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Net Energy Analysis: An Economic Assessment

Net energy analysis has serious limitations on its usefulness for public policy decisions.

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Public and private decision-makers are increasingly confronted with more complex and far-reaching public policy decisions concerning energy. Examples include responsible development of energy resources, allocation of energy research and development funds, legislated restrictions or subsidies for energy production and use, land use restrictions, and government regulation of major energy-producing industries. Decisions regarding all of these require analysis of the many social, economic, environmental, and political options and the delicate balancing of disparate yet competing interests, goals, and values.

Economists have for many years endeavored to develop concepts and measures broad enough to encompass the major issues in public policy decisions. Generally they argue that, given unlimited wants and scarce resources, the real cost to society of allocating inputs to one undertaking is that alternative uses of those inputs are forgone. Under ideal conditions, the market values of inputs and outputs or costs and benefits could be summed, with appropriate allowance for the time value of money (discounting), to assess any undertaking. Recognizing that conditions are generally less than ideal because of market imperfections and so on, economists have generally made various adjustments to market values and even estimated market values when no markets exist.

One of the more ubiquitous and difficult problems encountered in public policy decisions is that inputs and outputs or costs and benefits (including environmental and social impacts) are commonly measured in different units. One may optimize in a multivariate framework or one may attempt to convert these "apples and oranges" into common units so that optimizations may proceed in a univariate framework. Economists have tried variations of both approaches, but the most frequently used approach is to transform all or most variables into dollars, thus making dollars the numeraire.

Increasingly in energy analyses, however, the use of market-determined values, economic techniques, and even analyses that evaluate all, or even most, effects in terms of dollars is being challenged. Woodwell (*1*), Schumacher (*2*), and others have argued that services provided mankind by the environment are extremely undervalued. Mead's well-intentioned effort (*3*) to place a dollar value on birds was strongly protested by environmentalists.

Others, including Congress, have proposed that traditional economic analysis at least be supplemented with the net energy analysis utilized by Odum (*4*), Berry and Fels (*5*), Chapman (*6*), and Slesser (*7*). This congressional mandate is contained in section 5 of the Non-Nuclear Energy Research and Development Act of 1974 (*8*), which states that "the potential for production of net energy by the proposed technology at the stage of commercial application shall be analyzed and considered in evaluating proposals." Some net energy advocates take a stronger position, however, but have stopped short of proposing that net energy analysis replace traditional economic analysis in energy evaluations. For example, Gilliland (*9*) recently stated that net energy analysis is more comprehensive and "can provide more information of a less conflicting nature to policymakers" and has concluded that, in energy analyses, the use of "energy as the physical measure of environmental and social impacts, of material, capital, and manpower requirements, and of reserve quantities reduces the need to compare or add 'apples and oranges.' "

Many of the above criticisms are merely that traditional economic techniques cannot or have not yet achieved precise results, hence are inaccurate or inappropriate. Many economists have made these criticisms themselves and have attempted to correct these deficiencies (*10*). Of deeper concern, however, are criticisms that seek an alternative conceptual framework to guide decision-making or to value inputs and outputs. While no net energy advocate has, to my knowledge, explicitly favored that it replace traditional economic analysis, the use of net energy accounting to value inputs and outputs and to guide decision-making is more than a switch to a different numeraire and has far-reaching implications, particularly for the allocation of resources. Economists have traditionally used market-determined prices (corrected for market imperfections and so forth) to fulfill these functions; hence the use of net energy accounting represents, perhaps unknowingly, a marked departure from economic theory.

Since Congress has mandated the use of net energy analysis in assessment of new energy resources and net energy analysis represents a marked departure from economic theory, it is surprising that economists have not published any assessments of net energy analysis.

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What is needed is an assessment of the important assumptions and concepts underlying net energy analysis and a comparison of the different conclusions reached by net energy analysis and economic analysis.

