Center for Advanced Computation

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
URBANA, ILLINOIS 61801

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ENERGY COSTS, BENEFITS, AND NET ENERGY

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ABSTRACT

Methods for quantifying net energy impacts of individual energy facilities and entire energy-economic systems are presented. The analytical framework is developed first in the case of an economic system having only one energy sector, then it is generalized to a multifuel system where gross (rather than net) energy analyses are shown to be more useful. The relation between energy and economic feasibility is discussed by constructing an energy analog of conventional benefit-cost analysis. Empirical results are presented, comparing shale oil technology to conventional onshore drilling.

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1. INTRODUCTION

The term "net energy" refers to the output of an energy production system determined by taking full account of the energy required for inputs to the process. Energy used directly as well as indirectly must be considered. Examples of direct energy include that used to power oil wells and the energy consumed in refining processes. Indirect energy uses include that used to manufacture the steel and pipes for refineries, pipelines, tankers, etc.

An engaging, and - on the face of it - simple concept, net energy has received widespread attention in the popular press.[2] Several net energy analyses of some new technologies have been reported[3], but their conclusions are conflicting due to differences in system boundary definitions and in value judgements implied by the addition of qualitatively different energy resource inputs. Attempts to standardize methodology are still in their infancy.[4]

Concern about the net output of energy-producing technologies stems from the fact that the U.S. is almost solely dependent on nonrenewable, limited energy resources. The measure of the theoretical potential of these resources to perform work is a quantity defined precisely in physics as 'free energy'.[5] It is the only quantity that is scarce in an absolute sense: it can be literally 'consumed' unlike material resources, which can be recycled and reassembled indefinitely given adequate free energy energy to do so.[6]

The earth's endowment of free energy-containing resources are of relatively little value <u>in situ</u>; additional energy must be consumed to extract, transport, and process them into a usable form. For competitive resources such as liquid petroleum and oil shale, this 'energy to get energy' may not be equal, so it is said that the net yields of these technologies differ.

One of the five governing principles of the Federal Nonnuclear Energy Research and Development Act of 1974, speaking of evaluating proposed new energy technologies, states: "The potential for production of net energy by the proposed technology at the stage of commercial application shall be analyzed and considered ...". This creates a need for a consistent and workable methodology for evaluating new technologies. The primary purpose of this report is to suggest such a method, one in which value judgements are explicit and are left to the analyst.

It is emphasized, however, that there is nothing inherent in this method that requires subscription to an 'energy theory of value'. Quantitative assessments of the energy impact of new technologies may provide useful information for policy analysis in much the same way that environmental impact statements address external effects not adequately dealt with by the market. Among the situations where net energy assessments may be useful are:

1. An oil embargo or Alaskan earthquake suddenly disrupts oil supply to the extent that energy scarcity may significantly influence relative price movements and changes in the structure of the economic system.
2. Aggregate energy reserve figures (Btu's recoverable at a certain cost) are overestimated due to double counting because, for example, the coal estimate did not consider the oil needed to mine the coal.
3. Government must decide whether to subsidize a particular energy resource (e.g. coal by vetoing the Strip Mine Act) as part of the drive toward U.S. energy self-sufficiency. Such

policy decisions may be based in part on environmental, political, employment, and - perhaps - net energy considerations.

In this paper, I will develop the net energy concept first in the context of a world having only one energy resource. The relation between physical and economic feasibility will be discussed, along with the effects of discounting and analogies with conventional economic benefit-cost analyses. Next, generalizing to a system having several energy sectors, it will be shown that gross, rather than net, energy analyses may be more meaningful. Empirical results will be presented for two technological alternatives for producing refined oil.

2. NET ENERGY IN A SINGLE FUEL ECONOMY

Consider an economic system having only one energy resource, say coal. We may wish to evaluate the effectiveness of two technologies, such as deep and strip mining to determine which has the greatest 'net energy yield'. First we shall determine whether a given mining technology has a positive net energy yield, then compare the two alternatives.

For reasons that will become clear soon, we will need a model of the entire economic system, so we choose the simple linear Leontief one. Let X_j be the gross output of sector j and let Y_j be that portion delivered for final consumption. The output distribution equation (in matrix notation) becomes

$$(I-A)X=Y \qquad (1)$$

where A_{ij} is the amount of output from sector i needed as an intermediate input by sector j, per unit output of sector j. Denoting the energy sector row of $(I-A)^{-1}$ by ε, we interpret it as the vector of direct and indirect energy required to produce a unit of final output from each sector. This method is described in detail by Bullard and Herendeen (1975a).

It is emphasized that the system of equations (1) may be interpreted in purely physical terms,[7] where all transactions are measured in physical units unique to each sector.

