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NET ENERGY AS A POLICY CRITERION

By

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ABSTRACT

Methods for quantifying net energy impacts of individual energy facilities and entire energy-economic systems are presented. Special emphasis is placed on system boundary definitions to facilitate comparison of competing technologies. Shortcomings of the conventional framework for gathering data and allocating energy consumption to process inputs are discussed in light of the motivation for net energy concerns.

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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.

Net energy analyses could certainly be used to test the feasibility of a proposed energy production technology; if it required more electricity to construct and operate a nuclear power plant than the plant produced, the technology would clearly be infeasible. It follows, therefore, that if a set of comparably defined "net energy ratios" could be determined for a set of technological options, they would be useful parameters for technology assessment.

Figure 1 shows schematically the nature of all energy inputs to and outputs from an energy production and processing system. Since the system's output is needed to produce the non-energy inputs to the process, feedback loops (not shown) exist and are accounted for in the diagram by assuming the direct and indirect energy costs of all inputs are known. Methods for determining these are discussed in sec. 2.2.

Results of some net energy analyses have been reported [2,3,13], and the matter has received considerable attention in

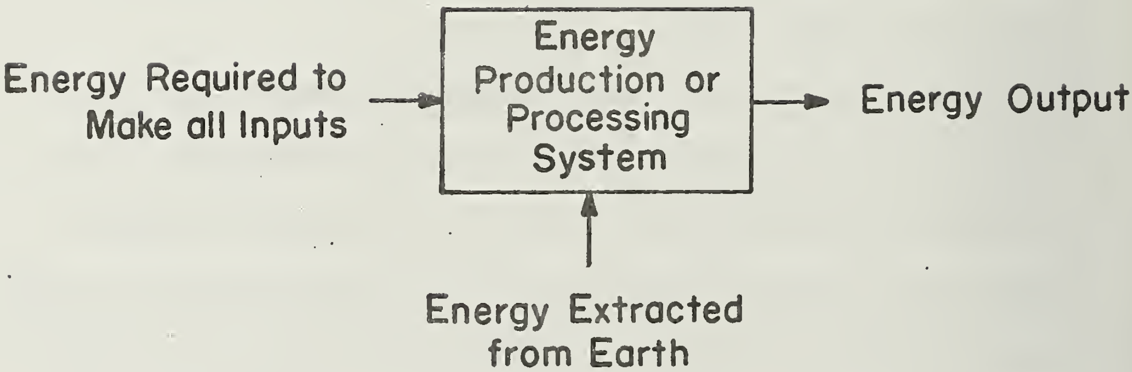

Figure 1. Energy Balance for an Energy Production System

the popular press [4,12]. Their conclusions are conflicting, primarily due to differences in system boundary definitions, and in value judgements implied by addition of qualitatively different energy resource inputs.

The purpose of this paper is to present quantitative methods for technology assessment in the light of net energy concerns. Static and dynamic models will be presented, and the implications of alternative system boundary definitions will be discussed.

1.1 Motivation

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 release heat or perform work is a quantity defined precisely in physics as 'free energy'.[1] 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 to do so.[2]

The earth's endowment of free energy-containing resources are of relatively little value _in situ_; additional energy must

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1. 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.

2. For a discussion of the relationship between the physical concept of free energy and economic theory, see Georgescu-Roegen [8,9].

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. Therefore in an absolute physical sense, total energy resource reserves would in general be overestimated if the Btu contents of such dissimilar resources were simply added.[3] Said another way, some energy technologies may accelerate the rate of depletion of total energy reserves (measured by simple addition of Btu contents), since it would take more Btu's of energy resources to produce a given gross national product.

Finally, to the extent that taxes, subsidies, and other non-market forces can affect the economic feasibility of various energy technologies, it is possible that certain processes with minimal or negative net energy output could look quite attractive from a purely financial point of view. My purpose in this paper is to stay within the framework of a purely physical model to quantify total energy requirements. As we shall see in the next section, however, choice of the system boundary for the entire analysis will depend on economic and other social values.

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3. Attempts are often made to avoid this type of overestimation by defining reserves as those 'recoverable at less than a given dollar cost'. Results thus obtained may not in general be applicable long-term policy decisions involving depletion of exhaustible resources because they are based on current market prices which reflect only current social values, and may inadequately account for numerous external costs, future changes in social values, and other non-market factors.

1.2 Model Structure

There are two fundamentally different ways of evaluating the net energy output of a system. They are based on quite different sets of values which lead to almost diametrically opposite mathematical problem specifications.