The remainder of this article is divided into three parts: (i) the concept of net energy and its important assumptions are defined; (ii) net energy analysis is subjected to an economic assessment; and (iii) some observations are made concerning the uses and limitations of the technique in the public policy-making process.

Net Energy Analysis

Net energy has been defined as the amount of energy that remains for consumer use after the energy costs of finding, producing, upgrading, and delivering the energy have been paid (4). Labor, capital, information, and material inputs (including the environment) are used to produce energy. Since each input requires some energy for its production, the energy contained in these inputs subsidizes energy output, with society receiving only the difference or "net" energy between the two. In summing the various types of energy subsidies, all energy measures must be of the same quality. Energy quality is calculated by evaluating the energy used in converting from one energy form to another—from coal to electricity, for example. Quality in this context does not refer to the distinction between enthalpy (free or available energy, which can be transformed into work) and entropy (bound or unavailable energy, which cannot be transformed into work).

Primary resources such as energy or copper are viewed as a gift of nature. Society has merely to commit inputs to locate, extract, upgrade, and manufacture commodities from these primary resources. All inputs have an energy measure to account for their total value, although the energy value of labor is quite unsettled, depending on the standard of living assumed. All inputs are included in energy analysis, and if one resource such as copper were exhausted, energy would be used to synthesize substitutes from other materials.

The exclusive emphasis on energy and the energy content of inputs in net energy analysis rests on the concept of energy as the ultimate limiting factor, since substitutes for other inputs can always be synthesized from it. Energy may be divided into available energy (enthalpy) or unavailable energy (entropy). The second law of thermodynamics tells us that the entropy of a closed system increases continuously and irrevocably toward a maximum. In addition, it has been noted that (i) energy is the only commodity for which a substitute cannot be found, (ii) potential energy is required to run every type of system or production process, and (iii) energy cannot be recycled without violating the second law of thermodynamics (9).

As society uses up its higher-grade energy resources it will require more and more energy inputs (a larger energy subsidy) to produce a given amount of energy. While gross energy production may increase rapidly over the next few centuries as we consume our remaining fossil fuel resources, net energy will certainly increase less rapidly and may eventually begin to decline, particularly if one views the earth, moon, and sun as a closed system. Regardless of the exact scenario assumed, however, energy is clearly regarded as the ultimate limiting factor, particularly since substitutes for other inputs can always be synthesized from it.

Given the net energy concept and the unique characteristics of energy, some proponents of net energy accounting have concluded that, in energy analyses, the use of energy as the physical measure of environmental and social impacts and of material, capital, and manpower requirements reduces the need to compare apples and oranges. Kilocalories therefore replace dollars as the common unit of measurement and as a method of valuing inputs and outputs.

One of the major advantages claimed for net energy analysis by some of its proponents is that the resulting energy evaluation will not change with time or with changes in factors that usually affect traditional economic analyses. For example, Gilliland (9) has stated that

> . . . dollar evaluations often obscure the larger scale effects of an action because the dollar costs and benefits accrue to different people at different times. Dollar evaluations also change with time due to the changing value of money and assumptions concerning, for example, the discount rate. For a specific technology, such as the present nuclear fuel cycle and its supporting techniques, the energy evaluation will not change with time.
>
> Energy analysis of alternative energy supply technologies can provide more information of a less conflicting nature to policy-makers.

An Economic Assessment

A starting point for an economic assessment of net energy analysis is to determine under what conditions economic analysis and net energy analysis would reach similar conclusions. Beginning first with a simple economic analysis, we define the production function for energy output Q as

$$Q = f(X_1, X_2, \ldots, X_n) \qquad (1)$$

where f is a monotonic increasing function, the X_i's are inputs, and the partial derivatives

$$f_i > 0 \qquad i = 1, 2, \ldots, n$$
$$f_{ii} < 0$$

The production function is assumed to be concave from below, continuous, and at least twice differentiable with respect to the inputs. Note that the production function is a mathematical function describing the most technically efficient physical relationship between the quantity of each input used (the X_i measured in tons and so forth) and the quantity of energy output (Q) measured in kilocalories. The n inputs include inputs required to reduce pollution to levels required by society.

