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ENERGY MODELING AND NET ENERGY ANALYSIS

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If energy prices continue to increase, industry will make capital investments and operating changes to save money in the purchase of energy. Governmental policies can affect this situation, both in controlling prices and in providing economic incentives for energy conservation. The rate of implementation of technological change (such as new alloys) and institutional change (such as municipal solid waste recovery agencies) is difficult to forecast, also.

CONCLUSION

We feel that net energy analysis and energy analysis of materials flows are valid analytical and management tools. Much more research and demonstration is in order before these tools will find their best and most useful applications. A problem remains in fostering the understanding of energy analysis by potential users.

There is continuing debate amongst net energy analysts on the desirability of developing standard ground rules for net energy analysis. There is some merit in such an approach, especially if Federal agencies intend to utilize net energy analysis in decisions.

We feel that net energy analysis provides a new dimension to information which can be used in decisions and planning. It provides physical data which cannot be gleaned from the scrutiny of economic information.

The user of net energy analysis must be aware of the different qualities and types of energy which are all measured by British thermal units (or some other physical energy measurement unit.) The utility of each type of energy will be different. The same principle applies in using economic units of measurement, of course. For example, a company may have physical and intangible assets, all represented by dollars. Some of these asset dollar values will have been depreciated according to rather arbitrary rules established by accountants and governments. however, the corporate executive will have a different utility function for a dollar representing fixed assets, liquid assets or quick assets. In utility or qualitative terms, dollars vary according to what they represent. This concept applies to physical units of energy as well.

Possible applications of net energy analysis are in engineering studies, technology assessments and comparisons, alternative policies vis-a-vis alternative trajectories and end uses, resource and depletion studies, and resource allocation to meet end use goals.

The main problems with net energy analysis seem to lie, not with net energy analysis itself, but in semantics and decision theory.

SOME THEORETICAL CONSIDERATIONS OF NET ENERGY ANALYSIS

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ABSTRACT

Several methodologies have been developed to perform net energy analysis. However, considerable confusion still surrounds the purpose and definition of the concept. This paper develops a working definition of net energy analysis based on fundamental principles. It is ascertained that the critical element of the approach is the determination of the gain function: the function that describes the relationship between the energy produced by and the energy required for an energy production process. Furthermore, it is determined that the temporal dimension of the gain function is a key item of interest. This results from the two major factors that can impact the gain of an energy production process over time: technological advance and resource depletion. The former is responsible for gain enhancement while the latter contributes to gain deterioration. Evaluation of technological advancement requires a methodology that can account for all the subtle and pervasive "energy subsidies" that contribute to the successful deployment of the technology. Most of the existing methods of net energy analysis attempt to accomplish this task. However, only one methodology, energy circuit analysis, addresses impacts related to the resource depletion component of the gain function. Nonetheless, the method relies on an "energy quality" scale that is itself technology dependent.

The major hypothesis of this paper is that a gain function can be determined independent of technology. Such a function, based on thermodynamic principles, would be utilized to determine the minimum theoretical work necessary to process an energy resource of any particular quality and spatial distribution. Several forms of the gain function are explored to investigate possible modes of dynamic behavior. In addition, ramifications and potential applications are discussed.

SOME THEORETICAL CONSIDERATIONS OF NET ENERGY ANALYSIS

INTRODUCTION AND SUMMARY

Net energy analysis is a theoretical construct that attempts to identify and contrast the energy expended with the energy produced in the process of providing energy to society. The rationale for performing net energy analysis is that energy production processes in which energy expenditures exceed energy yields are unproductive to society at large. In such a case, energy expenditures would be better "spent" on alternative processes that provide more energy than they consume. Proponents of net energy analysis argue that conventional economic valuation of energy resources is inadequate to make such determinations. The principal reason for the alleged deficiency is that economic theory fails to account fully for the myriad energy "subsidies" that are provided to most energy production processes. For example, it is hypothesized that the production of nuclear power is subsidized by the availability of "cheap" oil. A net energy analysis would thus attempt to determine the "gain" (i.e., the ratio of the energy provided to society to the energy expended by society) of the nuclear fuel cycle by evaluating all direct and indirect energy expenditures applied (e.g., coal, oil) and comparing the sum to the total energy product (kilowatt-hours). Several methods have been developed to make this type of calculation. The principal methods are process analysis, input/output analysis, hybrid analysis and energy circuit analysis.

Process analysis is a procedure in which the energy production process is differentiated into a series of connected "modules." Energy flows into and out of each module are evaluated as direct or indirect contributions. The values are summed across all modules according to source types (e.g., electricity, fossil fuel, etc.) and compared by ratio to the final process yield. The chief disadvantage of this approach is that no mechanism is provided to examine indirect energy contributions on a consistent basis. Also, because each type of energy is evaluated separately, the multitude of ratios does not provide a basis for evaluation of the gain of the overall process.