The first paradigm is the conventional or flow maximizing one. As fig. 2 shows, energy resources are extracted from the earth and can be allocated among the goods and services produced by the system. The energy balance equations used to solve for the energy thus "embodied" in the various goods and services will be discussed in section 2. The main point here is that energy is a necessary input to every production process; it is necessary to change the physical state of material inputs into another state perceived as having increased value.[4] The conventional value function that calls for maximizing the flow through the system (GNP) does not recognize the resultant pressure on depleting finite energy resources as intrinsically 'bad', assuming there are no external costs and that future costs and benefits have been properly discounted.[5]

In another paradigm, however, the opposite is true. Daly [5] and others have proposed a model of a steady state economy

4. Food energy would have to be included to make this statement exactly true, but it accounts for only 1% of U.S. energy consumption (based on figures from ref. [14]).

5. For an overview of the state of the act in the economics of exhaustable resources, see Dasgupta and Heal [6].

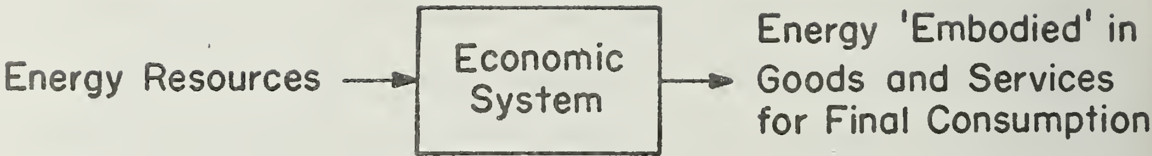

Figure 2. Allocation of Energy Resources Among System Outputs

in which utility is primarily a function of the stock of accumulated wealth, and the flows necessary to maintain these stocks are costs, and therefore should be minimized. Such a system could result in far less pressure on nonrenewable energy resources for two reasons: the stocks of free energy reserves would be valued in themselves, and they would be consumed at a minimal rate to support the flows necessary to maintain other stocks of wealth.

This latter, or flow minimizing, paradigm would give rise to a different system boundary than the conventional one. In such a model, the energy needed to operate the Nuclear Regulatory Commission (NRC), for example, would be included among the inputs to nuclear power plants. The conventional model does not; the inputs to the NRC are just another component of the GNP. Similarly, the flow minimizing model would include among the energy inputs to shale oil plants the energy required to construct support facilities, including new towns and other infrastructure, in the heretofore undeveloped areas near the resources. The problem would be to distinguish new stocks of wealth from simple transfers, and to account for all transportation and dislocation costs.

In this paper, the conventional paradigm will be employed, primarily as a matter of convenience since adequate data are available to determine the energy costs of goods and services. This is not meant to diminish the importance of the flow-minimizing model, rather I will treat it separately in a subsequent paper.

2. QUANTIFYING ENERGY REQUIREMENTS

To develop and sustain any energy production process such as that shown in fig. 1, energy is required to produce the inputs to the process. In this section I present two equivalent methods for determining the energy cost of goods and services, then proceed with analyses of energy systems in Sec. 3. A detailed description of both methods, and a proof of their equivalence is contained in ref. [1].

2.1 Process Analysis

The first method, called process analysis, begins with an assessment of the direct inputs of coal, oil, electricity, etc. to the production process for a commodity. Next the direct 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 production to shale oil! Such an incorrect system boundary definition would