2.1 The Feasibility Criterion

To determine net energy feasibility, we need only to verify that energy leaving the coal sector exceeds the energy entering that sector embodied in non-energy inputs to the process (see fig. 1). Algebraically the net energy condition is given by

$$\sum_{i=1}^{N} \varepsilon_i A_{ij} X_j \leq \varepsilon_j X_j \qquad (2)$$

where j = coal and i is summed over inputs from all N sectors of the economy. When applied to each sector, eqs(2) are simply the well-known conditions derived by Hawkins and Simon (1949), that all leading principal minors of (I-A) are positive, guaranteeing positivity of the Leontief inverse matrix. These conditions guarantee that the net yield (measured in physical units) of every sector, including the energy sector, is positive. Evaluating eq. (2) using the column of A corresponding to each mining technology separately, one may determine the net energy feasibility of each. Note that since ε is a function of the entire matrix A, it must be re-evaluated for each technology to properly account for feedback effects.[8]

Alternative treatment of feedback effects may influence the magnitude of terms in eq. (2). Specifically, a sector's output (say coal) may be defined to include that coal used in the mining process (say, to power machinery). If so, $A_{jj} \neq 0$ and X_j is larger than if that coal were

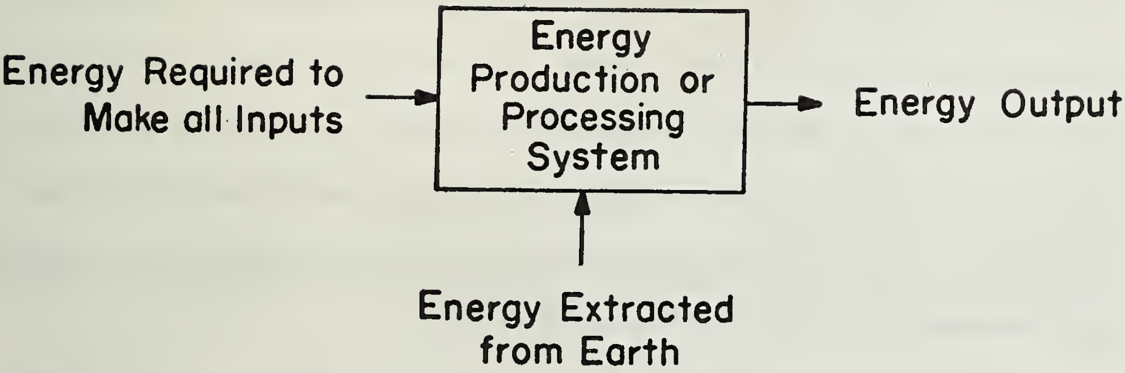


Figure 1. Energy Balance for an Energy Production System

not counted. As long as the A and X are treated consistently, the feasibility criterion (2) is valid; only the magnitudes of the terms on both sides of the inequality change. To compare strip and deep mining technologies in terms of their net energy yield, we look at the values ε_{coal} in each case. This number will always be greater than unity, representing the Btu's of coal sector output required directly and indirectly to produce one Btu of coal for final consumption.[9] It is here that the choice of the system boundary becomes important. If, as is usually done, we count coal consumed in the mining process as part of the sector's output, ε_{coal} may become arbitrarily large. For example, if it were necessary to burn 5 tons of coal to mine 6 tons (leaving only one ton to sell), ε_{coal} would be 6 and the net energy feasibility condition (2) would still be satisfied. Such a technology may be physically and economically feasible, although an out-of-context quotation of the value ε_{coal} may mislead an unsophisticated listener.

Another system boundary problem becomes apparent when we consider the coal left as pillars in underground mining. This too may affect the magnitude of ε_{coal}[10] but not the net energy yield condition, eq. (2). The decision on whether to include it may be discussed in terms of figure 2. If the analyst considers the coal in the pillars 'lost forever', he may consider the energy resource base depleted by that amount when goods and services requiring coal are consumed.[11] This is a value judgement, however, and may play a significant role in a comparison of deep and strip mining.

The points to be remembered are a) that the feasibility condition assuring a positive net energy yield may be affected by technological change anywhere in the economic system, and b) that the choice of the

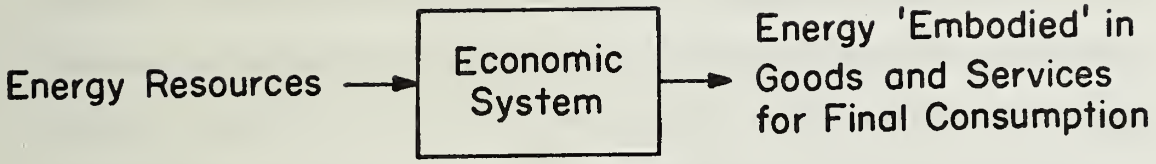


Figure 2. Allocation of Energy Resources Among System Outputs

system boundary at the energy resource (earth) interface may affect the relative magnitudes of so-called 'net energy ratios'.

