available energy." Various empirical analyses support this view, and cross-sectional and temporal changes in labor productivity are correlated with the quantity of fuel used to empower a worker's efforts. Boretsky (*31*) noted that higher labor productivity rates in the United States than in Western Europe nations were associated with the substantially greater quantities of fuel used per employee in the United States. We found that in the U.S. manufacturing sector, output per worker-hour is closely related to the quantity of fuel used per worker-hour (*32*) (Fig. 4). A similar relation exists in the U.S. agricultural industry.

Such relations can be merged with standard economic models to explain historical changes in labor productivity. From 1900 to 1973 the real price of fuel declined relative to the wage rate, and fuel was substituted for labor in many processes. Labor productivity increased during this period. Since 1973 the price of fuel has risen relative to the wage rate, and labor has been substituted for fuel, thereby reducing productivity. While other factors certainly affected the decline in labor productivity in the 1970's, a biophysical analysis supports those analyses which indicate higher fuel prices as a significant contributor (*33*).

Table 1. Estimates of energy return on investment (EROI) ratios for some existing and proposed fuel supply technologies (*54*). Numbers in parentheses for electricity generation include a quality factor based on a heat rate of 2646 kcal/kWh.

Process	EROI
Nonrenewable	
Oil and gas (domestic wellhead)	
1940's	Discoveries >100.0*
1970's	Production 23.0, discoveries 8.0
Coal (mine mouth)	
1950's	80.0
1970's	30.0
Oil shale	0.7 to 13.3
Coal liquefaction	0.5 to 8.2
Geopressured gas	1.0 to 5.0
Renewable	
Ethanol (sugarcane)	0.8 to 1.7
Ethanol (corn)	1.3
Ethanol (corn residues)	0.7 to 1.8
Methanol (wood)	2.6
Solar space heat (fossil backup)	
Flat-plate collector	1.9
Concentrating collector	1.6
Electricity production†	
Coal	
U.S. average	9.0 (27.0)
Western surface coal	
No scrubbers	6.0 (18.0)
Scrubbers	2.5 (7.5)
Hydropower	11.2 (33.6)
Nuclear (light-water reactor)	4.0 (12.0)
Solar	
Power satellite	2.0 (6.0)
Power tower	4.2 (12.6)
Photovoltaics	1.7 (5.1) to 10.0 (30.0)
Geothermal	
Liquid dominated	4.0 (12.0)
Hot dry rock	1.9 (5.7) to 13.0 (39.0)

*Based on discovery rates reported by Hubbert (*44*) and the assumption that energy use in drilling was less than 1 barrel per foot [Hall and Cleveland (*44*)]. †Does not include energy in fuel.

Energy and Inflation

The high rates of inflation that have recently plagued most industrialized nations can be explained by uniting the importance of fuel use and money supply. If an expanding money supply stimulates demand beyond the level that can be satisfied by existing fuel supplies, price levels must rise (*34*). A historical analysis indicates that changes in the ratio of money supply to fuel use are significantly correlated with changes in the consumer price index since 1890 (*35*) (Fig. 5). Manipulation of the monetary, and even fiscal, policy as a means of stimulating economic growth may now be less effective due to the increasing real physical cost of obtaining new quantities of fuel from the environment.

Natural Resource Quality from an Energy Perspective

The issue of natural resource scarcity has received considerable attention in recent years (*36*). Many suggest that the negative economic effects of depleting high-quality mineral deposits can be mitigated indefinitely through technical innovation and/or the use of more energy and capital structures to mine vast quantities of low-quality ore (*9*). Evidence for this hypothesis is that capital and labor inputs per unit output in the extractive sectors have either declined or remained stable throughout most of this century (*37*), a trend attributed to technical advance in those industries.