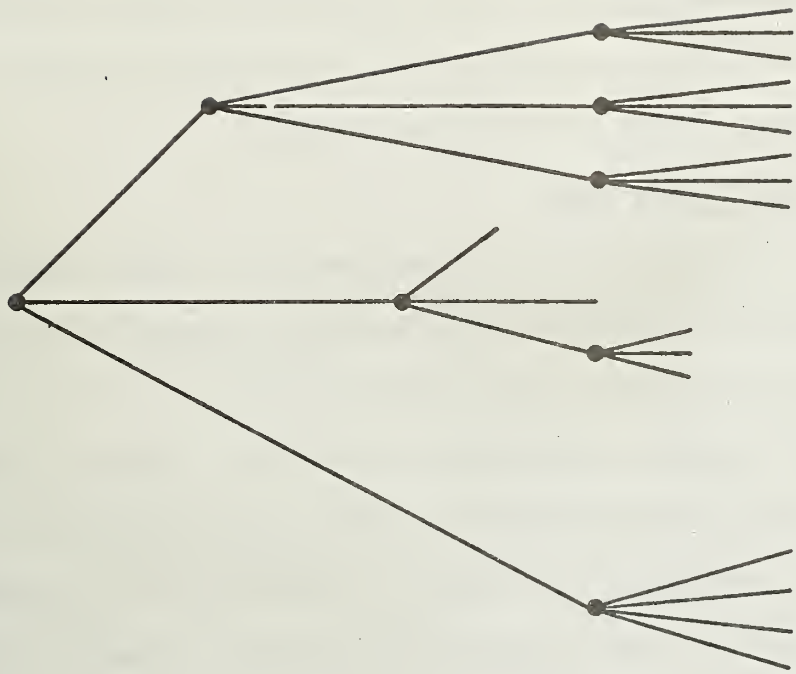

Figure 3. The Process Analysis "Tree"

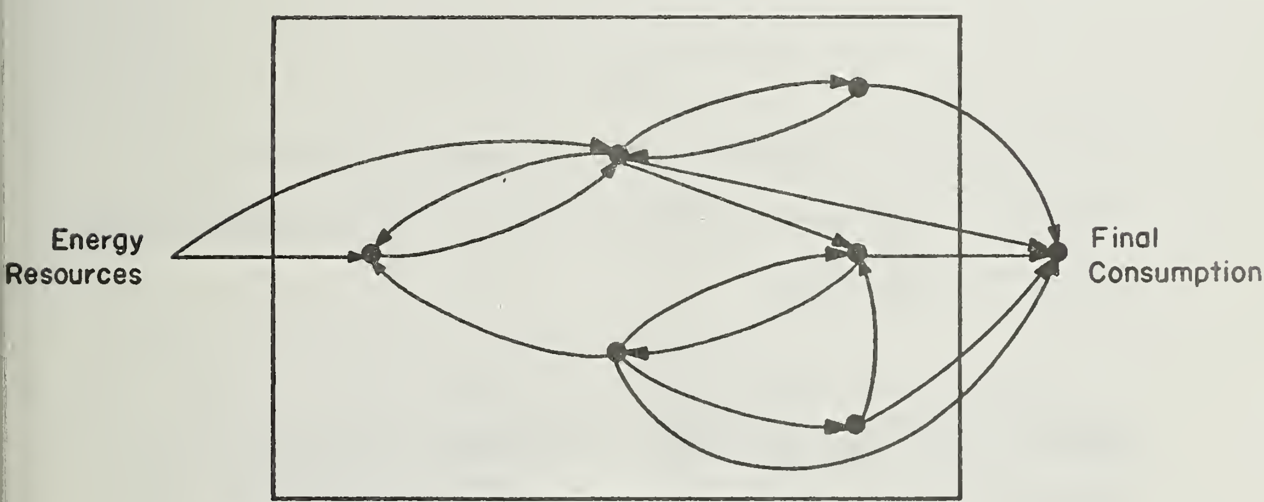

Figure 4. Network Representation of Energy Flow Through an Economic System

imply that shale oil production was the ultimate end of the system under examination. This absurd example is meant to underscore the importance of carefully defining the system boundary before proceeding with a net energy analysis.

2.2 Total System Model

The second method for computing gross energy resource requirements of (energy and non-energy) commodities is based on a linear system model of the network shown in fig. 4, with the system boundary corresponding to the final consumption part of GNP.

In the linear system, the production technology of a sector at node j is given by a vector of coefficients a_{ij} representing the amount of input from sector i needed to produce a unit output from sector j. Each sector i can distribute its output to each of the other N-1 sectors and to final consumers. The corresponding output distribution equations

$$X_i = \sum_{j=1}^{N} a_{ij} X_j + Y_i \qquad (1)$$

can be solved for the output vector $\underline{X}$ required directly and indirectly to produce a specified final bill of consumption goods $\underline{Y}$. In matrix notation,

$$\underline{X} = (\underline{\underline{I}} - \underline{\underline{A}})^{-1} \underline{Y} \qquad (2)$$

where $\underline{\underline{I}}$ is the identity matrix. The primary energy resource requirements are given by the output X_k of those energy sectors. The energy resources of type k required directly and indirectly to produce one unit of final output from sector j are designated ε_{kj}, where the matrix $\underline{\underline{\varepsilon}}$ is simply the energy sector rows of $(\underline{\underline{I}}-\underline{\underline{A}})^{-1}$.[6]

6. Terms in these equations from input-output theory (see Leontief [11]) represent physical quantities, not their dollar values. Outputs of all sectors need not necessarily be measured in the same physical units.