2.2 Problems with System Boundaries

The feasibility conditions given by eq. (2) are consistent with the conventional definition of GNP, the final bill of goods and services shown leaving the system in fig 2. It has been suggested by Schatz (1975) that not all these goods and services should be considered 'final' outputs, such as the inputs to government agencies regulating the energy sectors (e.g. NRC, FTC, FPC, etc.). Rather than being counted as social benefits, these may be perceived as social costs[12] and accordingly, some net energy analysts consider the energy costs of these portions of final demand an input to the energy sectors. With those transactions included in the matrix A, all elements of ε will be larger than in the conventional case described earlier, and perhaps the feasibility condition (2) would not be satisfied.

Unfortunately, the computational technique chosen by many net energy analysts[13] utilizes a framework where precise specification of the system boundary is more difficult. Commonly called 'process analysis', it begins with an assessment of the direct inputs of coal, oil, electricity, etc. to the production process for a commodity. Next the direct energy inputs to production of all the non-energy inputs are tabulated. This process proceeds ad infinitum until all direct and indirect energy inputs to the production of the commodity are counted (see fig. 3). Besides obvious computational difficulties there are unknown truncation errors as well as a danger of double-counting (e.g. coal plus electricity made from coal).

Other potentially serious errors could result if the system boundary is not carefully defined and observed. If one node of the network shown in fig. 4, say that corresponding to the oil shale sector, were pulled outside the boundary and all else (including final consumption) were inside, a complete process analysis would ascribe the entire U.S. energy resource consumption to shale oil production. Such an incorrect system boundary definition would imply that shale oil production has the ultimate end of the economic system.[14]

2.3 The Effect of Growth

Nothing was said above to differentiate between the static and dynamic conditions of the system. Consider eqs. (1,2) to hold at a single point in time, regardless of whether that "snapshot" depicts a static or dynamic state. If the system is growing, the technology will reflect it in values of A larger than for the static case, for the inputs to production would include capital for plant expansion. For identical instantaneous values of Y, the growing system will require more gross production X (due to the larger A) and therefore more energy resources than the same system in a steady-state condition. The Hawkins-Simon conditions still hold and signal when the effect of growth has accelerated the rate of depletion of basic resources to the point that gross requirements exceed outputs. As in the static case, feasibility of a single technology is defined with respect to the entire economic system.

For a process analysis of the effect of growth rate on the energy resource requirements for nuclear fission, see Chapman (1974).

2.4 Energy Benefits and Costs

Let us consider the relationship between economic and energy feasibility by constructing an energy analog to traditional economic benefit-cost analysis.

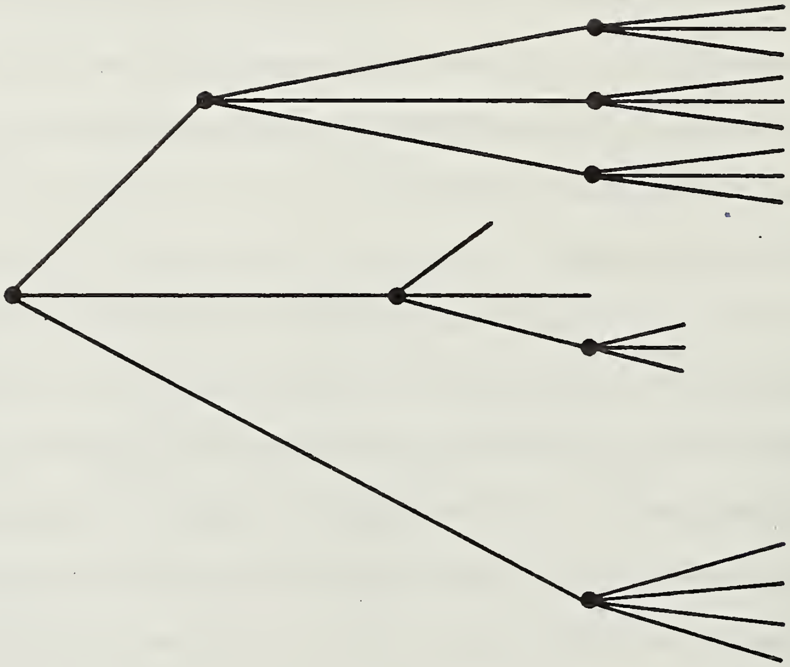


Figure 3. The Process Analysis "Tree"

