SYMPOSIUM PAPERS

ENERGY MODELING AND NET ENERGY ANALYSIS

Presented

August 21–25, 1978

Colorado Springs, Colorado

Symposium Chairman
Fred S. Roberts
Rutgers University

Symposium Director
Wendell W. Waterman
Institute of Gas Technology

Sponsored by

Institute of Gas Technology
3424 South State Street
Chicago, Illinois 60616

Price: $60.00

December 1978
Printed in U.S.A

Produced by
Jack W. White
and

COMPARING METHODS OF ENERGY ANALYSIS IN AN ECONOMIC FRAMEWORK

Thomas Veach Long, II
The Committee on Public Policy Studies
The University of Chicago
1050 East Fifty-Ninth Street
Chicago, Illinois 60637

ABSTRACT

Energy analysis involves the accurate assessment of direct and indirect energy required for the provision of goods and services, and the definition may be extended to encompass the use and eventual discard of manufactured items. Also, the analysis of the policy implications of the assessments should be included. Some early energy analysis studies made claims for the policy relevance of their results that clearly exceeded the content of the assessments. Some economists, sensing an intrusion on their turf and having little knowledge of the development of this new analytical method, criticized it by setting up straw men that they then dismantled using conventional economic observations. A more reasoned view of the relation between the two policy analysis tools, energy analysis and economics, is that they are complementary rather than antagonistic. Here, the three principal methods of energy analysis (process analysis, input-output analysis, and energetics) are outlined and contrasted in a standard economic framework. The overall contention is that energy analysis can furnish valuable information for economic decision making, particularly through pointing up opportunities for factor substitution and technological change.

COMPARING METHODS OF ENERGY ANALYSIS IN AN ECONOMIC FRAMEWORK

Energy analysis is a relatively new endeavor that is directed at the accurate assessment of both the direct energy (fuels and electricity) used in the provision of goods and services and the indirect energy incorporated in material and other non-fuel inputs to the production process. In understanding the intellectual underpinnings of the technique, it is important to realize that effort in this area predated the oil embargo and the subsequent perceived energy crisis. As early as 1965, workers who can be identified as energy analysts (and who were principally engineers and physical and biological scientists) were applying this method to problems of environmental significance, and their initial publications appeared in the early 1970's [Berry and Fels (1973), Berry and Makino (1974), Chapman (1973), Hannon (1972, 1973), Herendeen (1973), Leach and Slesser (1973), Odum (1971, 1972)]. It is clear that the impetus for their work derived from recognition of the difficult task that faced economists in assigning reasonable valuations to externalized costs of production and consumption. Krutilla and Fisher (1975) provide the economists' view of this subject. Odum (1971, 1974) has been notably original in emphasizing valuation of the positive inputs that natural services make to productive processes. My first point is that energy analysis has focussed on the accurate measurement of physical inputs (including both energy goods and materials) to production, to consumption and to recycling, remanufacture or disposal.

Although the techniques had been developed to analyze general environmental problems, it was obvious following the events of October, 1973, that another potential application of energy analysis was in accurately assessing energy demand. This led to a number of papers examining the implications of energy analysis for energy policy [Berry, Long and Makino (1975), Bullard and Herendeen (1973), Hannon (1975), Herendeen and Bullard (1974), Long (1975), U.S. House of Representatives (1976), Wright (1974)] and the first international meeting on the subject [International Federation of Institutes for Advanced Study (1974)]. Unfortunately, the scientific backgrounds and the enthusiasm of some early workers led them to propose that society should adhere to a "natural" system of value with energy as its standard [Hannon (1973), Odum (1971)], and another worker [Gilliland (1975)] implicitly adopted such an energy theory of value although she also expressed agnosticism [Gilliland (1976)]. This produced a flood of literature from the economics profession, which had earlier rejected a similar single commodity theory, the labor theory of value, and replies from energy analysts [Anon. (1975), Chapman (1977), Common (1976, 1977), Darmstadter (1975), Gilliland (1976), Huettner (1976, 1977), Langham and McPherson (1976), Leach (1975, 1976), Mueller (1976), Odum (1977), Peskin (1976), Reichle (1976), Slesser (1976, 1977), Webb and Pearce (1975, 1977)].

