Embodied Energy and Economic Valuation

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Summary. Input-output analysis has been adapted to calculate the total (direct plus indirect) energy required to produce goods and services in the U.S. economy; this quantity has been termed the embodied energy. Usually, the energy required to produce labor and government services and the solar energy input to the economy are ignored by analysts. The former omission can be traced to the assumption that traditional primary factors of economic production—land, labor, and capital—are independent. A strong case can be made that these input factors are not independent and that energy is required for their production. Embodied energies can be calculated in this case by using input-output data. The results of such an analysis show that there is a strong relation between embodied energy and dollar value for a 92-sector U.S. economy if the energy required to produce labor and government services is included.

The thesis that available energy both limits and governs the structure of human economies is not new. In 1886, Boltzmann suggested that life is primarily a struggle for available energy. Soddy stated in 1933: "If we have available energy, we may maintain life and produce every material requisite necessary. That is why the flow of energy should be the primary concern of economics" (*1*, p. 56). The flow of energy has not been the primary concern of mainstream economists, although the importance of energy to the functioning of economic systems has by now been recognized by almost everyone. The debate now focuses on the nature and details of the energy connection, and the conclusions are critically important to several aspects of national policy. In this article, the earlier input-output analyses of energy-economy linkages are extended by incorporating the energy costs of labor and government services and solar energy inputs.

The flow of energy is the primary concern of what has come to be known as energy analysis (*2*–*4*). An important aspect of energy analysis is the determination of the total (direct and indirect) energy required for the production of economic or environmental goods and services. This total has been termed the embodied energy. For example, the energy embodied in an automobile includes the energy consumed directly in the manufacturing plant plus all the energy consumed indirectly to produce the other inputs to auto manufacturing, such as glass, steel, labor, and capital. A problem immediately apparent from this definition is the choice of procedures for calculating indirect energy requirements. Embodied energy values are thus contingent on methodological considerations.

Input-output (I-O) analysis is well suited to calculating indirect effects in a systematic and all-inclusive accounting framework. Hannon (*5*) and Herendeen and Bullard (*6*) adapted this technique to calculate embodied energy. Controversy still exists concerning the relevant system boundaries for such calculations (*3*).

System Boundaries

The choice of system boundaries is critical because it determines the distinction between net inputs and internal transactions. Net inputs are considered to be independent and exogenously determined, whereas internal transactions are endogenous and interdependent. The net inputs are what economists refer to as primary factors. In the national income accounts, they are "value added." The I-O technique, in essence, distributes a net input vector through a matrix of internal interactions to balance against a net output vector.

Most recent embodied energy calculations based on national I-O tables have employed the standard definitions of economic I-O boundaries (*6*). With these definitions, the net input (or value added) vector includes labor, government services, capital services, and energy and other natural resources (raw materials). The corresponding financial categories are employee compensation, indirect business taxes, and property-type income. The sum of these net inputs, in dollar units, is the gross national product (GNP). Energy (fossil fuels, nuclear fuels, and solar) is a small component of the GNP in dollar units. This has led several people to conclude that energy is a minor component in economic production, a conclusion that would be accurate if the components of the net input vector as currently defined (GNP) were mutually independent, as is usually assumed.

Most proposals to increase the "energy efficiency" of economic activity are ultimately based on the assumption of mutual independence of primary factors, since increasing energy efficiency entails substituting other primary factors (capital, labor, government services, or other natural resources) for fuel inputs. The question is: Are the components of the net input vector as currently defined really independent? Are the conventional primary factors—capital, labor, natural resources, and government services—free from indirect energy costs? A strong case can be made for the contention that they are not (*7*–*9*). In this article, I present the case for the interdependence of the currently defined primary factors, detail a method for using I-O data to calculate embodied energies so as to take account of this interdependence, and interpret the results.