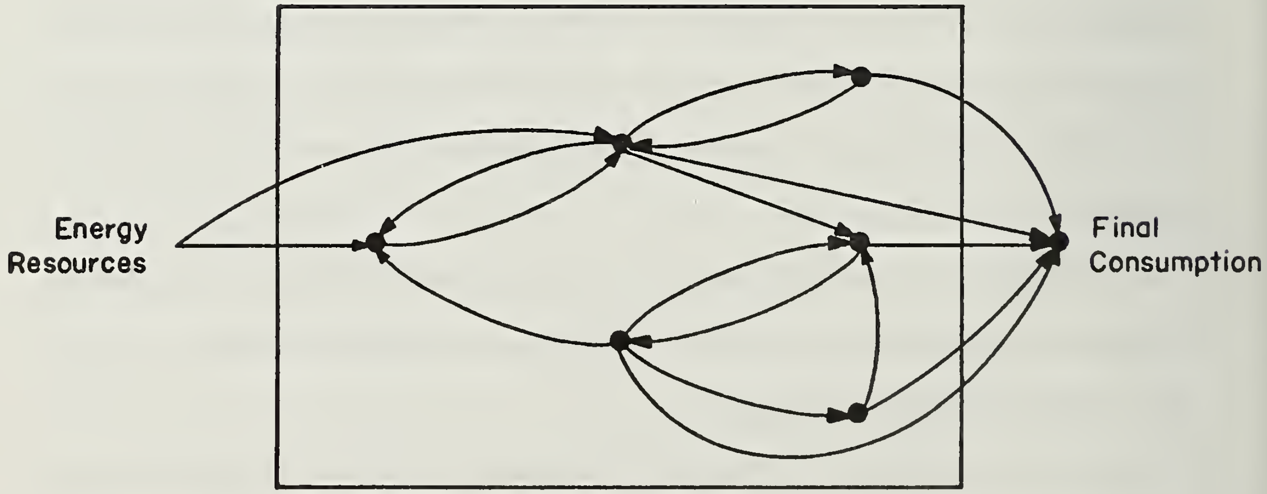


Figure 4. Network Representation of Energy Flow Through an Economic System

Consider a capital investment of K dollars in a new facility for producing energy. Assume operating expenses amount to Q dollars per year and that gross output is E Btu per year. A monetary rate of return might be defined as

$$r_\$ = \frac{P_E E - Q}{K} \tag{3}$$

Where P_E is the price of energy (remember we have assumed a single-fuel economy). Analogously, we may define an energy rate of return,

$$r_E = \frac{E - \varepsilon_Q Q}{\varepsilon_K K} \tag{4}$$

where ε_K and ε_Q (scalars) are the average energy intensities (Btu/$) of capital and operating expenditures, respectively. The relation between the two rates of return is therefore

$$r_\$ = r_E P_E \varepsilon_K + \frac{Q}{K}(P_E \varepsilon_Q - 1) \tag{5}$$

In an economic system where primary factors of production other than energy account for part of the dollar values of Q and K, we have

$$P_E \varepsilon_K \leq 1, \; P_E \varepsilon_Q \leq 1 \tag{6}$$

in general, with equality corresponding to the case of an energy theory of value where relative prices are determined solely by energy intensities. Substituting (6) into (5) we see that

$$r_\$ \leq r_E \tag{7}$$

That is, any investment having a positive dollar rate of return is also energetically feasible, and the energy rate of return exceeds $r_\$$.

This result may not convince some persons concerned about net energy who fear that the economic system may be so far out of kilter due to subsidies, budget deficits, and the like, that investments apparently economically feasible may actually be net energy losers.[15] The result (7) is based on the inequalities (6) which assume a well-behaved price system, and was derived for two reasons. First, the inequalities (6) are (perhaps) easier to roughly estimate than the Hawkins-Simon conditions (2). Secondly, the benefit-cost analogy provides a framework for dispensing with several other issues, as discussed below.

2.4.1 Energy Conservation Measures. Investments in energy conservation may be expressed in terms exactly analogous to the energy supply development investments described above. In both cases the characteristics of the cost and benefit curves are the same; an initial period of investment is followed by a stream of annual net benefits.

2.4.2 Project Lifetime. In a single fuel economy, the concept of an energy payback period is straightforward; it is simply $1/r_E$. Clearly, the lifetime L of an investment must exceed one payback period

$$L > \frac{1}{r_E} \tag{8}$$

in order for it to be feasible. Since $\gamma_\$ < \gamma_E$, we have for an economically feasible facility

$$L \geq \frac{1}{r_\$} > \frac{1}{r_E} \tag{9}$$

That is, its lifetime must exceed the energy payback period. On the other hand, an energetically feasible facility may not live to pay itself off in dollar terms.

2.4.3 Discounting. If we discount dollar costs and benefits but not energy, the dollar payback period is lengthened due to the characteristic shape of the cost and benefit curves, while the energy payback period remains the same. The same inequalities hold, and the lifetime of a feasible facility must be even longer.

