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It has long been recognized that available energy governs and limits the structure of human economies. While mainstream economists have not paid much attention to energy analysis, which is primarily concerned with the flow of energy, almost everyone has recognized the importance of energy to the functioning of economic systems. The nature, details and conclusions of the energy connection are important to several aspects of national policy. This article extends earlier input-output analyses of energy-economy linkages by incorporating the energy costs of labor and government services and solar energy inputs.

An important part of energy analysis is the determination of the total or embodied energy - i.e., direct plus indirect energy - required for the production of economic or environmental goods and services. For example, the embodied energy in an automobile is the energy consumed in the manufacturing plant (direct energy), plus the energy consumed to produce the glass, steel, labor, capital, etc. (indirect energy). A key problem in determining the amount of embodied energy is the choice of methodology used to calculate indirect energy requirements, since different methodologies will yield different results. Input-output analysis, adapted by Hannon[1] (1973) and Herendeen and Bullard[2] (1974), is well suited to calculating indirect effects, although controversy still exists concerning the relevant system boundaries for these calculations.

SYSTEM BOUNDARIES

The choice of system boundaries is important because it distinguishes net inputs from internal transactions. Net inputs are independent and exogenously determined, whereas internal transactions are endogenous and interdependent. Net inputs are what economists call primary factors, and are referred to as "value added" in national income accounts. In essence, the input-output technique distributes a net input vector through a matrix of internal interactions to balance against a net output vector. In recent embodied energy calculations, net input vectors include labor, government services, capital services, energy and other natural resources. The dollar sum of the net inputs is the gross national product (GNP). The share of energy (from fossil fuels, nuclear fuels and solar) in GNP is small in dollar units, leading to the conclusion that energy is a minor input in economic production. This conclusion is based on the assumption that the different components of net input are mutually independent. This article argues that the different components are not mutually independent, and contends that capital, labor, natural resources and government services have indirect energy costs. A method of using input-output data to calculate embodied energies that takes the interdependencies into account is proposed.

PRIMARY FACTORS

From a physical perspective, solar energy is the principal net input. Practically everything on earth can be considered a direct or indirect product of past or present solar energy, including all other "primary" factors. In an input-output framework, the interdependence of primary factors can be taken into account by expanding the boundaries so that the net input to the model coincides with the net input to the real system. In practice this can be done by considering households and governments as endogenous sectors. The system boundaries are then defined in such a manner that only current solar energy and the energy embodied in fuels and other natural resources enter as a net input.

INPUT-OUTPUT-BASED ENERGY ACCOUNTING

The input-output technique for calculating embodied energy involves defining a set of energy balance equations, with one equation for each sector. The resulting set of simultaneous linear equations can be solved to yield an energy intensity coefficient vector that represents the energy required directly and indirectly to produce a unit of commodity flow. When the transaction matrix is expanded to include the household and government sectors, GNP as currently defined is no longer the net input or output of the model. The new net input is made up of capital consumption allowances and payments to land and resources, and the new net output is gross capital formation, net inventory change and net exports. Even with these changes there are some problems with the input-output calculations adopted in this paper. Specifically, some categories that fall into consumption (like education) should be accounted for under capital formation. Also, while capital stocks are accounted for implicitly when gross capital formation is included, the picture is somewhat distorted because by convention gross capital formation is credited to the industries producing the capital, not to those using it. However, while only approximations were used, solar energy inputs were added to the vector of direct external energy inputs after correcting for the lower thermodynamic usefulness of direct sunlight as compared to fossil fuels.

RESULTS OF MODIFICATIONS TO SYSTEM BOUNDARIES

Embodied energy intensities were calculated for each of four alternatives:

A) using conventional economic input-output categories;
B) including solar energy inputs;
C) including labor and government as endogenous sectors; and
D) including the modifications of alternatives B and C taken together.

The variance of the energy intensities was greatly reduced under alternatives C and D as compared to alternatives A and B. A lower variance implies a more constant relationship from sector to sector between direct-plus-indirect energy consumption and dollar value of output.

Regressions were run for the four alternatives, with the direct-plus-indirect energy intensity as the independent variable, and the total dollar value as the dependent variable. Since the primary energy sectors were outliers, regressions were also run excluding them. When labor and governments are included as endogenous sectors, there is a significant relationship between embodied energy and dollar output. The more that indirect energy costs are taken into account, the more constant is the ratio of embodied energy to dollar output from one sector to the next. The only exceptions to this rule are the primary input sectors, where the energy intensities are high. This may be because the energy embodied in their outputs is much greater than the direct and indirect energy costs involved in their production.

RATIOS OF ENERGY TO GNP

There have been suggestions that economic growth can be pursued while reducing energy consumption by shifting from high energy intensity sectors to low energy intensity sectors. These suggestions are based on calculations of sector-to-sector differences in embodied energy intensities using conventional system boundaries. This study shows that decoupling energy and economic activity by shifting production between sectors is not a possibility. Given that total energy efficiency is fairly constant across sectors, any reductions in direct energy consumption will be offset by increases in indirect energy consumption through the increased use of labor, land or capital.

DOUBLE COUNTING

Slesser[3] (1977) has argued that including labor costs in embodied energy calculations involves double counting. This criticism is valid when using the conventional system boundaries. With modified system boundaries, the support of labor is an internal transaction, and is not included in net output. The problem of double-counting is therefore eliminated.

EMBODIED ENERGY THEORY OF VALUE

Neoclassical economists have rejected various proposals for an energy theory of value on the grounds that energy is only one of a number of primary inputs to the production process. The results presented in this article indicate that if there are interdependencies among the currently defined primary factors, then embodied energy values show a very good empirical relation to market-determined dollar values. It can be asked whether the same thing that has been done with energy cannot be done with any of the other currently defined primary factors, resulting in capital, labor, or government service theories of value. While on paper this could be done, we must look to physical reality to distinguish net inputs from internal transactions: no one would seriously suggest that labor creates sunlight. If the system boundaries are properly defined, an embodied energy theory of value makes theoretical sense.

CONCLUSION

The results presented in this paper indicate that given appropriate system boundaries, market values and embodied energy values are proportional for all but the primary energy sectors. Embodied energy values may therefore be used to determine "market values" where markets do not exist, and these "market values" can be used for "internalizing" externalities. The most important implication of the results for policy is that there cannot be unlimited economic growth with reduced energy consumption. This only appears to be true when looking at small sectors of the economy in isolation. When the whole system is analyzed, it is clear that, when output is constant, energy costs can only be transferred between sectors, not eliminated entirely.

Notes

1. B. Hannon, *Journal of Theoretical Biology* 41, 575 (1973).
2. R.A. Herendeen and C.W. Bullard, *Energy Cost of Goods and Services, 1963 and 1967* (Document 140, Center for Advanced Computation, University of Illinois, Champaign-Urbana, 1974).
3. M. Slesser, *Science* 196, 259 (1977).