Primary Factors

From a physical perspective, the earth has one principal net input—solar energy. Although very small amounts of meteoric matter also enter the earth's atmosphere, and deep residual heat may continue to drive crustal movement, there is no stream of spacecraft carrying workers, government mandates, and capital structures onto the planet. Thus, practically everything on the earth can be considered to be a direct or indirect product of past and present solar energy. The same cannot be said for the other "primary" factors. Fossil fuels and other natural resources represent millions of

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years of embodied sunlight. Environmental flows (such as winds, rain, and rivers) represent embodied sunlight of more recent origin. Humans, under this view, are the product of millions of years of solar-powered R & D and are maintained by an agriculture that uses both current sunlight and fossil sunlight. From this perspective, industrial capital is obviously created by the economic process and is not a net (or primary) input.

As Georgescu-Roegen points out: "On paper, one can write a production function any way one likes, without regard to dimensions or to other physical constraints" (*10*, p. 97). Doing just this has allowed some economists to ignore critical real interdependences and to conclude, for example, that "There are presently extensive possibilities of substitution between resources and other factors [capital]" (*11*, p. 64). Georgescu-Roegen goes on to say: "In actuality, the increase of capital implies an additional depletion of resources." Odum (*9*) has pointed out that the currently defined primary factors are really interdependent by-products of our one observable net input—solar energy.

How can this interdependence of primary factors be taken into account in an analytical model? In an I-O framework, one can simply expand the boundaries so that the net input to the model coincides with the net input to the real system. In practice, most of the interdependences can be captured by considering households and government to be endogenous sectors. This represents a return to Leontief's concept of a "closed" economic system (*12*), with the system boundaries, in this case, placed so that only current solar energy and the energy embodied in fuels and other natural resources enter as a net input.

In a closed Leontief model, households and government are treated like any other sector, with technical coefficients based on the household and government consumption (inputs) used to produce labor and government service outputs. As with standard I-O analysis, this is strictly an accounting of inputs and outputs. The question of whether the current standard of living and level of government spending is good or bad, too high or too low, necessary or wasteful is not and need not be asked in this format.

Input-Output–Based Energy Accounting

The I-O technique for calculating embodied energy involves defining a set of energy balance equations (one for each sector) and solving the resulting set of simultaneous linear equations for the energy intensity coefficient vector ϵ, which is the energy required directly and indirectly to produce a unit commodity flow.

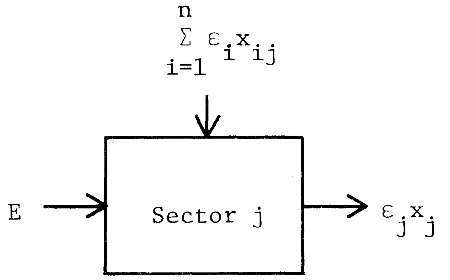

Fig. 1. Single-sector energy balance.

Figure 1 shows the basic energy balance for a sector, where x_{ij} is the transaction from sector i to sector j, x_j is the total output of sector j, ϵ_j is the embodied energy intensity per unit of x_j, and E_j is the external direct energy input to sector j. Thus the energy balance for the jth sector is

$$E_j = \epsilon_j x_j - \sum_{i=1}^{n} \epsilon_i x_{ij} \qquad (1)$$

In matrix notation for all n sectors

$$\boldsymbol{E} = \boldsymbol{\epsilon}(\hat{\boldsymbol{x}} - \boldsymbol{x}) \qquad (2)$$

where $\boldsymbol{E}$ is a row vector of direct external energy inputs, $\hat{\boldsymbol{x}}$ is a diagonalized vector of gross output flows, and $\boldsymbol{x}$ is the n by n transactions matrix. One can solve for ϵ as

$$\boldsymbol{\epsilon} = \boldsymbol{E}(\hat{\boldsymbol{x}} - \boldsymbol{x})^{-1} \qquad (3)$$

More detailed expositions of the technique and examples can be found in (*6*), (*13*), and (*14*).