If we discount energy benefits and costs, an interesting situation arises. Consider the case of a short-term energy shortfall where an energy developer and a conservationist agree to perform energy benefit-cost analyses on several competing energy supply and conservation programs to determine which are most feasible for meeting the crisis. A problem arises over which discount rate to use; in previous confrontations over energy development the conservationist has expressed preference for a low discount rate to slow depletion of exhaustible resources. On the other hand, the energy developer preferred a much higher rate. In the present situation, ironically, the roles are reversed. The conservationist uses a high discount rate to justify the short lead-time, quick payback conservation measures (e.g. home insulation) while the energy developer needs a low discount to maximize net benefits from a long lead-time supply development program.[16]

3. THE CASE OF SEVERAL ENERGY SECTORS

In a system with only one energy sector, the Hawkins-Simon conditions are sufficient to insure that the free energy content of the energy sector's output exceeds that of its inputs. When there are several energy sectors, it is possible for one to 'subsidize' another. For example, the free energy content of the output from a fossil-fueled electric utility sector is less than that of its inputs. The Hawkins-Simon conditions are satisfied, however, because they concern only the <u>electricity</u> content of the inputs and outputs. Such a process is economically feasible because we value one Btu of free energy in the form of electricity more than three Btu's in a lump of coal.

It should be clear now that if, for example, shale oil technology were a 'net energy loser' (requiring more oil embodied in inputs than it produced), it could physically exist alongside a conventional liquid crude petroleum technology, assuming the oil produced by each was valued equally. The Hawkins-Simon conditions could be satisfied in such a situation,[17] which of course would be economically infeasible unless the two processes were differentially taxed or subsidized. A similar situation exists with pumped-storage electricity. Peak load electricity is in a sense a different type of energy than base load electricity, and the latter technology 'subsidizes' the former in an energy sense. The pumped storage is economically feasible because of values ascribed to full utilization of capital.

3.1 Gross Energy Requirements

To quantify the extent to which one energy technology depends on another, one would simply compute for each technology the terms shown in fig. 5 (gross energy requirements) for all energy resources k. In this way, energy production technologies can be distinguished from energy conversion technologies.[18] It must be emphasized, however, that once the terms in fig. 5 are computed, the analyst must make a value judgement to decide which of several technological alternatives has the superior net energy yield. The various energy inputs are in general not measured in the same units as the output, so are not directly additive.[19] The analyst's values might be quantified in the form of a weighting function applied to the resource requirements vector.

A more appropriate system boundary choice for such an analysis might be that corresponding to the definition of GNP, recognizing consumption rather than energy output as the purpose of economic production. In such a case, we would calculate the gross energy requirements (of several resource types) to produce that final bill of goods (fig. 2). In fact, eqs. (1) could be rewritten in a linear programming format where one would solve for the mix of competing energy technologies that minimizes a weighted sum of gross energy resource requirements.

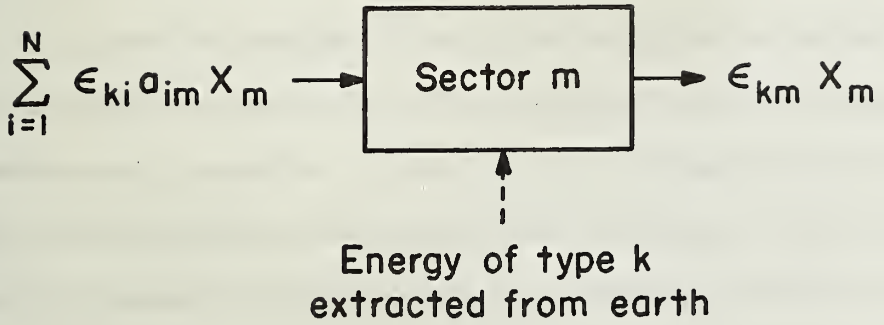


Figure 5. Balance of Energy Resources (type k) embodied in Sector Inputs and Outputs

Depending on the weights chosen, such an objective function would reflect some sort of energy theory of value, and therefore would have only limited usefulness.[20] More appropriate for U.S. 'Project Independence' planning might be a similar formulation that would select a flexible mix of technologies minimizing the cost of assuring that an oil import cutoff could be accomodated to a specified extent.

3.2 An Empirical Example

In this section we consider two technologies for producing refined oil for final consumption. System I consists of conventional onshore oil wells plus a refinery, while System II includes oil shale mining and retorting facilities and a refinery. Capital and operating data consistent with the categories of the 90 sector CAC energy input-output model were used.[21] Output of both systems was normalized to 20×10^{12} Btu/yr. to facilitate comparison, assuming constant returns to scale for the facilities.