In part, this was an unfortunate turn of events, not only because the proponents of an energy theory of value are certainly wrong, but also because the heated debate tended to restrict discussion of the policy relevance of energy analysis to a polarized energy analysis vs. economics framework. Many of us felt that a more meaningful approach was to ask "What can energy analysis contribute to economic decision making," a position that I have consistently maintained [International Federation of Institutes for Advanced Study (1975), Long (1975, 1976); see also Buehring, Foell and Keeney (1976)]. My answer is that is can complement economics by empirically measuring more and more accurate data on the physical processes that economics seeks to describe and by developing the analytical structure that permits the incorporation of a greater quantity of physical information in the economic description. Thus, energy analysis furnishes input data for economic decisions.

There are, however, cases in which data on total energy use may be more important than other types of economic information. For example, the net amount of energy (output less input) yielded by an energy supply technology (and its form) will be of great interest to the research administrator who must choose which technology will be supported from a number that are economically competitive. The possibility that the government could end up subsidizing research and development on technologies that require more energy (and fossil fuel) than they furnish is recognized in Congressional Act 93-577, which instructs the Department of Energy to carry out energy analyses on supported technologies at the commercialization stage. It is true, of course, that in a competitive market environment or under an accurate economic accounting, such technologies would be shown to be economically unattractive and would not be developed. But government research support is often directed at those opportunities whose economics are the most difficult to evaluate and which are, thereby, risky.

Progress in energy analysis, and, in particular, in net energy analysis, has been the subject of several reviews [Bullard, Penner and Pilati (1978), Development Sciences (1977), Pearson (1976), Polenske (1975), U.S. General Accounting Office (1977), Winstanley (1976)]. In the following sections I explore how the information from energy analysis can be utilized by economics. In examining this question, it must be realized that there are three distinct methods of energy analysis rather than a single one: energy input-output analysis, process analysis, and eco-energetics. These methods have been described in detail elsewhere [input-output analysis, Herendeen (1973); process analysis, Long (1975); eco-energetics, Odum (1971)]. Consequently, I will concentrate on a comparison of the techniques and a discussion of how each interfaces with traditional economic modeling and evaluation.

ENERGY INPUT-OUTPUT ANALYSIS

An energy input-output matrix for the United States for the year 1963 was first developed by Herendeen (1973) and subsequently refined by Herendeen and Bullard (1974) at the University of Illinois at Urbana-Champaign, including the development of a matrix based on 1967 values. This matrix is derived from the financial input-output table for the U.S. by segregating it into two submatrices, one containing the five energy supply sector rows and the second, all other sector rows. The dollar flows from each of the energy supply sectors to the user sectors are then converted to physical units (Btu's, based on the enthalpy of combustion of the fuels) by dividing by the average producer's price paid by the user sector for the fuel. Flows between non-energy sectors are maintained in dollar units. This hybrid table is then inverted to include the infinite regression of indirect energy requirements that would be associated, for example, with the energy that is required to produce the steel that is needed to make the car that is purchased by the steel company to transport the steel...etc., in addition to the direct fuel and electricity inputs.

Thus, the energy input-output matrix is constructed from economic data that has been modified for only five of its approximately 360 sectors to reflect the fact that they sell units of production to different buyers at different producers' prices. No other physical information is incorporated. Economists have always used the financial input-output matrix with entries given in money value rather than physical units in the knowledge that possible disparities in a producer's price for sales to different sectors limited the accuracy of statements that could be made regarding quantity flows. However, it it obvious that the results of an energy demand analysis employing the energy input-output matrix are more accurate than evaluations using the financial input-output matrix, with the costs of direct plus indirect inputs from the fuel and electricity sectors converted to physical units at average sectoral producers' prices [Herendeen, undated].

To illustrate this procedure, let us develop their model of a three-sector economy. Exhibit 1 shows the input-output matrix manipulation techniques, and Exhibit 2 contains a transaction table that gives the dollar and energy flows in the hypothetical economy. The numbers in parentheses represent the numbers of Btu's that are purchased for the unparenthesized dollar flows. For example, the "car" industry purchases 10 Btu's from the "refined petroleum" industry for \$5.00. Using the Btu values for the two energy sectors and the dollar values for the "car" sector, the matrix is inverted, accounting for imports, and the inverted flow arrays in Exhibit 3 are produced. The correct interpretation of the entries in the row labeled "refined petroleum" is that each of their numbers reflects the total petroleum required to produce one unit of each of the outputs. For example, the production of \$1 of "car" requires \$0.40 of "refined petroleum" (Exhibit 3a).

The equivalent energy input-output matrix is given in Exhibit 3b. Construction of an input-output table in purely physical units at the 366 sector level would be exceedingly difficult because of the problem of aggregating the diverse products of a sector into a homogenous physical unit. However, Canadian work along this line is proceeding [McInnis and Hamilton (1975)].