3. SYSTEM ENERGY REQUIREMENTS

Fig. 5 shows the energy balance for a typical energy producing sector (say m = coal) where the gross energy (of each type k) content of all inputs equals that of its outputs. Using the notation introduced above, the net coal energy yield condition can be expressed by setting k=m as follows:

$$\varepsilon_{mm} X_m \geq \sum_{i=1}^{N} \varepsilon_{mi} a_{im} X_m \tag{3}$$

Generalized to every sector, eq. (3) reduces to the well-known Hawkins-Simon conditions, that the leading principal minors of $(\underline{\underline{I}}-\underline{\underline{A}})$ are positive [10]

$$\begin{aligned} &\det (1-a_{11}) > 0 \\ &\quad\vdots \\ &\det (\underline{\underline{I}} - \underline{\underline{A}}) > 0 \end{aligned} \tag{4}$$

which guarantee positivity of the Leontief inverse matrix. As derived above, the conditions guarantee that the net yield (measured in physical units) of every sector, including the energy sectors, is positive. The matrix of technological coefficients $\underline{\underline{A}}$ completely defines the production technology of the whole system, and any change in $\underline{\underline{A}}$ affects the relationship between final consumption patterns and free energy reserves via eqs. (2) and (4). Thus changes in non-energy technologies, such as substituting fiberglas for steel in auto production could have as profound an effect on the rate of energy resource depletion switching from crude petroleum to shale oil.

The above remarks would also apply to individual facilities,

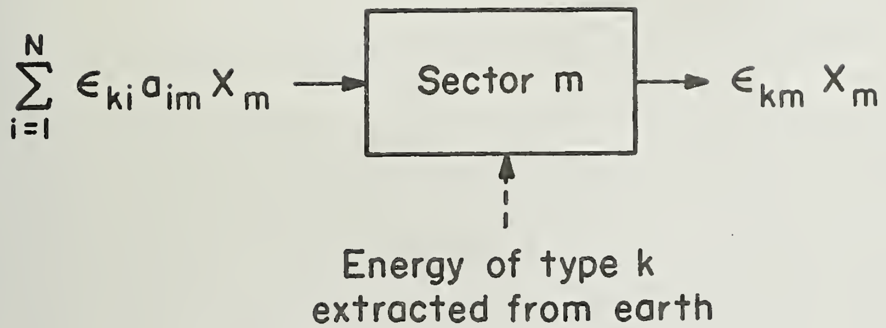

Figure 5. Balance of Energy Resources (type k) embodied in Sector Inputs and Outputs

for which eq. (3) must also hold. However, since the facilities are part of a feedback system, feasibility must be defined with respect to the system. Clearly during the development and construction phase, any energy facility is a net energy sink. Terms in eq. (3) could be evaluated and integrated over the lifetime of a facility, but as we shall see next, feasibility must also be defined with respect to the entire system in the dynamic case also.

3.1 The Effect of Growth

Nothing was said above to differentiate between the static and dynamic conditions of the system. Consider equations (1-4) 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 $\underline{\underline{A}}$ larger than for the static case, for the inputs to production would include capital for plant expansion. For identical instantaneous values of $\underline{Y}$, the growing system will require more gross inputs $\underline{X}$ (due to the larger $\underline{\underline{A}}$) 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.

For a process analysis of the effect of growth rate on the energy resource requirements for nuclear fission, see Chapman [2].

3.2 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 electricity 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 exist alongside a conventional liquid crude petroleum technology. The Hawkins-Simon conditions could be satisfied in such a situation,[7] which of course would be economically infeasible unless the two processes were differentially taxed or subsidized.

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 for all energy resources k. In this way, energy production technologies can be distinguished from

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

energy conversion technologies.[8] 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.[9] The analyst's values might be quantified in the form of a weighting function applied to the resource requirements vector. Two methods to facilitate comparison of technological alternatives will be discussed next.

3.3 Technology Assessment

To compare competing technologies, it is sometimes useful to attempt to define a 'bottleneck' in the system, or a common product that can be produced by either technology, to see which is more efficient. As an example, suppose one technology, completely specified by a vector $\underline{a}_i$ of technological coefficients, produces gasoline from basic energy resources. In the first case let us select the vector $\underline{a}_i$ to represent the technology of producing it from shale, and the second case from drilled crude oil. Solving the energy balance equations implied by fig. 5 for the

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8. 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, competing with coal liquefaction technology.