The modifications to include labor and government in the model require expanding the transactions matrix (x) to include two more sectors, households and government (Fig. 2). These sectors receive goods and services from the other sectors in proportion to personal consumption expenditures and government expenditures. They provide services to the other sectors in proportion to employee compensation, indirect business taxes, and some percentage of property-type income. The modifications and approximations are discussed in greater detail in (*14*), along with the method employed for estimating solar energy inputs based on land and water use. With household and government sectors considered endogenous, the GNP as currently defined is no longer the net input and output of the model. Personal consumption and government expenditures are now internal transactions, leaving gross capital formation, net inventory change, and net exports as the new net output. Likewise, wages and taxes are internal payments, leaving capital consumption allowances and payments to land and resources as the new net input. To be complete, gross capital formation should include human and government capital formation as well. This implies that some consumption categories in the current model (such as spending on education) would be better handled as capital formation categories. Data on these categories for the U.S. economy have recently been calculated by Kendrick (*15*), but have not been incorporated here. The effects of this omission will be discussed later.

Input-output methodology does not include capital stocks explicitly, since a static equilibrium is assumed. The flows produced by stocks and the flows necessary to maintain and expand stocks are included (as gross capital formation), so stocks are taken into account implicitly. However, even this picture is somewhat distorted, because by convention gross capital formation is credited to the industries producing the capital, not to those utilizing it. This distortion is correctable, and modifications of the I-O model that give a more accurate picture of capital flows have been constructed (*16*). These modifications were not included in the results presented here; they have been shown to cause only a 7 to 8 percent change in the average energy intensity (*16*).

Solar energy inputs were added to the $\boldsymbol{E}$ vector after correcting for the lower thermodynamic usefulness of direct sunlight in comparison with fossil fuel. Electricity represents an upgraded, more useful form than fossil fuel, requiring, directly and indirectly, about 4 British thermal units (Btu's) of fossil fuel per Btu of electricity to produce (*6*). Likewise, fossil fuel represents an upgraded, more useful form than the solar energy that produced it. To account for this difference in quality, an I-O model of the biosphere showing the complete production relations from sunlight to fossil fuel would be necessary. Since such a model does not yet exist, an approximation based on the conversion of sunlight to tree biomass to electricity in a wood-burning power plant was used. This yielded a conversion factor of 2000 Btu's of solar energy per Btu of fossil fuel (*17*). The total solar input for the United States was estimated at 103×10^{18} Btu's of solar energy per year [from data in (*18*) and (*19*)] or the functional equivalent of 51.5×10^{15} Btu's of fossil fuel per year. Solar energy was assumed to enter the economy through the agriculture, forestry, and fisheries sectors, according to their relative land areas. This distribution is crude and will need to be improved as better data become available. For example, the solar inputs to industrial sectors via the hydrologic cycle in providing water for processing and for carrying away wastes are not properly allocated with this approximation.

Results of Modifications to System Boundaries

The 90-sector model of energy input and output maintained by the Energy Research Group at the University of Illinois was used to determine the effects of making the above modifications. The model is based on 1967 financial transactions in the U.S. economy. Physical flow I-O data would be preferred for embodied energy calculations, but are not available in the required form at the national level. Calculations made with financial data are nevertheless useful, because they yield information on the direct and indirect energy required to produce a dollar's worth of each of the commodities in the economy.

Selected embodied energy intensities (in Btu's of fossil fuel per dollar) were calculated for each of four possible alternatives, with the results shown in Table 1. The complete calculations may be found in (*13*). Alternative A is calculated with the conventional economic I-O boundaries and yields essentially the same results as those of Herendeen and Bullard (*6*). Alternative B includes solar energy inputs; alternative C includes labor and government as endogenous sectors; and alternative D includes the modifications of alternatives B and C together.

Figure 3 shows frequency plots for the four alternatives, which indicate the reduction in variance of the energy intensities when labor and government are included. Including solar energy did not increase or decrease the variance greatly, but this may be due to the rather crude method used in this study to estimate the distribution of solar energy to the economic sectors. A low variance indicates a more constant relationship from sector to sector of direct-plus-indirect energy consumption and dollar value of output.