The greatest utility of the energy input-output method would seem to be in evaluating the impacts on total national energy use of specific policy options. Conversely, it might also be used in assessing the macroeconomic impacts of restrictions on energy use. These analyses require that the energy input-output matrix be interfaced with a macroeconomic model that produces estimates of the demands for the outputs of economic sectors. The sectoral demand (in dollars) can then be multiplied by the sectoral energy intensity (in Btu's per dollar) to yield the implied energy demand. Hoffman and Jorgenson (1977) recently provided a clear exposition of a similar method for integrating economic and technological models for use in energy policy assessment. Even though the current macroeconometric models are a product of years of experience and intellectual effort, it seems likely that use of energy input-output methods should produce results that are as accurate as the econometric models with which they are interfaced. For a critical view of macroeconomic models, see Lucas and Sargent (1978).

The use of input-output techniques in evaluating micro-level energy questions, such as the total direct plus indirect energy consumption by a specific technology, appears to be more limited. This is both because of the high level of aggregation of differentiated industrial products,

Exhibit 1: Energy input-output matrix manipulation.

Energy balance

$$\Sigma \ \varepsilon_i X_{ij} + E_j = \varepsilon_j (X_j - P_j)$$

$$\varepsilon = E_{earth} (\hat{X} - \hat{P} - X)^{-1}$$

Normalize with respect to output

$$\varepsilon = E_{earth} (\hat{X} - \hat{P})^{-1} (1 - X (\hat{X} - \hat{P})^{-1})^{-1}$$

$$A = X (\hat{X} - \hat{P})^{-1}$$

$$\varepsilon = e (1 - A)^{-1}$$

where

X_{ij} = transaction from i to j

$\hat{X}_j$ = total output of j

ε_j = "embodied" energy intensity per unit $\hat{X}_j$

E_j = energy extracted from earth by sector j

P_j = imported product j

Exhibit 2: Transaction table after Herendeen and Bullard (1974). Money value units are unparenthesized. Physical units are given in parentheses in the unit shown on the right hand side of the table.

OUTPUTS OF	INPUTS INTO				
	Refined Petroleum	Steel	Cars	Total	Physical Unit (in parentheses)
Refined Petroleum	10(10)	10(40)	0	20(50)	(Btu)
Steel	5(5)	5(5)	5(10)	15(20)	(Tonne)
Cars	5(5)	0	5(5)	10(10)	(No.)
Transfer Imports	0	10(10)	10(10)		

Exhibit 3a: Pure financial transaction table and inverted matrix.

$$X = \begin{array}{cc} & \text{Unit} \\ \begin{pmatrix} 10 & 10 & 0 \\ 5 & 5 & 5 \\ 5 & 0 & 5 \end{pmatrix} & \begin{array}{c} \$ \\ \$ \\ \$ \end{array} \end{array}$$

$$(1 - A)^{-1} = \begin{pmatrix} 14/5 & 9/5 & 2/5 \\ 4/5 & 9/5 & 2/5 \\ 6/5 & 6/5 & 8/5 \end{pmatrix}$$

Thus it requires \$2/5 refined petroleum to produce \$1 of car.

Exhibit 3b: Mixed (University of Illinois) transaction table and inverted matrix.

$$X = \begin{array}{cc} & \text{Unit} \\ \begin{pmatrix} 10 & 40 & 0 \\ 5 & 5 & 5 \\ 5 & 0 & 5 \end{pmatrix} & \begin{array}{c} \text{Btu} \\ \$ \\ \$ \end{array} \end{array}$$

$$(1 - A)^{-1} = \begin{pmatrix} \frac{75}{44} & \frac{30}{11} & \frac{10}{11} \\ \frac{3}{11} & \frac{18}{11} & \frac{6}{11} \\ \frac{5}{22} & \frac{4}{11} & \frac{16}{11} \end{pmatrix}$$

Thus it requires $\frac{10}{11}$ Btu to produce \$1 of car.

even at a 360 sector level breakdown, and because of the difficulty in obtaining up-to-date input-output data. Current financial input-output tables are available with a several-year lag, and it has proved difficult to project energy input-output coefficient behavior accurately [Herendeen and Shiu (1975)]. Therefore, in assessing specific technologies or processes, it seems preferable to utilize the process analysis method, to which we now turn.