The input/output approach, a derivative of the economic input/output technique developed by Leontief, is more suited to the valuation of indirect energy subsidy. In this method, the economy is divided into a large number of economic sectors. Through matrix manipulation, the "embodied" energy in any sector can be determined and energy flows ascertained between each pair of sectors. Embodied energy is defined as the contribution of energy to any sector from all other sectors. It is then normalized for each sector on a per-unit-of-output basis. The resulting set of coefficients can then be applied to each element in a production process to determine the total requirement. The chief disadvantage of this approach is that the coefficients are based solely on a flow basis. Sectors in which inventory levels are changing (e.g., electric utility stockpiles of coal in preparation of a coal strike) or sectors in which production flows are diverted for expansion of new plant and equipment, will "distort" the values of the coefficients. Because of this limitation, the energy I/O approach can only provide a "snapshot" of net energy. Net energy calculation based on the coefficients could thus vary widely and inconsistently from year to year.

Hybrid analysis is a synthesis of process analysis and input/output analysis. While maintaining the disadvantage of the I/O technique, it provides a basis to account for the indirect energy contribution in process analysis formulations. Its proponents argue that, as a coupled approach, it is capable of examining the details of specific energy technologies.

The energy circuit approach attempts to determine all energy contributions on a comparable "energy quality" basis. In this approach all energy contributions, including dollars, are converted to a common energy quality and evaluated accordingly. The main problem with this method is that energy quality conversions from one form to another are process dependent and are themselves a priori measures of net energy. A main feature of this approach is its concern with the "state" (i.e., size, population, mass, etc.) of the system that is receiving the energy and how it interacts with the energy source over time.

With the exception of the energy circuit approach, the above methods concentrate on developing a gain ratio (the ratio of energy produced to energy expended) or a series of ratios as an end product. However, investigation of the gain ratio reveals that such emphasis is misplaced. What is important is how the gain changes over time. The change in the gain is due primarily to two major factors:

- advances in technology
- depletion characteristics of energy resources

The impact of technology advance is heralded as the driving force of improved and expanded energy extraction from energy sources.* In this regard, advances in technology would act to improve the gain over time. Opposing such improvements is the deterioration of the mineable energy resources (fossil and nuclear fuels). As the better resources are usually mined first, those that remain are of poorer quality and are more difficult to obtain. Thus, over time, these characteristics tend to worsen the gain. Technology aside, energy sources that are of a flux nature (i.e., solar and the "renewable") would tend to have a constant gain over time.

To incorporate the impact of technology advance, complete enumeration of all indirect energy subsidies is required. However, for the assessment of depletion impacts on net energy position, it is hypothesized that gain determinations can be calculated solely on the basis of change in the state of energy resources over time (i.e., the change in concentration and spatial distribution of the resources). Just as the Carnot ratio provides the basis for determining the maximum efficiency possible for a heat engine operating between two reservoirs of heat at different temperatures, a gain function dependent on resource state provides a basis for the minimum thermodynamic work necessary to process that resource. Determination of gain in this fashion has the substantial advantage of avoiding assessment of the subtle and pervasive indirect energy subsidies. The disadvantage is that such determinations are necessarily ideal valuations and therefore do not provide a mechanism to identify the gain associated with a particular technology. However,

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*One of the purposes of net energy analysis is to substantiate these claims.

the advisability of implementing novel or exotic technologies for non-yielding energy processes could be ascertained in advance.

There are many ramifications of this approach to net energy analysis. The power of the analysis lies in its ability to ascertain an elusive measure of the "health" of the system in contrast to the detailed accounting of potentially misleading physical indicators. The fact that physical energy production may grow at exponential rates does not indicate that energy available to do productive work increases in a similar fashion. In addition to pretesting the efficacy of new technologies on poor yielding energy sources, evaluation of the dynamic net yield can aid planners in determining the energy available for future economic growth and maintenance. Another key implication is in the realm of policy analysis. For example, the advisability of controlling prices of energy resources can be ascertained. If, for example, net energy first increases and then decreases over time, decontrolling the price of an energy resource (such as natural gas) may stimulate production but accelerate the gap between gross and net. The result could be a very small increase or even a decrease in the amount of energy available to perform other useful work. Similar implications may result for environmental policy analysis. For example, if pollution control efforts are concentrated on energy production technologies that have rapidly deteriorating gain ratios, then the expense of controlling polluting emissions in proportion to the net energy made available could grow to mammoth proportions. For this reason, a more effective means of measuring environmental impact would be to evaluate the impact and control of pollutants on a net energy basis rather than a gross energy basis.