Using a simple static model for maximization of profit, π, and assuming that output price, P_q, and input prices, P_i, are determined by competitive markets, profits may be stated as revenue less costs or

$$\pi = P_q Q - \Sigma_i P_i X_i \qquad (2)$$

or upon substitution

$$\pi = P_q f(X_1, \ldots, X_n) - \Sigma_i P_i X_i \qquad (3)$$

The first-order conditions for profit maximization are

$$P_q f_i - P_i = 0, \qquad i = 1, 2, \ldots, n \quad (4)$$

or

$$P_i = f_i P_q \qquad (5)$$

Second-order conditions require that the nested Hessian determinants alternate in sign starting with $f_{11} < 0$ (11).

Turning to net energy analysis, we define α_i as the competitive, market-determined kilocalories of energy used directly and indirectly to produce one unit of input i. Net energy, Ω, may then be defined as energy output less the energy contained in the inputs or

$$\Omega = Q - \Sigma_i \alpha_i X_i \qquad (6)$$

or

$$\Omega = f(X_1, X_2, \ldots, X_n) - \Sigma_i \alpha_i X_i \qquad (7)$$

Again, using a simple static model and assuming that one wishes to maximize net energy, the first-order conditions are

$$f_i - \alpha_i = 0, \qquad i = 1, 2, \ldots, n \quad (8)$$

or

$$f_i = \alpha_i \qquad (9)$$

The second-order conditions are identical to those stated above for profit maximization.

Comparing the first-order conditions from Eqs. 5 and 9 we have upon rearrangement

$$P_i = \alpha_i P_q \quad (10)$$

Equation 10 states that economic analysis and net energy analysis would yield identical results if inputs were priced according to their energy content alone.

But what does it mean to value or price inputs such as labor, raw materials, machinery, and so on according to their direct and indirect energy content alone? Clearly, it is an energy theory of value, with the relative prices of all goods determined solely by the ratio of their energy content

$$P_i/P_j = \alpha_i/\alpha_j \quad (11)$$

More than just the appropriate selection of the numeraire is implied, however; prices are formulated as if energy were the only relevant resource constraint, and the relative scarcity of nonenergy inputs becomes a factor only if it leads to a change in the energy content of these inputs. In essence, all nonenergy resources are viewed as transformed energy, and in this one-commodity world all derivative products are priced according to their energy content.

Even in this type of world, however, there would be short-term needs to deviate from energy content pricing simply because unexpected shifts in either supply or demand would alter existing market conditions and create windfall gains or losses on existing stocks—that is, energy embodied in inventories or capital equipment. As long as there is a lag, for example, between an increase in demand and the increase in capacity to supply energy (or one of its derivative products), existing inventories and capital equipment as well as current output will have a temporary scarcity value completely unrelated to energy content or the past or future price of energy.

A short-term deviation from energy content pricing would be socially useful since it would indicate that something has increased in relative scarcity and is a constraint (at least temporarily), that consumers should conserve it and find substitutes, and that producers should search out new supplies, technologies, and capacity to meet increased demand. If market prices are not allowed to prevail, then nonmarket actions such as government rationing and production incentives would be required.

This example indicates that energy content pricing is an efficient short-term pricing or resource allocation method, even in an ideal world where perfect substitutes for nonenergy inputs can be synthesized from energy, albeit with a finite lag. The longer and more uncertain these lags become, the less perfect our capability to synthesize substitutes, and the less perfect our ability to predict demand or supply shifts, the greater the need for frequent and longer-duration (mid-term and long-term) departures from energy content pricing.