PROCESS ANALYSIS

A process analysis provides an accurate description of all the flows of energy and materials, beginning with the process of interest and tracing back (at least, conceptually) to the original extraction of all materials from the earth. A detailed description is provided by Long (1975). For example, in the production of aluminum, the first process considered is the Hall-Héroult process for electrolysis to the pure metal. Material flows are first evaluated. Inputs to the electrolysis include alumina and cryolite. The production of alumina is then traced back through the Bayer process and further back to bauxite ore extraction, and there is a similar chain for the cryolite.

After the material quantities have been evaluated for each of these steps (normalized to 1.0 tonne of output), the disaggregated fuel and electricity inputs are assessed. It may be useful to aggregate these quantities into a single energy input value (based on the combustion enthalpies of the fuels), but it is not necessary to do so.

Finally, one should note that approximately 0.55 tonne of carbon anode is chewed up in the production of 1.0 tonne of aluminum, and this anode has required energy for its production in addition to its own heat of combustion. An analysis of the indirect energy associated with the carbon anode should contain both of these data.

The results of a process analysis are individual values of fuels, electricity and materials required for 1.0 tonne of aluminum output in each of the processes and in the total aluminum manufacture. These are the inverses of the average products for each of these inputs, and, if the data are available, they could be interpreted as marginal products. The marginal (or average) physical products of inputs must be evaluated in order to economically optimize a production system. Also, these are the quantities that would be entered as input-output coefficients in a matrix that utilizes more accurate (physical) data. Thus, the process analytic method could be used to update and increase the accuracy of an energy input-output matrix.

It has also been suggested that the process analysis methods be wed to those of input-output analysis, so that process analysis is used to provide accurate evaluations of the first- and second-order inputs to the process of interest and input-output analysis is used in the otherwise tedious tracing of earlier production stages [Bullard, Penner and Pilati (1978), Woo, Noguchi, Long and Berry (1977)].

The type of aggregate energy use data that can be obtained from a process analysis are illustrated for coal production and beneficiation in Exhibits 4 (aggregate U.S. data, primarily from Census sources) and 5 (disaggregated primary data compared with aggregate data). As will be observed, the energy required to mine a tonne of coal is only a small fraction of the energy that is contained in it.

ECO-ENERGETICS

An alternative method of energy analysis has been proposed by Odum (1971). Unfortunately, complete presentations of this procedure are found only in unpublished manuscripts and reports to funding agencies,

Exhibit 4: Coal extraction energy requirements (MJ/tonne).

	Year			
	1954	1958	1963	1967
Underground	298	285	269	261
Surface	279	254	205	284
Underground with Prep. Plant	367	325	264	226
Surface with Prep. Plant	246	237	213	195

Exhibit 5: Comparison of strip mine with mechanical cleaning for 1967, Census average vs. representative Midwest mine.

	MJ/tonne	
	Average	Midwest Mine
Total	195	243
Coal	0	0
Electricity	113	130
Fuel Oil	57	90
Natural Gas	0	0
Gasoline	10	19
Explosives	2	4
Steel	13	?

and quantitative details have often been omitted from published materials in favor of qualitative argument.

Exhibit 6: Energy flows in estuary at Crystal River over an area affected in 1 day (9.2×10^6 m^2). After Odum (1974).

ITEM	kcal m^{-2}	10^6 kcal/day
Metabolism (day production plus night respiration)	28	252
Tidal energy absorbed	0.085	0.8
Wave energy absorbed	2.5	23
Solar energy absorbed and connected to potential energy of thermal gradient	27	249
Plume potential energy	62	570
Plume consumption (canal metabolism)	1.3	12
Plume kinetic-energy contribution	0.2	2
Energy to replace 20% plume zooplankton	0.2	2
Cooling tower ($5 x 10^6 year)	30.5	275

The basic form of this method is a modified process analysis in which non-market energy inputs from the environment are explicitly included. In reading the eco-energetics literature one should keep in mind that its principal focus is the elaboration of a system that explicitly embeds economic life in the ecological setting in which it operates. See also Westman (1977) for a more conventional view of this problem. Exhibit 6 displays a comparison of energy flows associated with two options for cooling an 800-MW power plant at Crystal River, Florida. This was taken from a published study by Odum (1974), and avoids the use of the systems dynamics diagram and the conversion to the "fossil-fuel-work-equivalent (FFWE)" units that often obscure his evaluations. The data presented are directly comparable to those resulting from a process analysis that includes environmental impact factors, and this allows us to examine the method in its barest outlines.