The results were put in a regression format to highlight relationships and for significance testing. The calculated energy intensity for each sector (in Btu's per dollar) was multiplied by the sector's dollar output to yield the direct-plus-indirect energy input (in Btu's). This was used as the independent variable, with total dollar output as the dependent variable. Figure 4 shows the results for each of the four alternatives. The primary energy sectors (sectors 1 to 7) were found

Table 1. Embodied energy intensities for selected sectors evaluated for the 1967 data base (A) excluding labor and government energy costs and solar energy inputs, (B) including solar energy inputs, (C) including labor and government energy costs, and (D) including both labor and government energy costs and solar energy inputs. Numbers in parentheses are Bureau of Economic Affairs sector equivalents.

Sector	Embodied energy intensity (Btu's of fossil fuel per dollar)			
	A	B	C	D
1. Coal mining (7)	5,143,600	5,172,000	5,455,600	5,807,500
2. Crude petroleum and natural gas (8)	2,920,300	2,929,200	3,188,600	3,469,050
4. Electric utilities (68.01)	505,500	513,900	796,220	1,099,950
6. Other agricultural products (2)	81,567	775,090	381,090	1,385,400
10. Iron and ferroalloy ores mining (5)	65,904	99,605	406,060	800,800
14. New construction (11)	54,804	230,245	389,770	913,950
21. Apparel (18)	38,845	295,135	371,107	974,600
33. Paints and allied products (30)	107,100	160,680	425,290	809,300
73. Air transportation (65.05)	122,630	143,910	452,230	814,700
75. Transportation services (65.07)	5,672	11,615	346,970	706,750
79. Wholesale and retail trade (69)	29,302	43,265	411,490	814,350
91. Government			717,160	1,393,050
92. Households			358,350	738,050

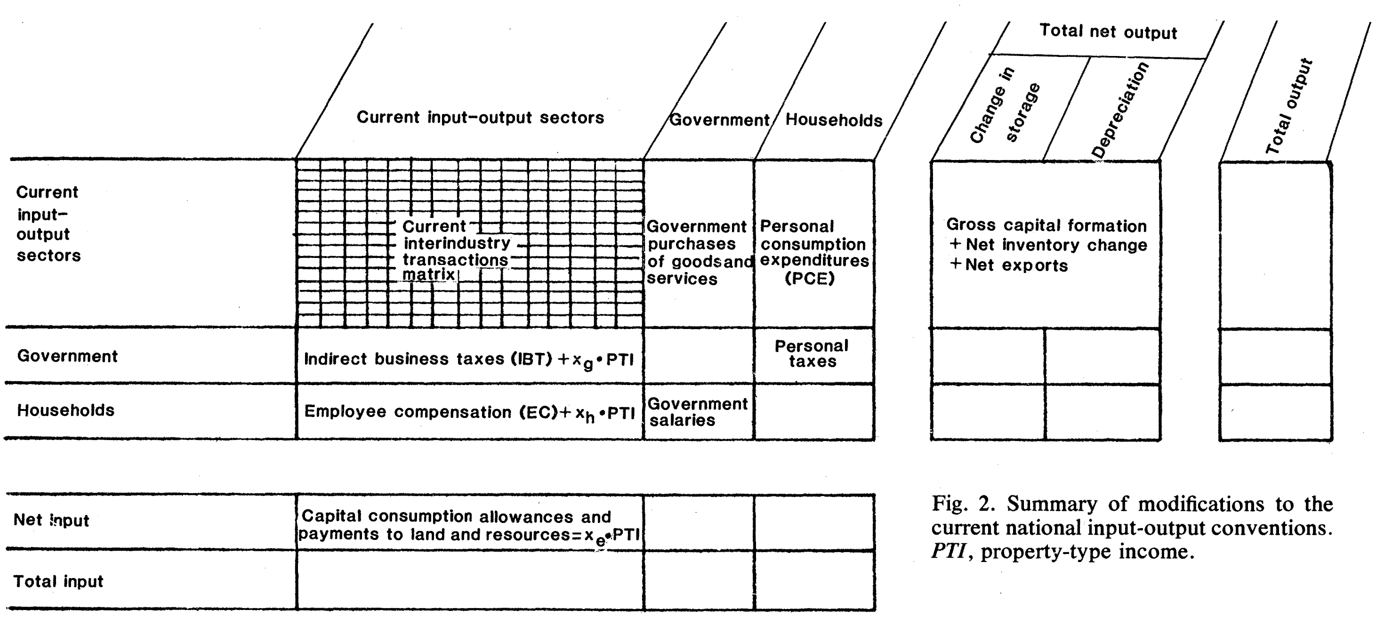

Fig. 2. Summary of modifications to the current national input-output conventions. *PTI*, property-type income.