Another advantage of the dynamic net energy approach is in the assessment of problems involved in making transitions from one principal energy source to another. For example, in a transition from oil to coal or from coal to solar, evaluation of net energy can indicate whether the transition can succeed on a thermodynamic basis. Just as a minimum energy requirement is defined for a rocket attempting to escape the earth's gravitational pull, a minimum amount of net energy may be required to undergo a successful transition from one energy source to another. In this case, a transition "window" would be defined as the time in which net energy in excess of that required for maintenance could be used to build the infrastructure for the transition source. Once the window is passed, other alternatives would have to be examined.

In summary, this report reaches the following conclusions:

- The critical aspect of net energy analysis is the dynamic behavior of net energy gain over time.
- Existing methods of performing net energy analysis are deficient in determining time-varying gain.
- Search for a gain-function, independent of process, based on thermodynamic considerations, will provide the foundation for a credible analysis.
- Many uses of net energy analysis are conceivable. Planning and policy analyses in economic, regulatory, environmental and energy areas could all benefit from net energy calculations.

BACKGROUND

The Net Energy Controversy

The concept of net energy and interest in methodologies to perform net energy analyses were boosted into national prominence with the passage of PL 93-577, the *Federal Nonnuclear Energy Research and Development Act of 1974*. This law mandates ERDA [DOE] to direct comprehensive programs in research, development and demonstration of new energy technologies. It also requires "the potential for production of net energy by proposed technologies at the stage of commercial application [to] be analyzed and considered in evaluating proposals" (1).

In response to this requirement, a workshop was convened by the National Science Foundation in August 1975, at Stanford University, to "afford an opportunity for extended discussion on details of methodology and application of net energy analysis and a chance to seek consensus on various points" (2). Review of the workshop proceedings shows that these ambitious goals were not realized. In addition to the fact that no consensus was reached on acceptable net energy methodology or its proper application, the 47 workshop participants (including many nationally and internationally recognized researchers who had attended a similar international workshop the previous year (3)) could not agree on a *definition* of net energy terms or what a "proper" net energy analysis is capable of providing. The controversy over the scope and utility of net energy has continued with many claims and counterclaims appearing in the recent literature (e.g., 4-5).

Amid the controversy of potential applicability and useful methodology, the objective of net energy analysis is straightforward. *Briefly stated, the concern of net energy analysis is to determine which processes associated with the production and delivery of energy to the economy require more energy to maintain than they yield.* The motivation for this concern was expressed by Odum in a paper to the Royal Swedish Academy of Science in 1973 (6). The following points summarize the proponents' case for net energy analysis.

1. *Energy must be expended for the production of energy.* As with all physical processes, the Laws of Thermodynamics require the expenditure of available energy to provide useful work. Energy production and processing is no exception.

2. *As the availability of "cheap" energy sources declines, the amount of energy required to produce additional energy increases.* As is the case with fossil fuels, the depletion of energy resources is a monotonic function in which (ideally) the "best" resources (those with high energy content) are mined and processed first. As a result, the difficulty of mining and processing remaining fuels always increases. In view of the first point, the minimum energy required must by necessity increase as well.

3. *At some point, a time will be reached when the amount of energy expended for production of new energy will exceed the value of the energy produced.* The time at which this point is reached is accelerated by two counter-yielding trends of resource depletion. First, as discussed above, the energy required to process remaining resources increases monotonically with time. Secondly, the "quality" of the energy mined decreases as remaining resources become more dilute and dispersed, delivering less energy per unit processed. The effect may result in a "useful" resource life considerably less than "physical" or "economic" valuations.

4. *When the actual yield becomes negative (produced energy minus expended energy is less than zero), then the energy produced can no longer be considered a viable energy source.* Energy expended on continued production past this point would best be spent on other "yielding" technologies or expended directly in the main economy.

These points are, for the most part, consistent with conventional economic and engineering approaches to the energy resource problem. However, proponents of net energy analysis argue that conventional economic and engineering techniques have inherent limitations that preclude adequate net energy determinations. These shortcomings can be categorized in three major areas:

- assessment of indirect energy subsidies
- economic distortion of energy value
- accountability of externalities

The principal requirement of any net energy calculation is the need to determine the value of all energy produced and the value of all energy expended in the process of production, both direct and indirect. Proponents concede that conventional forms of analysis can account for most of the energy produced and most of the direct energy expended for production. However, it is felt that the indirect component of necessary energy expenditures involves many subtle and pervasive "energy subsidies" that conventional analysis can not account for in any systematic way.

Proponents point out that conventional approaches rely on market determined price to assess the relative contribution of energy to the production of additional energy. Based on such an approach, the value of energy to the economy at large is approximately 4% of the total value of the economy. Its contribution to the energy production sector is estimated to have a similar relative value. Thus in economic terms, only 4% of the requirement to process energy for use in the economy is derived from energy resources. Proponents argue that if the actual flow of energy through the economy is determined including the indirect flows that cannot readily be measured, the contribution of existing energy sources to the production of new energy sources would be substantially greater.