The question that is posed is: is optimal cooling of the 800-MW power plant accomplished by venting the energy in an aqueous thermal plume to an estuarine ecosystem (9.2×10^6 m^2 in area) or through the use of an air cooling tower? Odum argues that the energy of the thermal plume has not had a destructive effect on the estuary, even though the daily energy flow from this source is more than double the ecological metabolism, and that a portion of the effluent energy is utilized in estuarine circulation.

Odum's method should be viewed as an attempt to carry out a social benefit-cost analysis, but using an energy numeraire rather than a money unit. Obviously, the precise quantification of energy flows in the ecological system and the benefits and costs arising from such flows is worthy of attention. Although Odum does not claim that the net effect of thermal plume release is positive, he does assert that it has an effect that is positive in comparison to the costs (in the form of an energy requirement) to society of building and operating the cooling tower. There are two facets of his analysis that are troublesome. First, his evaluation of the energy that must be expended by society for the cooling tower utilizes a gross conversion from money units to energy units based on the ratio of total energy used in the U.S. in a year to the GNP. The dollar cost of the cooling tower alternative includes all capital and labor costs and operating expenses, in addition to material and fuel costs. Because GNP is defined as the dollar value of goods delivered to final demand, one must be careful to avoid multiple counting errors arising from including goods delivered to intermediate demand in the calculation and from counting the services utilized by an individual fully in each of his activities.

Second, because the dollar costs utilized by Odum include capital and labor costs and because the direct energy requirement is often small (relatively), multiplying all money unity by the energy/GNP ratio does no more than convert from denomination of economic units in dollars to denomination in some energy unit, be it kcal's or Btu's or kwh's or MJ's The figure for the societal unit is then compared with that for the natural energy input. Formally, no economist will object to this procedure if it is properly carried out, since it represents only a change in numeraire and would not modify market-related decisions on the part of entrepreneur or consumer. The price of any good will remain precisely the same <u>relative</u> to the price of any other good, but given in different units. However, there does not seem to be a commanding reason for a change in numeraire. In the benefit-cost comparison above, the energies furnished by the environmental factors could equally well have been converted to dollar units. If this conversion had utilized the arbitrary GNP/kcal ratio employed by Odum

$$\frac{\$1}{2 \times 10^{4}\text{kcal}} = 5 \times 10^{-5}\ \frac{\$}{\text{kcal}}$$

we would find that the plume potential energy provided an input worth \$28,500 per day to the estuarine body, versus a cost of \$13,000 per day for the cooling tower. Economists would prefer to price the economic contribution of the plume at its shadow price, which undoubtedly will be far smaller. Thus, we conclude that Odum's purpose has been the design of a method that permits one to compare the value he perceives from the work that is done by the environment with values generated by the economic system, and that there is nothing to recommend the simplistic conversion of either dollars-to-energy units or vice versa. Also, we note that, properly applied, a social benefit-cost analysis should give attention to the subject of time discounting and the appropriate discount rate.

Gilliland (1975) employs this method in her comparison of the energy requirements for the development and operation of 100-megawatt dry steam reservoir and wet steam reservoir geothermal power systems. Exhibit 7 displays this comparison, and those interested are referred to her paper for details. For present purposes, we should observe the following:

1) The items denoted by an asterisk were calculated on the basis of dollar-to-energy conversions. For the dry steam reservoir, 3575/4588 = 78% of the total energy requirement is evaluated in this manner, while 3685/5395 = 68% of the energy requirement for the wet steam reservoir is assessed using this procedure. Although different conversion ratios for each of the starred categories are used, the origin of these values is unclear. Presumably, they result from a physical evaluation similar to that using process analysis. Why, then, convert from directly-evaluated energy requirements to dollars and back to energy units?

Exhibit 7: Energy subsidies required for the development and operation of a 100-MW geothermal power system for 30 years. Electricity use is computed at its fossil fuel equivalent value. After Gilliland (1975).

ENERGY INPUTS	DRY STEAM RESERVOIR* (10^9kcal)	WET STEAM RESERVOIR† (10^9kcal)
Exploration**	50	50
Extraction and separation		
Fuel	135	150
Construction and maintenance materials	135	150
Transport of materials	5	6
Steam transport		
Construction and maintenance materials	25	35
Transport of materials	3	4
Construction‡ and operation of the steam field**	140	185
Conversion to electricity		
Construction materials	570	1,140
Maintenance materials**	25	35
Transport of materials	70	140
Construction‡ and operation of the power plant**	160	215
Transmission and distribution		
Construction and maintenance materials**	2,800	2,800
Construction‡ and operation of the transmission lines**	400	400
Environment		
Field site	35	50
Transmission corridor	35	35
Total energy requirement	4,588 (3,575)**	5,395 (3,685)**
Total energy delivered to consumer §	57,750	57,750
Net energy ratio		
Delivered energy to subsidy	12.6:1	10.7:1

*Steam-driven turbine. †Two-stage flashed steam-driven turbine.