to be outliers, and the regression results excluding them are also presented. The regression lines are indicated in Fig. 4 along with the r^2 values, equations, and t statistics on the parameters (in parentheses below the parameter values). Table 2 lists the r^2 values, F statistics, and significance levels for each of the alternatives.

The results indicate a significant relationship between embodied energy and dollar output when labor and government are included as endogenous sectors (alternatives C and D). Several problems still exist, but the trend is clear. As more of the indirect energy costs are taken into account, the ratio of embodied energy to dollars becomes more nearly constant from sector to sector. The primary input sectors (sectors 1 to 7) are the important exceptions to this rule. Their departure from the regression lines in Fig. 4, C and D, has several possible interpretations. One interpretation is that the energy intensities for these sectors are high because they represent the points of entry of available energy into the economy. Their degree of departure from the line is an indication of the net energy yield or "energy profit" they provide. In other words, their direct and indirect production costs in energy terms are much less than the energy embodied in their outputs, the difference being the amount brought into the economy from outside.

Table 2. Regression analysis results for direct plus indirect energy consumption (embodied energy) versus dollar value of output for 92 U.S. economy sectors evaluated for the 1967 data base: (A) excluding labor and government energy costs and solar energy inputs, (B) including solar energy inputs, (C) including labor and government energy costs, and (D) including both labor and government energy costs and solar energy inputs.

Alternative	Including energy sectors 1 to 7			Excluding energy sectors 1 to 7		
	r^2	F	Significance level of F-test	r^2	F	Significance level of F-test
A	.0210	1.89	0.1729	.5539	100.57	0.0001
B	.0629	5.90	0.1710	.2042	20.78	0.0001
C	.7809	313.73	0.0001	.9907	8633.95	0.0001
D	.8535	512.74	0.0001	.9454	1401.31	0.0001