Since this is an evaluation of real systems in a world with more than one energy source, it is difficult to summarize the results graphically. To show the approximate magnitude of the terms involved, however, the following assumptions were made. First, the system boundaries were drawn at the refinery outlet, so the outputs shown are the Btu contents of gross outputs. All energy inputs to both processes were converted to their total primary energy equivalents. That is, total coal, crude oil and gas, and the fossil fuel equivalent of hydro and nuclear power were added without regard to qualitative differences in their energy contents. This most pessimistic assumption (in net energy terms) results in the system operating energy inputs shown by the first line below the horizontal axis in fig. 6. Even if one would (conservatively) subtract this total primary energy from the refined output shown above the axis, it is easily seen that the capital energy investment is 'paid back' almost immediately. Most of the operating energy inputs to both systems are for the refining process.

The bottom line on each graph shows the basic primary resource (crude oil or oil shale) extracted from the earth by each process. The contribution of shale is much larger because of process losses and the fact that the data source defined the system boundary for the shale processing plant outside all the internal feedbacks of partially or completely processed oil.

It can be seen that the capital investment for onshore oil drilling is quite energy demanding. This is primarily due to the assumption by the data source that 3 out of 4 wells are dry holes, and all drilling energy is charged to the fourth. Since oil shale is an emerging technology, it is possible that capital cost estimates (and therefore energy estimates) might be somewhat low, but the effect of first exhausting the most easily accessible resources is apparent.

The calculations underlying fig. 6 were simplified by treating them as 'marginal' technologies, ignoring higher order feedback effects. All system inputs were assumed produced by the existing energy technologies. The errors resulting from such assumptions (e.g. that the oil used to produce non-energy inputs to the shale oil plant came from wells, not shale) are well within the ±20 to 30% error bounds estimated for some of the source data. Moreover, once we are assured that the new technology under consideration is feasible, treating it as a marginal technology is the appropriate method for ascertaining impacts of its introduction.

4. SUMMARY AND CONCLUSIONS

There is no magical 'net energy ratio' that can lead to an automatic thumbs up or thumbs down decision or any new energy technology.

Figure 6(a)