‡Excluding materials. §16,500 kcal (electric) x 3.5 is 57,750 kcal of petroleum equivalents.

**These entries are evaluated using dollar/energy conversions rather than physical analysis; they total 3,575 x 10^9 kcal for the dry steam reservoir and 3,685 x 10^9 kcal for the wet steam reservoir.

2) The energy requirement that is designated as environmental is small (approximately 1.5% for both the dry and wet processes).
3) The possible errors in the dollar-energy conversion are so large (25%) as to preclude any decision based on a net energy calculation using this method, even it this were admitted to be the decision parameter of choice. Further, observing that the environmental subsidy is small, in any case, why should this project evaluation method be superior to a social benefit-cost analysis, which would presumably incorporate the information from the more transparent process energy analysis?
4) Although the data in Exhibit 6 from Odum do not contain his correction of caloric values for "energy quality" (Odum, undated), Gilliland's analysis (Exhibit 7) does. The statement usually made by these workers is that "not all calories are equal," because a calorie of wood energy will do less work than a calorie of coal energy (e.g., the "quality" ratio that is assumed is coal calorie/wood calorie = 2/1). The motivation behind establishing an energy quality scale would appear to be an attempt to put solar energy utilized by the environment on a scale having a magnitude comparable to conventional fuels. To do this, they adopt the following procedure: each energy type is assigned a "quality" that is equal to the number of calories that would be required to generate a unit of electricity using the best-available technology. This procedure is not altogether novel, because energy analysts have often performed an inverse conversion in assessing the electrical input at its thermal equivalent, the number of units of fossil fuel that were used in its generation. However, in this latter case, the electrical generation efficiency correction can be justified in one of two ways. First, observing that electric energy is actually generated utilizing fossil-fuel consuming boilers, the important question may be what is the impact of the energy use in driving a given process on the fossil fuel resource base. Second, if electrical energy were not used to drive the process, then fossil fuels would be the logical substitute power source. Neither of these justifications can be argued in constructing the "energy quality" scale. There are several difficulties in using such a scale, a principal one being that the conversion values are not constant but subject to technological change. Another would be that a process efficiency measure is directly incorporated in the energy analysis, rather than separating the analysis and the assessment of physical efficiency into two wel defined steps. Thermodynamicists do not find it necessary to establish an energy quality scale because they realize that an energy unit is of interest only in defining a change in the thermodynamic potential during a physical process and not as an abstract quantity. Thus, the efficiency of a process is measured by comparing the <u>actual</u> energy (thermodynamic potential) change in a process with the ideal change in a second-law calculation (*vide supra*).

Although the energetics approach has made a contribution in emphasizing the importance of environmental energy flows that could be substitutes for fuel energy flows from society, it has not developed a sound construct for their inclusion. A fair view of this method is that is does not provide as thoughtful a framework for social benefit-cost analysis as that provided by traditional economics, and that for analyzing specific energy questions, process analysis is more straightforward and more accurate.

SUMMARY

I conclude that energy input-output analysis, which can be integrated with econometric models, is useful in macroeconomic decisions. For micro-level decisions, process analysis is the method of choice and furnishes physical information that is useful in economic decision making. There appear to be a number of ways in which the information from energy analysis can complement and be incorporated into economic analysis:

- — Through a precise physical description of real-world processes.
- — In the evaluation of energy conservation measures and in the assessment of new energy-supply and new energy-using technologies.
- — By examining substitution possibilities between energy goods and other factors over the total life cycle and recycle of the commodity.
- — In the calculation of fuel price elasticities.
- — By determining the physical bounds on economic activity.
- — Through interfacing energy information systems (input-output matrices) with macroeconomic models.

BIBLIOGRAPHY

Anon., "Appendix G, The Application of Net Energy Analysis to Synthetic Fuels," a study prepared for the American Energy Resources Council (1975) April.

Berry, R.S. and Fels, M.F., "The Energy Cost of Automobiles," <u>Science and Public Affairs</u> (<u>Bulletin of the Atomic Scientists</u>) (1973) December.

Berry, R.S. and Makino, H., "Energy Thrift in Packaging and Marketing," <u>Technology Review 76, 4</u> (1974) February.