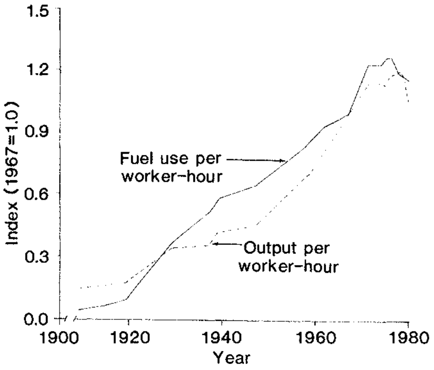
When analyzed from a physical perspective, the trend in the scarcity of some important natural resources is less reassuring. Technical improvements in the extractive sectors have made available previously uneconomic deposits only at the expense of more energy-intensive forms of capital and labor inputs (*38*). Physical output per kilocalorie of direct fuel input in the U.S. metal mining industries has declined 60 percent since 1939 (Fig. 6a), although a few exceptions to the trend are known (*39*). The energy cost per ton of metal at the mine mouth for industrially important metals such as copper, aluminum, and iron has risen sharply as their average grade declined. For all U.S. mining industries (including fossil fuels), output per unit input of direct fuel has declined 30 percent since 1939. This and other analyses (*40*) substantiate Brobst and Pratt's (*41*) statement that the cost and physical availability of fuel may well be the most important factors determining the limits to the economic exploitation of many nonrenewable resources.

Claims such as "it is simply not true . . . that average rock will never be mined" (*42*) to meet society's needs must be evaluated in light of the energy and environmental costs associated with mining and processing vast amounts of elements at or near their crustal abundance. Such costs had little negative economic impact prior to the 1970's, when domestic oil production was still increasing and real fuel prices were stable or declining. Energy costs of mineral extraction are especially important now because the energy costs of extracting fuel itself have increased substantially.

U.S. oil discoveries peaked in about 1930 and oil production in 1970 (*43*). For natural gas these dates were 1950 and 1973, respectively. As we have increasingly exhausted the possibilities of finding new large petroleum deposits, the rate at which we find new oil per unit of drilling effort in the lower 48 states has declined precipitously (*44*). The large increase in drilling effort since 1973 has not reversed this decline. As a result, the running average EROI for oil and gas at the wellhead has declined precipitously (Fig. 6b) (*45*). In Louisiana, a region that has accounted for 17 percent of all domestic oil and gas discovered and produced to date, the EROI for natural gas extraction declined from 100:1 in 1970 to 12:1 in 1981 (*46*). There has been a similar decline in the ratio of the energy in the petroleum we obtain from foreign sources compared to the energy required to make the goods and services we exchange for that petroleum (Fig. 6b) (*45*). Foreign suppliers acquired the leverage to raise oil prices dramatically in 1973 because domestic production could not keep pace with domestic demand, a gap that began in the late 1940's and was accentuated following the 1970 peak in domestic oil production. The bituminous coal industry shows a similar but less dramatic trend over the past 15 years. The EROI for coal at the mine mouth has decreased from about 80:1 in the mid-1960's to about 30:1 in 1977 (Fig. 6b) (*45*).

Declining resource quality and higher fuel prices impede economic growth by diverting increasing amounts of capital and labor to the extractive and resource processing sectors. Throughout most of this century, the real dollar value of the mining sector share of real GNP was relatively small and constant, averaging 3 to 4 percent (Fig. 7). This led some to conclude that natural resources were a small and unimportant factor of production (*47*). By 1982, however, more than 10 percent of real GNP was needed to extract mineral resources from the environment. Most of this increase was for fossil fuel purchases, which in 1981 were 4.5 times greater in inflation-corrected dollars than in 1972, despite the fact that total fossil fuel use was about the same in both years. Clearly, the cost of minerals is not "irrelevant" to our standard of living, as some suggest (*9*).

Alternative fuel sources. Because of the importance of net fuel supply, continued economic growth hinges in large part on our ability to develop new fuel



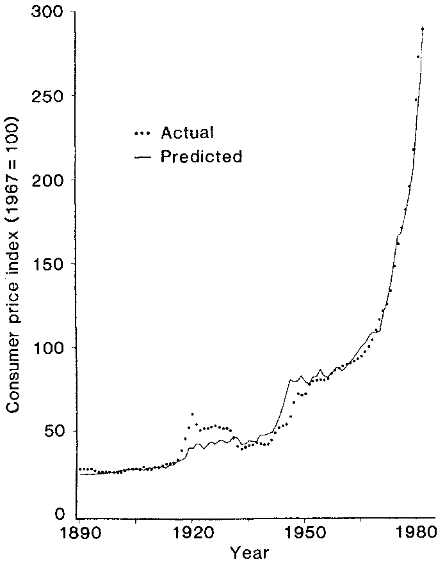
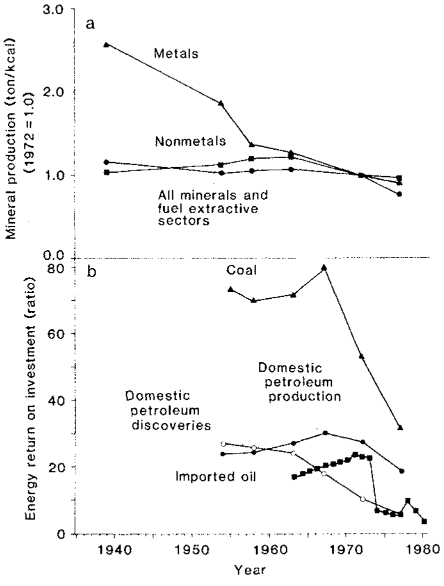