9. 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 free energy yield 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.

entire system in each case we obtain

$$\underline{\underline{\varepsilon}}^1 = \underline{\underline{r}}(\underline{\underline{I}} - \underline{\underline{A}}^1)^{-1}$$

$$\underline{\underline{\varepsilon}}^2 = \underline{\underline{r}}(\underline{\underline{I}} - \underline{\underline{A}}^2)^{-1}$$

where $\underline{\underline{r}}$ is a matrix containing unit elements which set $\underline{\underline{\varepsilon}}$ equal to the energy sector rows of $(\underline{\underline{I}} - \underline{\underline{A}})^{-1}$. The only difference in the two equations is the column of $\underline{\underline{A}}$ corresponding to the gasoline sector. If the oil producing sector were sector no. 1. ε^1_{11} would represent the tons of oil shale required directly and indirectly to produce a gallon of gasoline. ε^2_{11} would indicate the total number of barrels of crude oil required to produce a gallon of gasoline for final consumption. Depending on how we valued the tons of shale vs. the barrels of crude oil, (or the free energy content of each) we might prefer one technology over the other.

The above example was a very special case because the two systems under consideration were defined identically except for a single bottleneck, at the gasoline production sector. We could just as arbitrarily evaluated the two technologies in the basis of the entire vector ε_{kl} which would have shown the extent to which other energy resources k "subsidized" the oil production technology. Again arbitrarily, we could have compared the technologies on the basis of their effect on the coal required directly and indirectly to produce cars for final consumption. This would of course simply reflect the different coal intensities of gasoline in the two cases because of the nature of the "bottleneck" defined. Or again, we could have evaluated the two technologies on the basis of the energy resources required to produce a large array of goods and services, say the projected 1990 GNP.

For cases involving general changes in any or all elements of $\underline{\underline{A}}$, this latter comparison is the most meaningful. It focuses on the system boundary defining final consumption goods and places the "bottleneck" there. Thus for a given final consumption pattern total energy resource requirements can be compared. It embodies the conventional paradigm's implicit assumption that production of goods and services for consumption is the overall objective of the system. The technological changes that are the object of the comparison could include single energy technologies, entire energy system alternatives, or even non-energy technologies.

To capture dynamic effects in such analyses, capital flows for expansion of capacity must be included in the matrix $\underline{\underline{A}}$. The nature and magnitude of consumption growth $\underline{Y}$ will determine the resultant technology matrix $\underline{\underline{A}}$ which must also satisfy the Hawkins-Simon conditions.[10] The same equations hold; each term becomes a function of time. This method relates evolution in production technologies and consumption patterns to gross depletion rates of all energy resources.

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10. Changes in $\underline{\underline{A}}$ due to capital flows are a function of $\underline{Y}$. For a discussion of alternative ways of treating this see Dorfman, et al. [7].

4. SUMMARY

There is no magical 'net energy ratio' that can lead to an automatic thumbs up or thumbs down decision or any new energy technology. Concern about net energy efficiency stems from concern that certain technologies may accelerate depletion 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 conventional paradigm, in which the system boundary is drawn to define GNP as the measure of system output, is not the perfect model for performing net energy analyses. It is however, a satisfactory point of departure, and one in which the energy costs of goods and services can be quantified because the necessary data have been collected in this framework. Some errors are involved, for instance the energy needed to support the Nuclear Regulatory Commission should be included as an input to the nuclear power sector, instead of an output of the system. Such factors must be considered separately as adequate data become available.

Many net energy analyses published to date are either incomplete (fail to include all inputs), have poorly defined system boundaries, or imply questionable value judgements by adding qualitatively different energy forms.[11] This paper presents a framework within which the necessary data[12] can be collected and used to quantify the extent to which a new technology (energy or non-energy related) accelerates the depletion of resources containing free energy.

Finally, it must be emphasized that once these data are collected and the relationships are quantified, the policymaker is left to make an explicit value judgement regarding the relative worth of various free energy-containing resources. It is a very important judgement, though, one which must be weighed with social, political, economic and other concerns.

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11. 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, this 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).

12. Most operating data for existing technologies are available from the U.S. Dept. of Commerce input-output studies [15]. Parameters are measured in current dollars, but for the energy sectors physical data are available [1]. It is hoped that this paper underscores the importance of obtaining capital and operating data on new and emerging technologies in a form compatible with this proposed framework for net energy analysis.

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plementary Notes

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