The second major contention for executing independent net energy methodologies is that conventional analysis relies on economic foundations that "distort" the value of energy sources. Proponents argue that such distortions result from delays in value determination and an incorrect concept of relative value. In the first case, proponents make the point that delays in the economic system cause the costs of energy production to be underestimated. Under this concept, the price which a potential energy source will command will always be equal to or less than its "energetic" cost of production. This is motivated by the belief that decreases in net energy are prime drivers of inflation. Thus, because of the structure of the economy, there will always be a delay from the time the inflationary impetus is introduced (from the production of inferior energy sources) and the time the effect is absorbed (an increase in the cost of production). Under such a scenario, an inflationary spiral is created that will cause the production of energy supplies to continue beyond the point of net yield.

A similar case is made for the production of alternate energy supplies. Conventional analysis assigns relative economic values among energy sources. As production costs vary among sources, those inferior resources that have high economic production costs relative to current prices are said to become "economic" when the marginal price of a competing source reaches the threshold of the inferior source's production cost.

Net energy advocates argue that the price/cost relationship between sources is *always* relative and thus it is impossible for the price of a superior energy source ever to "catch up" to the production cost of an inferior energy supply or for an inferior energy supply ever to become "economically feasible." They argue that only by making net energy calculations can the feasibility of an alternate energy supply be proven.

The third major point concerns the ability of conventional analyses to capture the impact of energy development on what are normally considered externalities: environmental, social, and institutional considerations. Of these areas, proponents feel the case for net energy analysis is exceptionally strong in the environmental area. This is because environmental attributes can be given energy assignments more readily than dollar assignments, based on their natural productivities and energy flows. Thus a more direct relationship between natural and man-made systems can be established and effects calculated more directly.

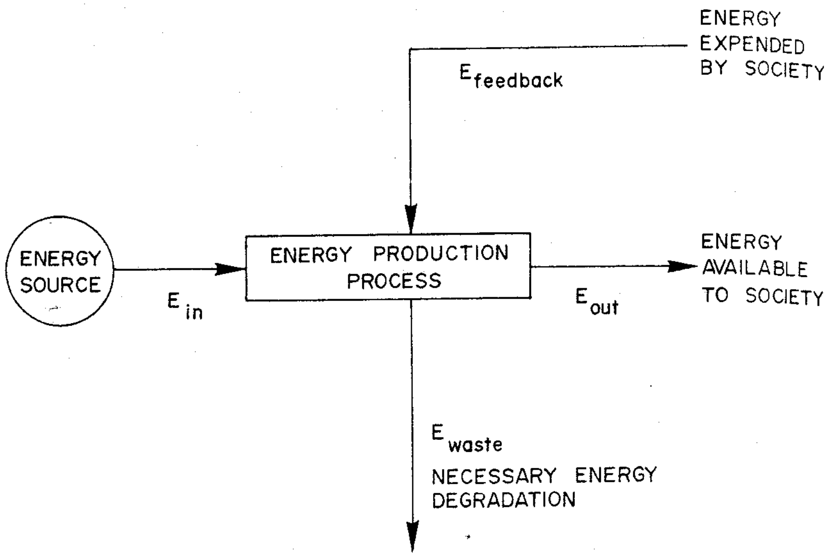
THERMODYNAMIC BASIS OF NET ENERGY ANALYSIS

For those familiar with the Laws of Thermodynamics, the concept of net energy would appear to clash with established thermodynamic principles. Net energy, like net profit, implies that a stream of energy "revenues" is sustained in excess of necessary energy "expenditures," i.e., more energy is gained than is spent. For an energy conversion process, the existence of such a positive gain would appear to violate First Law restrictions against energy creation and Second Law requirements of energy degradation.

Inspection of Figure 1 reveals the source of these apparent anomalies. When generalized as a single production process, four basic energy flows can be identified. These include the potential energy flow from the energy source (E_{in}), the energy flow ($E_{feedback}$) required for concentration and production, the flow resulting from necessary Second Law generation of waste heat (E_{waste}) and a flow of energy available to perform other useful work (E_{out}). Expressed in these terms, all thermodynamic conventions are upheld. First Law conservation requirements are maintained as the sum of the energy flows entering the production

FIGURE 1

BASIC ENERGY FLOWS INVOLVED IN NET ENERGY ANALYSIS



THERMODYNAMIC CONVENTIONS:

First Law (Energy Conservation): $E_{in} + E_{feedback} = E_{out} + E_{waste}$

Second Law (Energy Degradation): $E_{waste} > 0$

Net Yield: $E_{out} - E_{feedback}$

Net Gain: $\frac{E_{out}}{E_{feedback}}$

process (E_{in} + $E_{feedback}$) are equal to the flows resulting from the process (E_{out} + E_{waste}). In addition, Second Law requirements of necessary energy degradation are upheld by providing the waste heat pathway (E_{waste}) with a non-zero flow such that E_{out} is always less than the sum of E_{in} and $E_{feedback}$. Calculation of net yield and net gain is concerned with the flows in which society has a vital interest: the energy flow available to provide useful work (E_{out}) and the energy flow which society must provide to obtain it ($E_{feedback}$). Thus net yield is expressed as the difference of E_{out} and $E_{feedback}$ while ($E_{out}/E_{feedback}$) provides a relative measure of the gain obtained.