Fig. 4 (left). Productivity per worker-hour (as measured by real value added per worker-hour) and fuel use per worker-hour in the U.S. manufacturing sectors from 1909 to 1980. Fuel use includes fossil fuels and electricity (*32*). Fig. 5 (right). Results of regression model that predicts the level of the consumer price index (CPI) (1967 = 100) as a function of the ratio of the money supply (M2) to fuel use. Fuel use includes fossil fuels, nuclear, and hydropower. The curve represents values for the CPI as predicted by the ratio of M2 to fuel use. The points are actual CPI values (*35*).



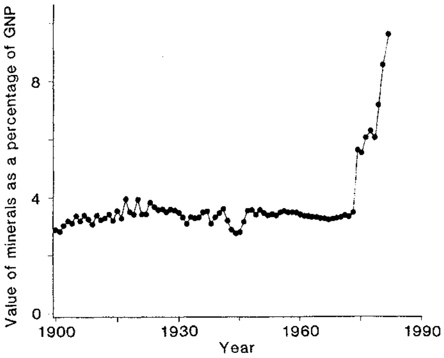


Fig. 6 (left). (a) Ratio of output per unit fuel (tons per kilocalorie) used by extractive sectors of the U.S. economy (Standard Industrial Code sectors 10 to 14). Index of physical output is from (*57*). Index of fuel use includes fossil fuels and electricity. (b) Net energy return (EROI) over time for U.S. fossil fuel sources. For domestic coal and petroleum (oil plus gas), energy use includes both direct use of fuels and electricity and energy embodied in purchased machinery installed and other supplies used as reported by the Census of Mineral Industries. EROI for imported petroleum is the ratio of energy in petroleum imports to energy embodied in goods exchanged for that petroleum (*45*). All the EROI ratios presented are conservative in that they exclude the energy costs of refining, transportation, labor, government, and environmental services. Fig. 7 (right). Real dollar value of fuel and nonfuel minerals as a percentage of real GNP in the United States from 1900 to 1981 (*58*).

sources with EROI's comparable to those we use today. As the values in Table 1 indicate, most alternative fuel sources have a positive but small EROI relative to fossil fuels. For proposed "inexhaustible" sources such as large-scale photovoltaics and fusion and breeder reactors, it is not yet clear whether the EROI will be large, marginal, or less than break-even. Current estimates of the EROI for new technologies are probably overly optimistic because the record shows we have routinely underestimated actual capital costs of new energy process plants by more than 100 percent (*48*). A recent survey of 40 nuclear power plants in various stages of construction in the United States indicates that they all will eventually cost an average of seven times their first cost estimates (*49*).

Conclusions

In one of the first detailed empirical analyses of fuel use in the United States, Tryon (*50*) stated in 1927 that

> Anything as important in industrial life as power deserves more attention than it has yet received from economists. . . . A theory of production that will really explain how wealth is produced must analyze the contribution of this element energy.

Toward this theory of production, our analysis emphasizes the economic importance of changes in the quality and availability of fuel and other natural resources faced by the United States. Declining energy return on investment for fuels and increasing energy costs for nonfuel resources have a negative impact on economic growth, productivity, inflation, and technological change. Some economic models that guided economic growth during the preceding period of high-quality resource abundance have become increasingly less powerful because they do not account for the importance of changes in natural resource quality and availability.