At some point the differences among commodities become sufficiently large to justify an n-commodity world. Nonenergy inputs are indeed constraints and energy content pricing becomes hopelessly inappropriate and inefficient for short-term or long-term decision-making. The important point is that the world is full of relative scarcities and always will be. A price or value theory that ignores this fact by assuming that all inputs are merely transformed energy and that energy is the only constraint would be unworkable. Markets would not clear; investment, resource allocation, and other decisions would be distorted; and real income would be suboptimized and improperly distributed since prices determined by energy content alone were not designed to accomplish these objectives. Net energy would, however, be maximized.

Net energy theories, of course, never intended these outcomes, nor were they designed to accomplish these objectives, but this is precisely the point. They are based on a very narrow set of assumptions and have a narrow objective. Prices determined by competitive markets under ideal conditions are capable of accomplishing these objectives, and this accounts for economists' interest in competitive market prices. Certainly, market imperfections and so on require that actual market prices be used with great care and even require government action in some cases, but there is little to suggest that prices or values based on energy content are in any way superior or even equally useful for either short-term or long-term analyses.

As far as extremely long run analysis is concerned, one can certainly question whether energy will be the ultimate limiting factor. The view that energy will ultimately limit human activities has been advanced by many individuals associated and unassociated with net energy analysis. Hubbert (*12*) and Georgescu-Roegen (*13*) have argued this point of view quite persuasively and the latter has called entropy the true "taproot of economic scarcity." Yet even the work of Meadows *et al.* (*14*) recognized that potential scarcity in the long run encompassed more than just energy. Furthermore, while the need to develop inexhaustible or quasi-inexhaustible energy sources is clear, the notion that energy resources are finite is questionable. Any assessment of energy resources is dependent on the state of knowledge assumed.

Fossil fuel reserves should last at least another century or two, but breeder reactors would provide energy for several hundred years. Fusion energy, if perfected, would be quasi-inexhaustible, with a supply of hundreds of millions of years available. Solar energy is, of course, nearly inexhaustible. In addition, solar arrays positioned in space could gather energy to be beamed back to the earth by maser beams. Resources on other planets could be exploited in a similar fashion. Finally, countless unknown energy sources such as gravity waves may be available in the future. Oil and gas were unknown energy sources more than a century ago, as were fission and fusion more than 50 years ago. Clearly, energy resources can only be defined relative to a current state of knowledge, and currently known fossil and fission resources alone will give humans many centuries to develop inexhaustible and perhaps now unknown energy resources.

Technological change is the only possible solution to this problem of intergenerational equity since the world is not finite as long as technological change is possible. The real issue is whether technological change can take place and be absorbed by society at a rate commensurate with society's needs; yet, as Gold (*15*) has noted, attempts to define and measure technological change and its impacts, let alone its rate of change, have been less than satisfactory.

Several additional points should also be made. First, it should be noted that inputs other than energy have been regarded as unique and have been emphasized in developing value theories. For example, 18th-century physiocrats, noting that man cannot create material things, regarded land as the unique input. Marxists have regarded labor as the unique social cost and have emphasized labor inputs in developing their economic theories. Both of these theories have encountered difficulties, at least as theories of relative values, principally because it has not proved useful to view all commodities as merely transformed land or labor.

Finally, with regard to the claim that the results of net energy evaluations will not change through time or because of changes in factors that affect economic analysis, it must be noted that this claim is absurd even if technology is assumed to be fixed. Net energy calculations are market determined in that they depend on the technology, the structure of the industry, and the prices existing at the time they are made. Changes in prices will alter the manner in which inputs are produced and will undoubtedly alter their energy content. A net energy analysis of a specific technology, such as the present nuclear fuel cycle and its supporting techniques, depends on the prices, discount rates, and other market conditions existing at the time it was made. As prices change through time, the energy content of steel, copper, cement, and all other inputs used in the nuclear fuel cycle are likely to change because of substitution effects, even if there is no change in technology and market structure. The energy used to manufacture steel, for example, differs depending on whether the open hearth, electric, or basic oxygen process is used, yet the selection of any one of these processes is an economic decision dependent on the relative prices of inputs. Similar conclusions follow for mineral reserve and resource estimates. Gilliland's assertion (*9*) that net energy estimates of mineral reserves or resources will not change through time or with changing dollar values is clearly erroneous—net energy estimates are price and market dependent even if technology is assumed fixed.