ENERGY INPUT (-) AND OUTPUT (+)
IN TRILLION BTUS, FOR SYSTEM:
OIL PRODUCTION FROM CRUDE

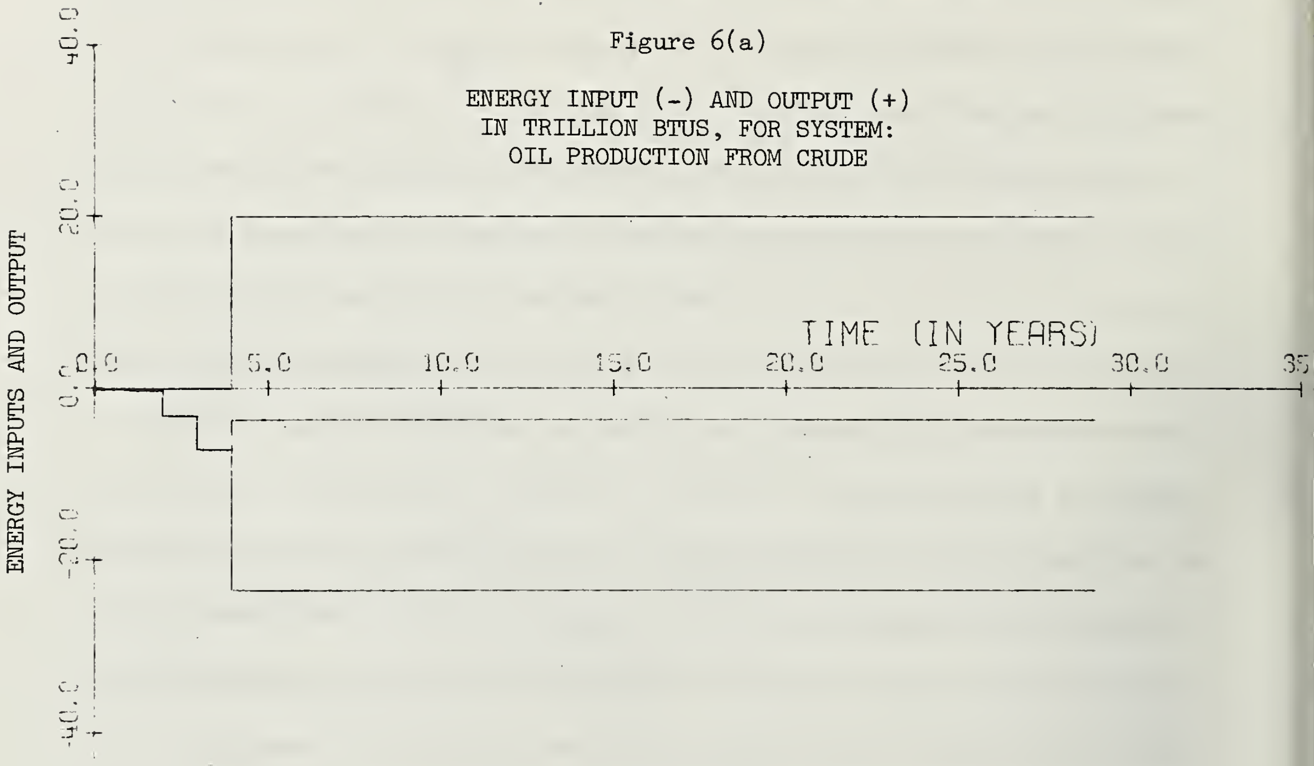
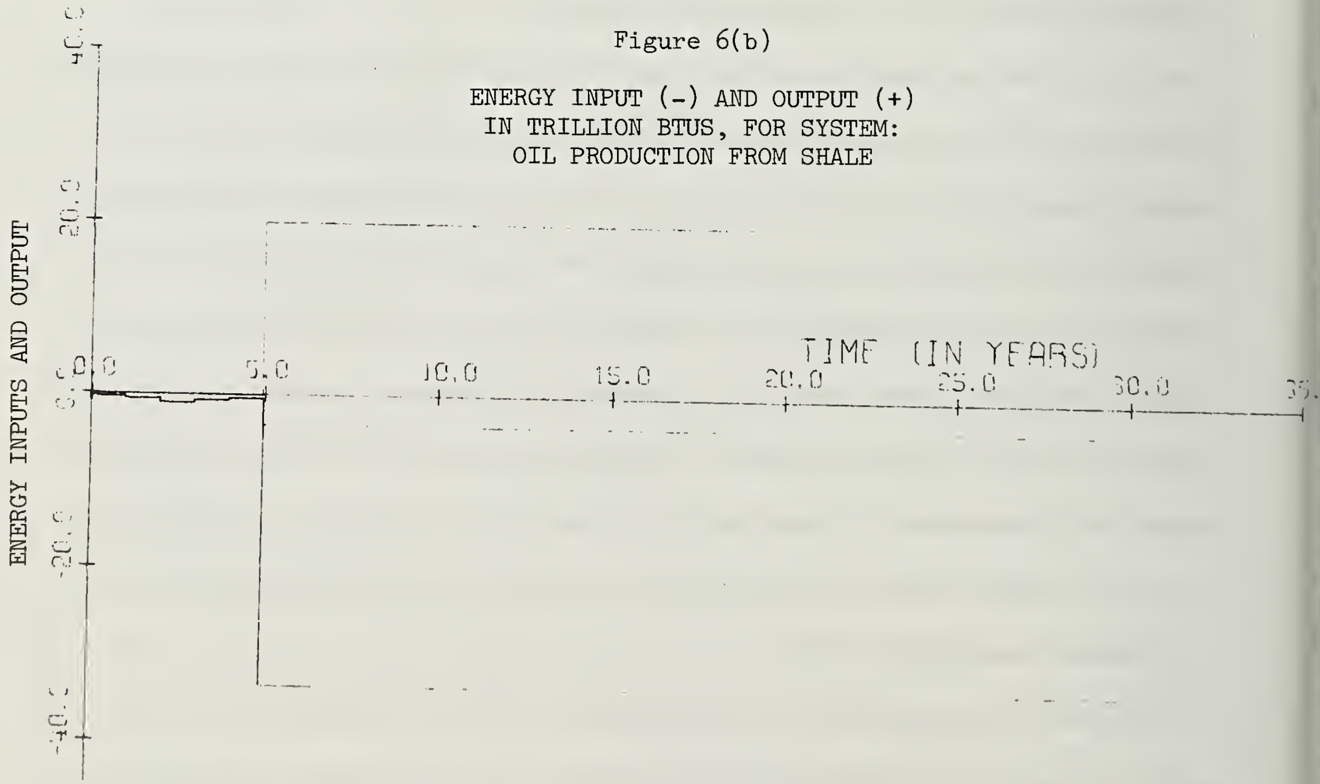


Figure 6(b)

ENERGY INPUT (-) AND OUTPUT (+)
IN TRILLION BTUS, FOR SYSTEM:
OIL PRODUCTION FROM SHALE



Concern about net energy efficiency stems from fears that certain technologies may accelerate depletion of free energy stocks - a quantity that is scarce in an absolute sense. To the extent that market prices of energy resources do not accurately reflect such external costs as environmental impacts, national security factors and - especially - the cost to future generations of depleting free energy resources, these concerns are well founded.

The net energy concept can be unambiguously developed in the context of an economic system having only one energy resource. An energy payback period can be defined, and it may be a useful parameter for technology assessment because it represents a lower limit to the doubling time of energy growth. In both the static and dynamic case, the net energy feasibility criterion must be defined with respect to the entire economic system; changes in non-energy technologies may be as important as changes in the energy sector.