CONCEPTUAL PERSPECTIVE

Review of the existing methodological approaches to net energy analysis reveals that some fundamental concepts may have been overlooked. For this reason, this section uses basic conceptual constructs to examine the core of the theoretical rather than the methodological approach. The development centers on the gain ratio (the ratio of realized to expended energies) and its significance in the overall analysis.

A Tentative Net Energy Formulation

Applying fundamental relationships, a time dependent function of net energy can be formulated. While several forms may be appropriate, a single approach is developed for illustrative purposes.

Using the basic definitions developed earlier, net energy is defined as the difference between gross energy delivered and the feedback energy required to sustain the gross production:

$$\text{NET} = \text{GROSS} - \text{FEEDBACK} \tag{1}$$

In addition, the relationship between gross and feedback is determined by the gain:

$$\text{GAIN} = \frac{\text{GROSS}}{\text{FEEDBACK}} \tag{2}$$

Substitution of expression (2) into (1) yields upon rearrangement:

$$\text{NET} = \text{GROSS}\ (1 - \frac{1}{\text{GAIN}}) \tag{3}$$

Clearly, when the gain falls to unity, no net energy is produced. However, for processes with high gain ($\sim$>10:1), little impact is realized on the overall process. Figure 2 plots gain vs. net as a fraction of gross. When the gain is 10:1, the net fraction is .9. Similarly, when the gain is 100:1, the net fraction is .99. Thus, for a high gain, the net fraction is approximately constant in an asymptotic manner. It is only when the gain drops below 6:1 that the net fraction is affected seriously. Table 1 shows the results of several investigations of the net energy of nuclear power. The calculated gains range from 3.82:1 to 5.15:1 while the net fraction varies from .738 to .806. However, what do such values reveal about the viability of nuclear power? It is the contention of this report that single valued gains (i.e., time independent) do not provide

FIGURE 2

NET FRACTION OF GROSS AS A FUNCTION OF GAIN

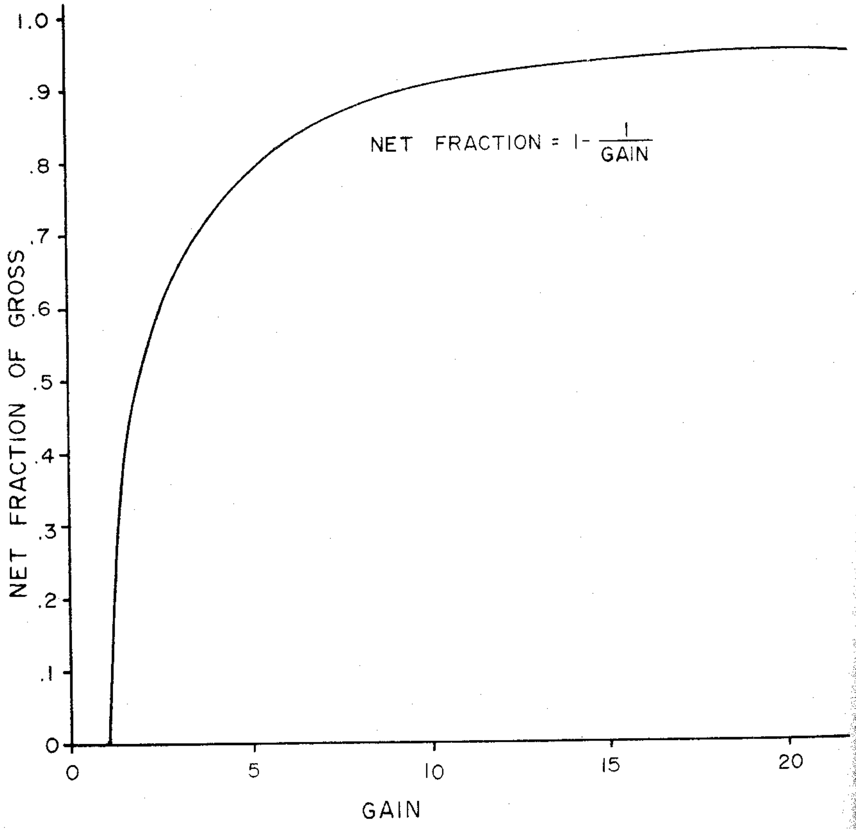


Table 1. Comparison of Some Calculated Gains for Nuclear Energy

Investigator	Units of External Energy per 1,000 Units of Output	Gain	Net Fraction $(1-\frac{1}{GAIN})$
Development Sciences, Inc.	238	4.20	.762
State of Oregon Study	194	5.15	.806
University of Illinois	210	4.76	.790
Institute for Energy Analysis	248	4.03	.752
ERDA-76-1	262	3.82	.738