Berry, R.S., Long, T.V. and Makino, H., "Energy Budgets 5. An International Comparison of Polymers and Their Alternatives," <u>Energy Policy, 3, 144</u> (1975).

Buehring, W.A., Foell, W.K. and Keeney, R.L., "Energy/Environment Management: Application of Decision Analysis," Document No. RR-76-14, International Institute for Applied Systems Analysis (1976) May.

Bullard, C.W. and Herendeen, R.A., "Energy Use in the Commercial and Industrial Sectors of the U.S. Economy, 1963," Document No. 105, Center for Advanced Computation, University of Illinois at Urbana-Champaign (1973) November.

Bullard, C.W., Penner, P.S. and Pilati, D.A., "Net Energy Analysis: Handbook for Combining Process and Input-Output Analysis," <u>RESOURCES AND ENERGY, 1</u> (1978) in press.

Chapman, P.F., "The Energy Costs of Producing Copper and Aluminum from Primary Sources," Open University Report ERG 001, Milton-Keynes, England (1973).

Chapman, P.F., "The Economics of Energy Analysis Revisited" (letter), <u>Energy Policy, 5, 160</u> (1977) June.

Common, M., "The Economics of Energy Analysis Reconsidered," Energy Policy, 4, 158 (1976) June.

Common, M., "The Economics of Energy Analysis Revisited" (letter), Energy Policy, 5, 159 (1977) June.

Darmstadter, J., " Energy Accounting vs. the Market," Resources, 50, 4 (1975) November.

Development Sciences, "Application of New Energy Analysis to Consumer Technologies," ERDA 77-14, UC95C (1977) February.

Gilliland, M.W., "Energy Analysis and Public Policy," Science, 189, 1051 (1975) September.

Gilliland, M.W., "Energy Analysis" (letter), Science, 192, 12 (1976) April.

Hannon, B.M., "System Energy and Recycling: A Study of the Container Industry," American Society of Mechanical Engineers, 72-WA-ENER-3, New York (1972).

Hannon, B.M., "An Energy Standard of Value, Annals of the American Academy of Political and Social Sciences, 410, 139 (1973) November.

Hannon, B., "Energy Conservation and the Consumer," Science, 189 (1975) July.

Herendeen, R.A., "An Energy Input-Output Matrix for the United States, 1963: User's Guide," Document No. 69, Center for Advanced Computation, University of Illinois at Urbana-Champaign (1973) March.

Herendeen, R.A., "Desirability of Several Input-Output Techniques in Calculating Energy Cost of Goods and Services," Division of Economics, University of Trondheim, Trondheim, Norway (mimeo, undated).

Herendeen, R.A. and Bullard, C.W., III, "Energy Cost of Goods and Services, 1963 and 1967," Document No. 140, Center for Advanced Computation, University of Illinois at Urbana-Champaign (1974) November.

Herendeen, R.A. and Shiu, K, "Comparison of Methods for Projecting Total Energy Coefficients," Technical Memorandum No. 47, Center for Advanced Computation, University of Illinois at Urbana-Champaign (1975) February.

Hoffman, K.C. and Jorgenson, D.W., "Economic and Technological Models for Evaluation of Energy Policy," Bell Journal of Economics, 444 (1977) Fall.

Huettner, D.A., "Net Energy Analysis: An Economic Assessment," Science, 192, 101 (1976) April.

Huettner, D.A., "Energy Analysis" (letter), Science, 196, 261 (1977) April.

International Federation of Institutes for Advanced Study, Report No. 6, The Workshop on Energy Analysis, Guldsmedshyttan, Sweden (1974) August.

International Federation of Institutes for Advanced Study, Report No. 9, The Workshop on Energy Analysis and Economics, Stockholm, Sweden (1975) June.

Krutilla, J.V. and Fisher, A.C., The Economics of Natural Environments. Baltimore: Johns Hopkins University Press, 1975.

Langham, M.R. and McPherson, W.W., "Energy Analysis" (letter), Science, 192, 8 (1976) April.

Leach, G., "Net Energy Analysis—Is It Any Use," Energy Policy, 3, 332 (1975) December.

Leach, G., "NEA Reexamined" (letter), Energy Policy, 4, 177 (1976) June.

Leach, G. and Slesser, M., "Energy Equivalents of Network Inputs to the Food Production Process," Strathclyde University Report (1973).

Long, T.V., II, "Net Energy Via Process Analysis," Report of the NSF-Stanford Workshop on Net Energy Analysis, Stanford University (1975) August.