In general, net energy analysis is plagued by many of the same problems that confront economists. Externalities; imperfect competition in important labor, capital, and resource markets; government actions including subsidies, taxation, and regulation; uncertainty; problems of intratemporal and intertemporal equity raised by the uneven distribution of risks and benefits arising from nuclear energy or climate modification—all of these complicate any energy analysis whether it be guided by net energy or economic principles. For example, an economic assessment of the risks and benefits of the many U.S. energy supply or conservation options would be complicated by uncertainties about the inputs required and the resulting outputs (including environmental residuals). A net energy assessment would be complicated by the same factors. By insisting that net energy analysis is somehow not bedeviled by the types of problems confronting economic analysis, some net energy advocates have merely avoided many of the issues of most concern to decision-makers. Public policy decision-makers should be aware of this limitation.

Energy is and will probably remain a small portion of the total costs of producing most inputs and outputs. The value weights with which net energy analysis aggregates apples and oranges are far different from those entering an economic analysis. To revalue all inputs and outputs according to net energy weights would certainly cause massive short-term and long-term changes and dislocations within a society. While no one is suggesting that this be done, one might ask why decision-makers should be guided by net energy analysis and allocate resources as if it had been done. Gross national product is certainly a poor indicator of social well-being (and was never intended to be one), yet net energy may be far worse. Allocating resources to maximize net energy may reduce our dependence on the Arab States, but it would be worth knowing the corresponding reduction in gross national product. As abused as our economic system is by politicians, unions, corporations, regulators, and individuals, it still makes sense to assess options and implement solutions by careful use of the scientific principles that govern the system.

Net Energy and Public Policy Decisions

Public policy decisions grow increasingly complex as we attempt to balance more and more precisely the legitimate concerns of all elements of society. While we recognize that the problems are multidimensional, we frequently seek unidimensional measures such as dollars, utiles, and kilocalories. But to squabble over the appropriate numeraire is to miss the point.

Complex social problems generally require complex analytical frameworks and have complex solutions. Economists have endeavored to develop concepts and measures broad enough to encompass the major issues in public policy decisions. While the concepts are far from perfect, the greatest weakness has been in our ability or willingness to measure. The 1960's, for example, sharpened our awareness of and ability and willingness to measure environmental and social costs, yet the concept itself was with us for decades.

Contrary to the assertions of net energy advocates, however, net energy analysis is plagued by many of the same problems that confront economists and is not comprehensive but extremely narrow both in assumptions and objectives. Our ability to synthesize substitutes from energy is limited, energy is certainly not the only relevant short-term or long-term resource constraint, and inputs and outputs should not be valued according to their energy content alone for purposes of short-term or long-term economic or public policy decision-making. Yet Congress has mandated the use of net energy analysis and has therefore encouraged public policy decision-makers to allocate resources according to net energy theories. In addition, the Energy Research and Development Administration has stated that it plans to integrate net energy evaluation of technologies into the national plan for setting energy R & D priorities (*16*) and the Department of the Interior's Office of Research and Development has contracted for energy analysis of several technologies.

Assuming that public policy decisions require a broad analytical framework, one might wonder how net energy analysis will be used by these agencies. In addition, do decision-makers understand the limitations on its usefulness? Should additional studies of these types be funded, or are there better methods of analysis for integrating vitally needed inputs into the decision-making process? Should the congressional mandate on net energy analysis be rescinded? These are questions that deserve expanded debate now.

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