Source: "A National Plan for Energy Research, Development and Demonstration: Creating Energy Choices for the Future, Volume 1, The Plan," ERDA 76-1, Energy Research and Development Administration, Washington, D.C., April 1976.

sufficient information to make relevant inference of the adequacy of non-renewable resources technologies to provide more energy than they require. This results because even for non-renewable resources that are of uniform quality and density, the amount of work necessary to process a unit of resource may vary as the total resource is consumed. Thus the gain for any non-renewable energy source cannot be represented as a constant but as a variable that changes continually over time.

As a first approximation, assume the gain for a resource of uniform quality can be formulated as an exponential decay function driven by the function of the total resource consumed at time t:

$$GAIN\,(\rho(t)) = GAIN_0 \exp\,(-\lambda\rho(t)), \qquad (4)$$

where $GAIN_0$ is the initial gain, λ is the decay parameter, and $\rho(t)$ is the fraction of the resource consumed at time t. The form for this function is displayed in Figure 3.

The fraction of resources consumed is expressed as:

$$\rho(t) = \int_0^t \frac{GROSS(t)dt}{Q_0}, \qquad (5)$$

where Q_0 is the total amount of resources available and GROSS(t) is the gross consumption rate at time t. Let us further assume that the gross consumption rate is an exponential growth function defined as:

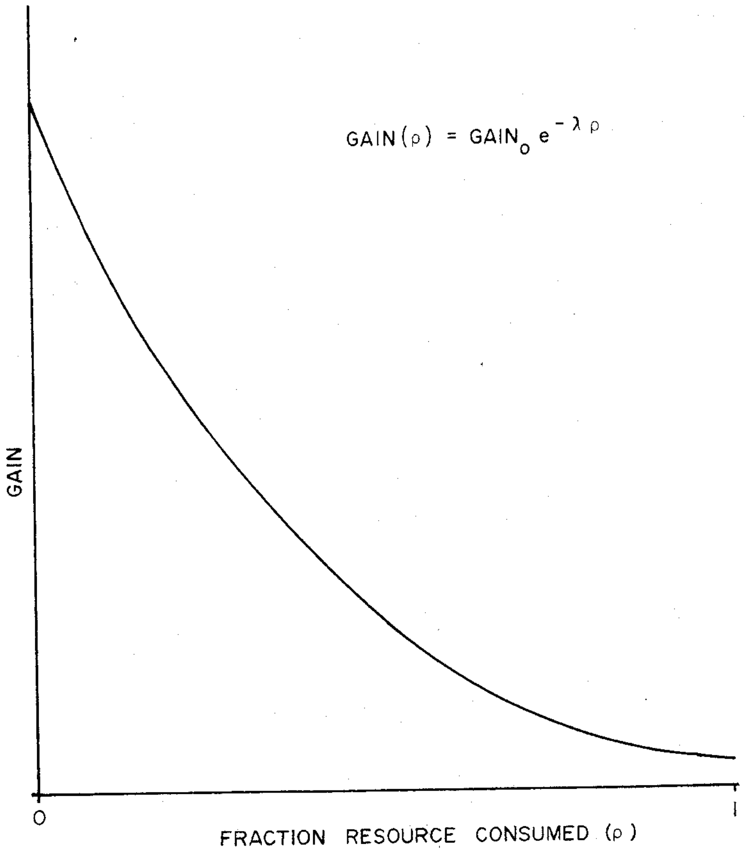
$$GROSS(t) = GROSS_0 \exp\,(\beta t), \qquad (6)$$

where $GROSS_0$ is the initial gross consumption rate and β is the growth rate of consumption. Substitution of (6) into (5) upon integration yields:

$$\rho(t) = \frac{GROSS_0}{\beta Q_0}\,[\exp\,(\beta t)-1]. \qquad (7)$$

FIGURE 3

EXPONENTIAL DECAY GAIN FUNCTION



Further substitution of (7) into (4) provides:

$$GAIN\ (\rho(t) = GAIN_0 \exp\ (\frac{-\lambda GROSS_0}{\beta Q_0}\ (\exp\ (\beta t)-1)). \qquad (8)$$

Finally, substitution of (6) and (8) into (3) yields:

$$NET(t) = GROSS_0 \exp\ (\beta t)\ \{1 - \frac{1}{GAIN_0}[\exp\ (\frac{\lambda GROSS_0}{\beta Q_0}\ (\exp\ (\beta t)-1))]\}. \qquad (9)$$

Figure 4 illustrates the behavior of this function for a set of hypothetical values. In the early years following the use of a non-renewable resource the gain is relatively high and thus net tracks gross fairly close. However toward mid-life, while gross consumption is still growing at an exponential rate, the rate of net growth slows down and peaks out with a rapid decline following. The key result from this exercise is that gain per se does not reveal the desirability or "goodness" of the process. What is important is the dynamic aspect of how the gain changes over time. For example, expectations of energy availability based on early year gain ratios will have disastrous consequences as the gain deteriorates over time.