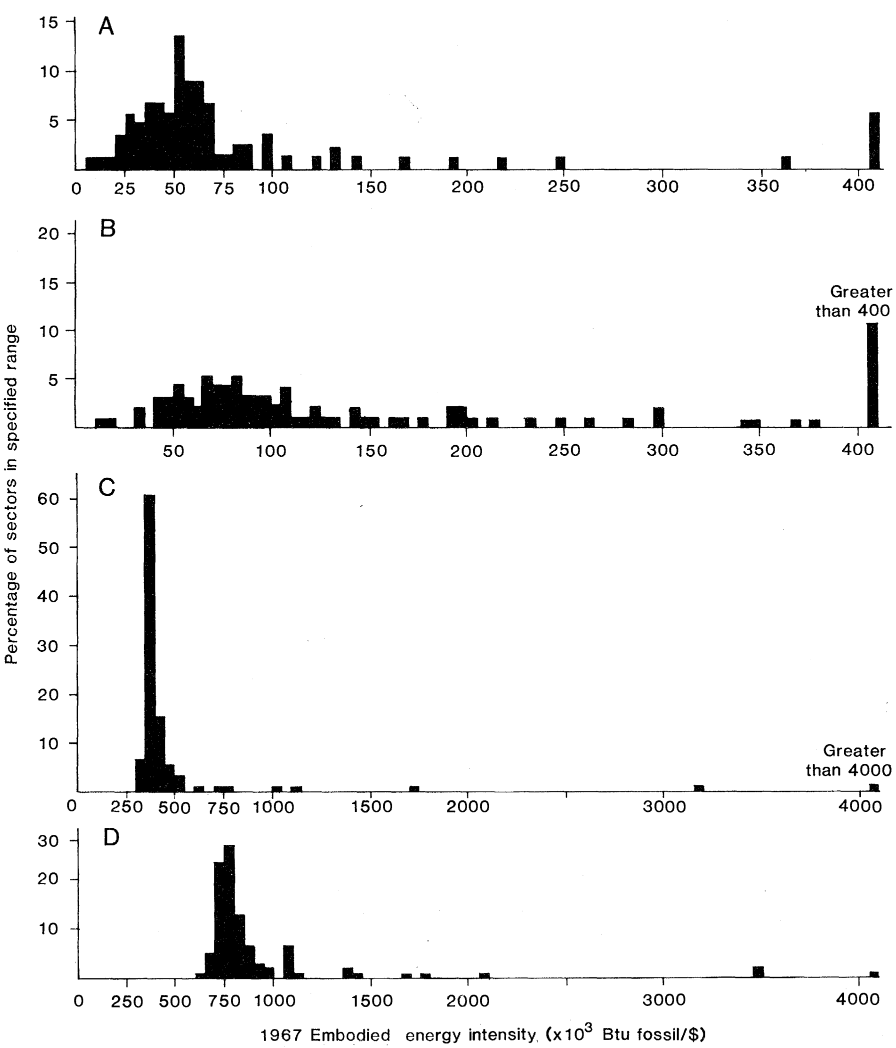

Fig. 3. Frequency plots of embodied energy intensity (in 10^3 Btu's per dollar) by sector for 92 U.S. economy sectors evaluated for the 1967 data base (A) excluding labor and government energy costs and solar energy inputs, (B) including solar energy inputs, (C) including labor and government energy costs, and (D) including both labor and government energy costs and solar energy inputs.

Ratios of Energy to GNP

Discussions of energy and economics frequently include time series or international comparison plots showing the relation of fossil, nuclear, and hydro energy to GNP or GDP (gross domestic product). The strong historical and international link between these variables is unmistakable. Several authors have suggested that "decoupling" energy and GNP is possible and would allow the economy to continue to grow while decreasing energy consumption (*20, 21*). Calculations based on the conventional system boundaries (Figs. 3A and 4A) are often used or implied in support of this idea. If the sector-to-sector differences in embodied energy intensities implied in these calculations were real, then it might be possible to simply shift production from high energy intensity sectors to low energy intensity sectors to lower energy use without sacrificing economic activity. This conclusion would follow from the underlying assumption that the currently defined primary factors are independent. But because it takes available energy to produce labor and government services, capital, and other natural resources, the assumption of independence is not warranted. The results presented in Fig. 3, C and D, and Fig. 4, C and D, reflect the implications of an attempt to relax the independence assumption and lead to the conclusion that decoupling energy and economic activity by simply shifting production between sectors is not a real possibility. The possibility for large changes in energy efficiency is small since, all things considered, total energy efficiency is fairly constant from sector to sector. Any reductions in direct energy consumption are offset by increases in indirect energy consumption through increased use of labor, land, or capital.

Actually, Fig. 4, C and D, lead to the conclusion that energy consumption is highly related to gross capital formation plus net inventory change plus net exports because these quantities are the net output from the economy under the revised boundary definition. The GNP includes these quantities, as well as personal consumption and government expenditures. The extent to which gross capital formation, net exports, and net inventory change are separable from the GNP as a whole represents the latitude for decoupling energy and GNP. I suspect that this latitude is small, especially if human and government capital formation are included as part of gross capital formation—as Kendrick (*15*) has suggested—and not as consumption. Inclusion of human and government capital formation would also significantly decrease the mean embodied energy intensity, since it would increase the redefined net output from the economy. For alternative D the mean would drop from 12.20×10^5 to 1.88×10^5 Btu's of fossil fuel per 1967 dollar (*14*).

Double Counting

Slesser (*22*) commented that including labor costs in embodied energy calculations would involve double counting. This criticism was directed against a specific method of including labor costs, and it remains a valid criticism of that method. If the conventional system boundaries for calculation of embodied energy are used, and then the energy necessary to support labor is simply added on, the same energy has indeed been counted twice. If the energy costs of labor are to be included without double counting, the system boundaries have to be changed. The net output with the revised boundaries does not include the support of labor, which is now an internal transaction (see Fig. 2). The total energy budget is now allocated to gross capital formation, net inventory change, and net exports. The total energy requirement is equal to the total energy input, and the energy cost of labor is accounted for. However, in any I-O accounting system, gross flows and net flows must be kept straight. One can never add up internal transactions in an I-O table and expect them to equal net inputs or outputs. With the expanded boundaries, net output and input are no longer equal to GNP, but rather to GNP minus labor and government transactions.