The relevant system boundary for net energy analyses depends on the question addressed. This paper deals with an overall system boundary consistent with the definition of GNP, and suggests that subsystem boundaries retain this consistency. While this conventional paradigm is not perfect, it has the advantage that most of the necessary data are collected in this framework. The gross energy requirements thus determined are meaningful for a multifuel economy and yield net energy figures for the single fuel case. It is recognized, however, that considerable controversy surrounds this system boundary choice; e.g. arguments are often made for treating (say) energy inputs to the Nuclear Regulatory Commission as inputs to the nuclear power sector rather than as part of GNP. The analytical framework presented here may be easily adapted to accommodate such suggestions as adequate data become available.

The relation between economic and energy feasibility was discussed in the framework of benefit-cost analysis. There I discussed the effects of increasing energy prices (energy theory of value), discounting, and comparison of conservation measures with energy supply development programs. Extension of these results to a multifuel system is straightforward using a weighting function to combine Btu's of different qualities.[22]

While some practitioners of net energy analysis may subscribe to an energy theory of value, there is nothing about the quantitative methods proposed here that demand it. I have suggested a method for physically quantifying energy inputs and outputs across well defined system boundaries. It is not necessary to assume, as some have, that all Btu's are equivalent. As presented here, these techniques may not only be useful for meeting the requirements of federal legislation, but also may provide a framework for developing unambiguous 'energy impact studies' to be used in public policy making in much the same way that environmental impact studies are now used.

FOOTNOTES

1. I am indebted to Dr. James Plummer of the National Science Foundation for many stimulating discussions and constructive criticism of several aspects of this problem.

2. See Business Week (6/8/74), (6,22,74) and Newsweek (1/13/74).

3. Schatz (1975), Clark and Varisco (1975), Chapman and Mortimer (1975).

4. The International Federation of Institutes for Advanced Study (IFIAS) held workshops in the summers of 1974 and 1975 in Sweden which addressed these issues.

5. For most energy resources, their typically quoted heat content, or total enthalpy (e.g. 5.8 million Btu/bbl of oil) is approximately equal to their Gibbs' free energy content.

6. For a discussion of the relationship between the physical concept of free energy and economic theory, see Georgescu-Rogen (1971, 1975)

7. See Leontief (1941). Due to problems of aggregation most input-output data are expressed in units of current dollars. Bullard and Herendeen (1975a) take the physical unit approach for the energy sectors in calculating the energy cost of goods and services to properly account for the fact that energy is sold to different consumers at different prices.

8. Note also that changes in non-energy technologies (e.g. substituting fiberglas for steel in auto manufacturing) affect net energy yield just as changes in coal mining technology do.

9. For the U.S. in 1967 this value was 1.003. Including the contribution of other primary energy sources brings the total to 1.007. See Bullard and Herendeen (1975b).

10. This same effect, as applied to shale oil technology, was observed by Penner (1975).

11. To be consistent, he must also count that coal in the coal sector's output, and consider it 'consumed' by the coal sector.

12. See Daly (1974).

13. Schatz (1975), Clark and Varisco (1975) Chapman (1975).

14. This is the type of error made when one converts total dollar costs (for facility construction and operation) to Btu's using the average energy/GNP ratio. This allocates employees personal energy consumption to the energy facility.

15. See for example Schatz (1974).

16. Putnam (1975) has calculated energy benefits and costs for two conservation programs (insulating homes and converting large car production capacity to small cars) and found that they pay back the initial investment and yield a net benefit stream considerably earlier than various energy supply development programs evaluated by Pilati and Richard (1975).

17. Whether viewed as two distinct sectors or combined into one.

18. For example, if it required more than one Btu of heat to cook one Btu of oil out of shale, the process could not be run on its own output. It might, however, be run on coal, in which case it would simply be a technology for converting coal to oil, competitive with coal liquefaction technology.

19. One could aggregate all 'energy sectors' into a single sector whose output was measured only in terms of its free energy content. The Hawkins-Simon conditions would in this case assure a positive net yield of free energy from feasible systems. However such a model would not capture the fact that some forms of energy output could be employed more efficiently than others in certain productive processes.

20. Khazzoom (1975) suggests a similar formulation reflecting an energy theory of value to simulate a situation with a severe energy shortfall. His objective function, since it is to maximize <u>excess</u> energy delivered for final consumption rather than minimizing resource depletion, may not be acceptable to those whose 'energy theory of value' derives from concern about exhausting nonrenewable resources.

21. For all facilities except oil shale capital data are from Carasso (1975); operating data from Bullard and Herendeen (1975b), where the model is described. Oil shale capital and operating data are from Just (1975).

22. A common practice is to measure all types of energy forms in a common unit (total enthalpy or heat content, approximately equal to free energy content) and then simply add. A useful measure for roughly estimating total energy reserves, it is not appropriate at the facility or sector level because it obscures the economic purpose of the facility; to produce an energy form having certain desired characteristics in addition to its free energy content (e.g. electricity).

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