The Form and Significance of the Gain Function

Obviously, the key to a credible net energy analysis in the context of the previous formulation is the specification of the gain function. It is hypothesized that a gain function can be found that is independent of the path used for production. If such a function can be identified then only the initial and final states need be identified. The power of a path independent gain function is that only the state of the resource and not the technology of its production need be considered. This eliminates the need to evaluate explicitly the indirect energy subsidies as required in the existing methodologies. For example an alternate gain function in lieu of equation (4) is:

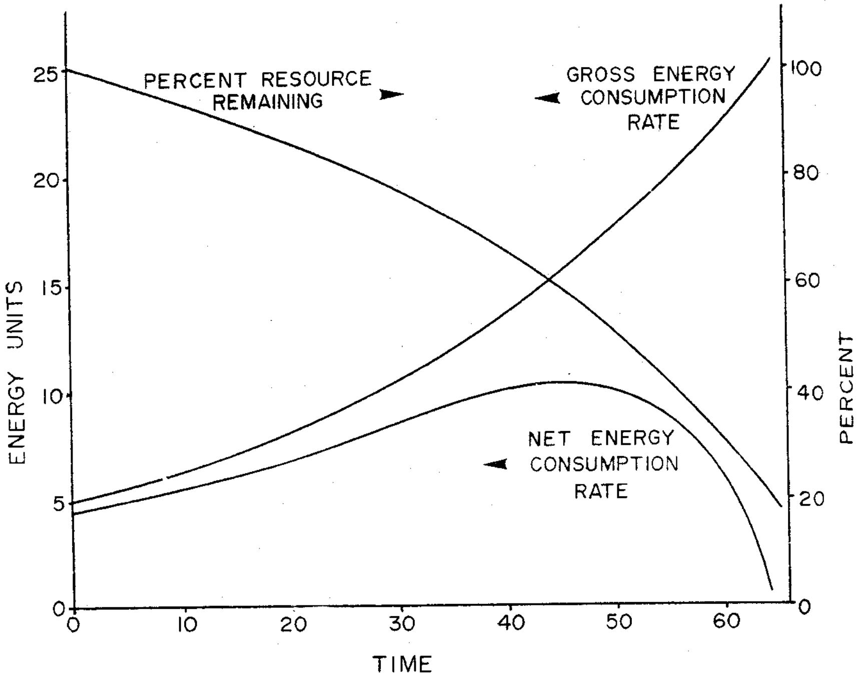
$$GAIN(t) = 1 + k \cdot \ln\ [\frac{AVAILABLE\ CONCENTRATION\ (t)}{CUTOFF\ CONCENTRATION}]\ ,$$

where available concentration (t) is the best energy mass concentration (joules/kilogram) at time t assuming all quantities with higher concentrations have been consumed prior to time t and cutoff concentration is defined as the concentration below which no net yield can be produced. Thus, when the available concentration falls to the cutoff concentration, the log of the ratio becomes zero and the gain becomes unity. Figure 5 indicates the results of an assumed hypothetical lognormally distributed resource. Note that in comparison to Figure 4, physical units have been separated into energy units. Namely, gross production is shown growing at an exponential rate in units such as tons per year while ensuing gross energy (due to the lognormal distribution of energy concentration) decays to an approximately constant rate at about mid-life. In contrast to the previous case, net energy declines continuously throughout the period.

Ideally, the proper gain function is based firmly on thermodynamic principles. A discussion of some possible formulation can be found in (7).