Embodied Energy Theory of Value

Several authors have proposed various forms of an energy theory of value (*1, 8, 23, 24*). The idea is summarily dismissed by neoclassical economists (*25–27*) on the ground that energy is only one of a number of primary inputs to the production process. This dismissal is unwarranted if the traditional primary factors are in reality interdependent. The results presented in this article indicate that if there are interdependences among the currently defined primary factors, then calculated embodied energy values that take this into account show a very good empirical relation to market-determined dollar values. Herendeen (*28*) has shown

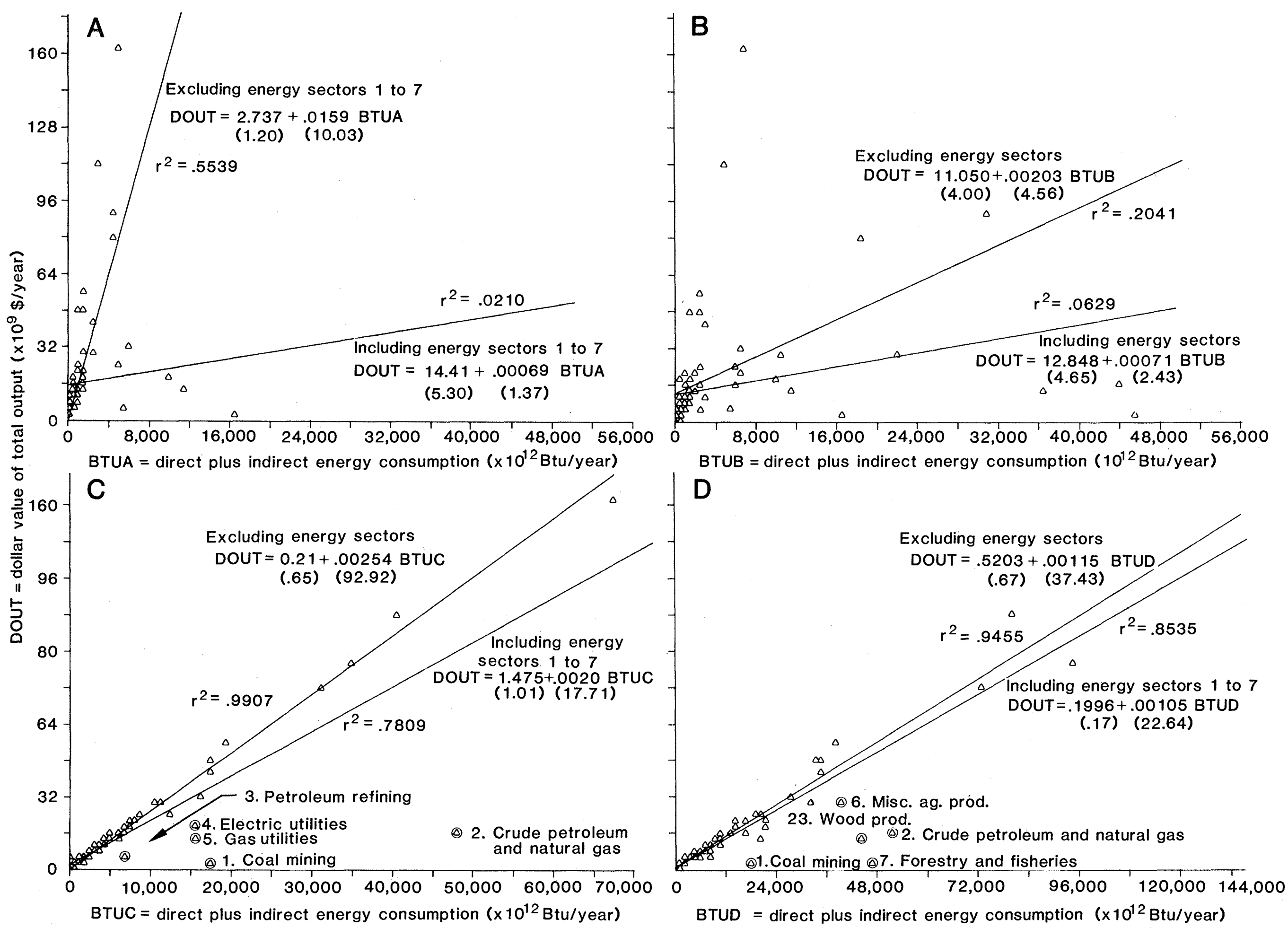

Fig. 4. Plots of direct plus indirect energy consumption (embodied energy) versus dollar value of output for 92 U.S. economy sectors evaluated for the 1967 data base (A) excluding labor and government energy costs and solar energy inputs, (B) including solar energy inputs, (C) including labor and government energy costs, and (D) including both labor and government energy costs and solar energy inputs. The primary energy sectors (sectors 1 to 7) were found to be outliers, and regression results excluding them are also presented.

that, with the I-O method, the necessary and sufficient condition for the energy intensity vector to be constant is that the value-added vector (in dollars) and the direct-energy input vector (in Btu's) be proportional. If all factors other than energy are moved from the net input vector to the transactions matrix, this proportionality is to be expected.

The question might be asked whether the same thing we have done with energy could not be done with any of the other currently defined primary factors and thus support capital, labor, or government service theories of value. The answer is that on paper this could be done. We must look to physical reality to determine which factors are net inputs and which are internal transactions. No one would seriously suggest that labor creates sunlight.

An embodied energy theory of value thus makes theoretical sense and is empirically accurate only if the system boundaries are defined in an appropriate way. It is really a cost-of-production theory with all costs carried back to the solar energy necessary directly and indirectly to produce them. The results indicate that there is no inherent conflict between an embodied energy (or energy cost) theory of value and value theories based on utility. The empirical equivalence of these estimates—one from the cost or supply side, and one from the benefit or demand side—supports basic economic principles grounded in optimization while giving them a biophysical basis. The flow of energy *is* the primary concern of economics.