Some resource analysts have suggested that there was no physical reason for domestic oil demand to outstrip domestic production by almost 100 percent in the 1970's (*51*). The degree of depletion of domestic petroleum in the 1970's, however, was predicted accurately with physically based models over a quarter-century ago by Davis, Hubbert, and others (*44*). The "energy crisis" and ensuing economic problems cannot, therefore, be blamed solely on misguided regulatory policies, the monopoly power of the Organization of Petroleum Exporting Countries, a conspiracy among the multinational oil companies, or lack of proper economic incentive for the petroleum exploration and development industry. While these factors may have exacerbated the situation, underlying the energy crisis and the ensuing economic malaise was the declining physical availability of high-EROI petroleum, and a reliance on economic and political models that did not account for it. Market incentives in response to a quadrupling of real oil prices and a 280 percent increase in drilling effort between 1972 and 1981 made no significant reversal in declining oil and gas production and discovery rates in the United States.

If we are to sustain current levels of economic growth and productivity as minimum long-run goals, alternative fuel technologies with EROI ratios comparable to that of petroleum today must be developed, or there must be unprecedented improvements in the efficiency with which we use fuel to produce economic output. Many discount the decreasing availability of high-quality fossil fuel deposits, stating that such depletion is merely a signal of our impending transition to a society based on a "boundless supply of energy at reasonably low cost" (*52*) such as breeder or fusion reactors or direct solar power. But past experience with capital-intensive ventures such as fission and synfuels suggests that it would be unwise to assume a priori that fusion or any other proposed fuel source will necessarily have a large EROI. Although we should research aggressively all potential fuel technologies, particularly in regard to their potential EROI, we should also plan for the contingency that new high-EROI sources might not be found.

Based on our analysis, the economic recovery from the 1980–1982 recession was due in part to declining OPEC oil prices, which themselves were due to decreased world oil demand brought about by the worldwide recession. In effect, the EROI for imported oil rose recently because importing nations had to divert less of their output to trade for oil. Rising economic activity and fuel use, however, will again confront the economy with the physical limits of declining domestic fuel quality, and thereby increase the chances of a tight oil market in the near future (*53*). Our ability to cope with any economic contingencies will depend on the ability of our economic models to account for the biophysical constraints on human economic activity, and on the ability of our citizenry to accept and adapt to the realities of physical constraints imposed on our economic possibilities.

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parameters. A residual analysis showed that the remaining part is a random process. The mean of the residual is 0.0004, the standard error of the mean is 1.9860, and the t value of the mean for a test against zero is 0.0002. We thank K.-G. Maler for bringing this point to our attention.

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27. The regression equation is E/GNP = 60.41 − 52.33 (%PETRO) − 344.27 (%ELEC) + 10.41 (%PCE), $r^2 = 0.95$, $P < 0.0001$. The quantity %PCE is the percentage of personal consumption expenditures spent on direct fuel. This was algebraically manipulated to yield:

$$\mathrm{E} + 52.33\,(\%\mathrm{PETRO})(\mathrm{GNP}) + 344.27\,(\%\mathrm{ELEC})(\mathrm{GNP}) = 60.41\,(\mathrm{GNP}) + 10.41\,(\%\mathrm{PCE})(\mathrm{GNP}) \tag{1}$$

The left side of the equation was set equal to a revised energy input $\mathrm{E_R}$:

$$\mathrm{E_R} = \mathrm{E} + 52.33\,(\%\mathrm{PETRO})(\mathrm{GNP}) + 344.27\,(\%\mathrm{ELEC})(\mathrm{GNP}) \tag{2}$$

Then $\mathrm{E_R}$ was regressed on uncorrected fuel use data to calculate implied quality factors without GNP as a variable:

$$\mathrm{E_R} = \alpha + \beta_1\,(\text{oil + gas}) + \beta_2\,(\text{coal}) + \beta_3\,(\text{hydro and nuclear power}) \tag{3}$$

The equation was fit yielding $\beta_1 = 1.74$, $\beta_2 = 0.92$, $\beta_3 = 16.8$, which are the implied quality factors. The α was not significant, $r^2 = 0.999$, $P < 0.0001$. This indicates that the economic value (or quality) of electricity relative to fossil fuels may be several times its conversion value. Equations 1, 2, and 3 were combined to calculate a revised GNP, $\mathrm{GNP_R}$:

$$\mathrm{GNP_R} = \mathrm{GNP}\,[1 + 0.172(\%\mathrm{PCE})]$$

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57. Index of physical output of extractive sectors (Standard Industrial Code sectors 10 to 14) from U.S. Bureau of Mines. Index of fuel use calculated from fuel use data reported by the U.S. Bureau of Census, *Census of Mineral Industries, 1954, 1958, 1963, 1967, 1972, 1977*.

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