FIGURE 4

DYNAMIC BEHAVIOR OF RESOURCE FRACTION, GROSS ENERGY AND NET ENERGY WITH EXPONENTIAL DECAY GAIN FUNCTION*



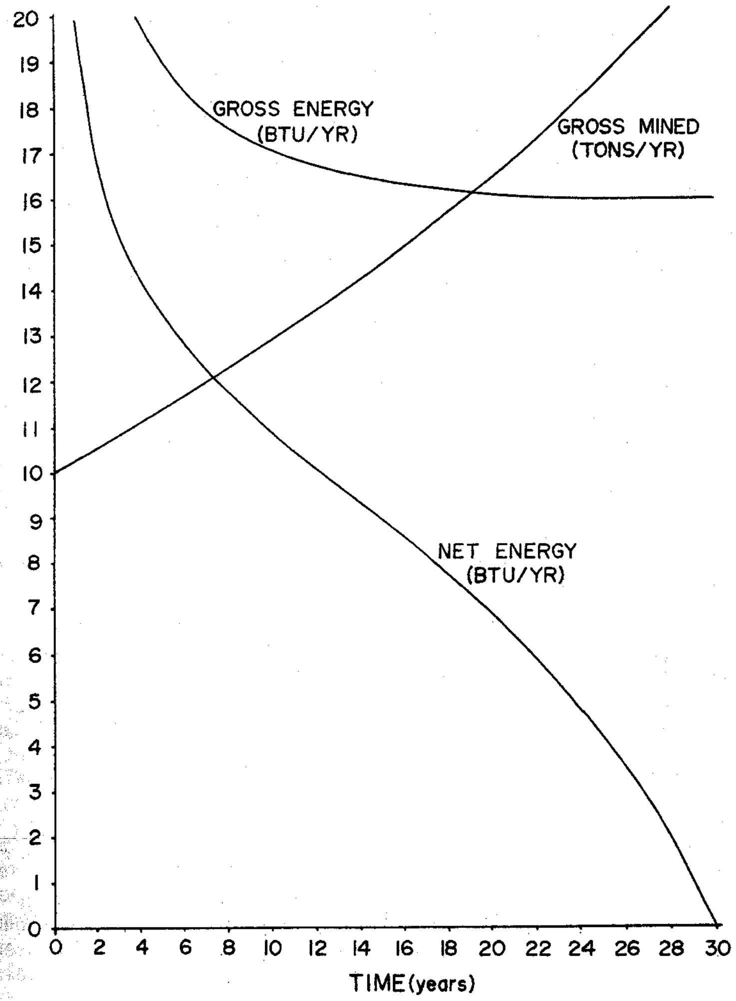
* $NET(t) = GROSS_0 \exp(\beta t)[1 - \frac{1}{GAIN_0}(\exp(\frac{\lambda\, GROSS_0}{\beta Q_0}(\exp(\beta t) - 1)))]$

Assumed values:

$GROSS_0 = 10$
$\beta = .025$
$\lambda = 2.878$
$Q_0 = 1000$

FIGURE 5

DYNAMIC BEHAVIOR OF GROSS PHYSICAL PRODUCTION, GROSS ENERGY PRODUCTION, AND NET ENERGY PRODUCTION FOR A LOG-NORMALLY DISTRIBUTED RESOURCE AND LOGARITHMIC GAIN FUNCTION*



* $GAIN(t) = 1 + k \cdot \ln (\frac{AVAILABLE\ CONC(t)}{CUTOFF\ CONC})$ with assumed values:

$k = 1$
CUTOFF CONC. = .006
AVAILABLE CONC(t) found by numerical methods from inverse lognormal distribution lnN (4.9618, .2697)

RAMIFICATIONS

As envisioned by some of the original proponents, the chief benefit of performing net energy analyses is the ability to compare the productive value of one energy source to another. The implicit assumption was that energy sources having high gain ratios are better inherently than sources having low ratios. Addition of a temporal dimension modifies this position to some degree. The reason is that when viewed as a dynamic process over time, it is conceivable that the gain ratios of different energy sources may change relative position during their respective lifetimes. Thus exclusive consideration of a singular gain ratio may be of only marginal interest.* However, the temporal aspect of the gain ratio provides several unique opportunities for application. For example, the introduction of a new technology can be evaluated over the time horizon that its principal energy source has a yielding net gain. If the "pay back" required for the new technology introduction is long compared to the time that the source will provide yielding net then the technology itself may not be worthy of introduction.

Another possible benefit of this form of analysis would be to assist planners in determination of how much net energy would be available to the economy at any given time. Then with such information, estimates of future economic growth might be executed in a more direct fashion decoupled from complex inflation corrections. Other potential policy applications include assessment of import/export energy mix and regulatory price control of energy resources. In the former category, it may be possible to evaluate the impact of oil imports against domestic production. For example, on a net energy basis, oil imports may provide more net energy than comparable domestic production. In the latter case, a net energy analysis of natural gas decontrol may show that in spite of higher physical production, increases in net energy production may be small if the gain ratio for natural gas is in a decay mode.

Net energy analysis may also have a role in environmental policy as well. For example, emission standards for fossil fuel combustion processes are expressed on a pounds of emission per million Btu of heat input basis. While providing a convenient means for regulatory purposes, environmental quality may be impacted more heavily on a net energy rather than a gross energy basis. If, for example, the gain ratio for coal is deteriorating rapidly, then emissions per million Btu of net energy input may be quite large. Such consideration could thus play an important role in the development of abatement strategies.

The above applications reveal that consideration of net energy aspects relative to other forms of analyses may provide new insight into complex problems of analysis and decision. However, much work needs to be done to insure that such analyses are based on firm fundamental principles.

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*In some circumstances, it may be useful to calculate an average gain over time:

$$\text{average gain} = \frac{\int_0^\infty \text{gross } dt}{\int_0^\infty \text{net } dt}$$

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