Long, T.V., II, "Economics and Energy Analysis," in The Energy Accounting of Materials, Products, Processes and Services (9th International TNO Conference), 15, Rotterdam, The Netherlands (1976) February.

Long, T.V., II and Fishelson, G., "An International Comparison of Energy and Materials Use in the Iron and Steel Industry, " in Dunkerley, J., ed., International Comparisons of Energy Consumption. Washington, D.C.: Resources for the Future, 1978.

Lucas, R.E., Jr., and Sargent, T.J., "After Keynesian Macroeconomics," preprint (1978) June.

McInnis, B.C. and Hamilton, K.E., "Gross Energy Requirements for the Production of Goods— An I/O Baseline," Working Paper 75-06-01, Structural Analysis Division, Statistics Canada (1975) June.

Mueller, R.F., "Energy Analysis" (letter), Science, 192, 11 (1976) April.

Odum, H.T., Environment, Power and Society. New York: Wiley-Interscience, 1971.

Odum, H.T., "Use of Energy Diagrams for Environmental Impact Statements," in Tools for Coastal Management Conference Proceedings, Marine Technology Society, 197 (1972) February.

Odum, H.T., "Energy Cost-Benefit Models for Evaluating Thermal Plumes," in Gibbons, J.W. and Sharitz, R.R., eds., Thermal Ecology, AEC Symposium Series (CONF. 730505), 1974.

Odum, H.T., "Energy Analysis" (letter), Science, 196, 261 (1977) April.

Odum, H.T., "Energy Quality Concentration Factors for Estimating Equivalent Types to Support Work," University of Florida, Gainesville, Florida (mimeo, undated).

Pearson, R.G., "Energy Analysis," Occasional Paper No. 2, Joint Centre for Environmental Studies (1976) December.

Peskin, H.M., "Energy Analysis" (letter), Science, 192, 11 (1976) April.

Polenske, K.R., "Net Energy Analysis in the Energy Research and Development Administration Plan," Massachusetts Institute of Technology Energy Laboratory, Working Paper No. MIT-EL 75-018WP (1975) December.

Reichle, D.E., "Energy Analysis" (letter), Science, 192, 12 (1976) April.

Slesser, M., "NEA Reexamined" (letter), Energy Policy, 4, 176 (1976) June.

Slesser, M., "Energy Analysis" (letter), Science, 196, 259 (1977) April.

U.S. General Accounting Office, "Net Energy Analysis: Little Progress and Many Problems," Report No. EMD-77-57 (1977) August.

U.S. House of Representatives, Committee on Science and Technology, "Energy Accounting as a Policy Tool," prepared by D.E. Gushee, Congressional Research Service, Washington, D.C. (1976) June.

Webb, M. and Pearce, D., "The Economics of Energy Analysis," Energy Policy, 3, 318 (1975) December.

Webb, M. and Pearce, D., "The Economics of Energy Analysis Revisited" (letter) Energy Policy, 5, 158 (1977) June.

Westman, W.E., "How Much Are Nature's Services Worth?," Science, 197, 960 (1977) September.

Winstanley, G., "Energy Analysis: Methods, Uses, Implications," Research Series No. 11, Office of Energy Conservation, Canadian Department of Energy, Mines and Resources (1976) February.

Woo. M.T., Noguchi, T., Long, T.V., II, and Berry, R.S., "Methodology for Energy Analysis," in Fazzolare, R.A. and Smith, C.B., eds., Energy Use Management. Elmsford, New York: Pergamon Press, 1977.

Wright, D.J., "Goods and Services: An Input-Output Analysis," Energy Policy, 2, 307 (1974) December.

ENERGY ANALYSIS AND ULTIMATE LIMITS

David A. Huettner, Ph.D.
Energy Program Director
Center for Economic and Management Research
Norman, Oklahoma 73019

ABSTRACT

Since the basic objective of energy analysis is to identify the ultimate sustainable limits to human activities, it is appropriate to identify ultimate limits to the usefulness of energy analysis. Human activities can take many forms and any assessment of ultimate limits is not only a forecast of technical progress and resource availability but is also a statement about human values i.e., what activities can or ought to be sustained. Current applications of energy analysis are not merely attempts to find common units of measurement (BTU's rather than dollars) but are attempts to value current human activities in accordance with their believed long run sustainability.

Physical laws (including those of thermodynamics) constrain man's activities but do not dictate values by themselves. The problems addressed by energy analysis are of definite social relevance but the science of economics indicates that the objectives of energy analysis are unattainable by the methods employed.