Conclusions

The results presented here indicate that, with the appropriate perspective and boundaries, market-determined dollar values and embodied energy values are proportional for all but the primary energy sectors. The required perspective is an ecological or "systems" view that considers humans to be a part of, and not apart from, their environment. A few economists have already taken this perspective (*29–31*), and the implications for a new ecological economics that links the natural and social sciences are great (*32*). The concept of embodied energy may help to provide such a link as an empirically accurate common denominator in ecological and economic systems. With the appropriate boundaries, embodied energy values are accurate indicators of market values where markets exist. Because they are based on physical flows, they may also be used to determine "market values" where markets do not exist—for example, in ecological systems. This is one way of "internalizing" all factors external to the existing market system and solving the natural resource valuation problem. From the ecological perspective, markets can be viewed as an efficient energy allocation device that humans have developed to solve the common problem facing all species—survival.

What does all this imply for national policy? The most important implication is that the physical dimensions of economic activity are not separable from limitations of energy supply. The universally appealing notion of unlimited economic growth with reduced energy consumption must be put firmly to rest beside the equally appealing but impossible idea of perpetual motion. It is easy to think you can get a "free lunch" by looking only at small parts of the system in isolation. When the whole system is analyzed, however, it becomes clear that all you can do is transfer the cost of your lunch to another segment of the system.

These conclusions should not be interpreted as pessimistic. Several authors, notably Daly (*31*), have pointed out the inadequacy of GNP and other yardsticks of physical economic production as measures of social welfare. Indeed, there is nothing inherently appealing about what Boulding (*30*) has called the "cowboy economy," the adolescent phase of rapid, self-conscious, often painful growth. If we are to manage our future wisely, we must be aware of the physical limitations on economic activity and learn to live well within our energy budget.

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