Rankings based on energy and material flows

Excerpt from draft SAB Committee report, *Valuing the Protection of Ecological Systems and Services*: *The second group of biophysical methods that the committee discussed quantify the flows of energy and materials through complex ecological systems, economic systems, or both. Ecologists have used these methods to identify the resources or resource equivalents needed to produce a product or service, using a systems or life-cycle ("cradle to grave") approach. For example, embodied energy analysis measures the total energy, direct and indirect, required to produce a good or service. Similarly, ecological footprint analysis measures the area of an ecosystem (e.g., the amount of land and/or water) required to support a certain level and type of consumption by an individual or population.*[*]

In addition to using these methods to measure required inputs, some ecologists have advocated using the cost estimates for embodied energy as a measure of value, based on an energy (or other biophysical input) theory of value. Although conceptually distinct, they have found that these estimates can be of similar magnitude to value estimates based on economic valuation methods.

Further reading

Embodied energy

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[*] Both embodied energy analysis and ecological footprint analysis use a consistent set of accounting principles based on input-output analysis to compute these costs. An alternative biophysical method, emergy, on the other hand, also seeks to measure the energy cost of producing a good or service, but it does not follow these principles, and hence, does not generally satisfy basic adding-up properties. Rather, it focuses on converting inputs of varying quality to a common energy metric – usually solar energy equivalents – so that they can be combined into a cost estimate measured in those units.

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Introduction

Energy and material flow analysis is the quantification of the flows of energy and materials through complex ecological or economic systems, or both. These analyses are based on an application of the first (conservation of mass and energy) and second (entropy) laws of thermodynamics to ecological-economic systems. A recent report by the National Research Council (NRC) covers the basic elements and need for such analyses (Committee on Materials Flows Accounting of Natural Resources, Products and Residuals 2004). The NRC report concludes that information about material flows can be a very useful input for policy decisions. It can be used to identify potential environmental concerns and key sources of pollution and to develop strategies for preventing environmental releases.

This section provides general background on energy and material flow analysis as a means of identifying and quantifying important relationships within ecological and economic systems. It then discusses two methods that translate the physical energy and material flows into measures that could be used in the context of ecological valuation. The first is embodied energy analysis, which estimates the direct and indirect energy (or more correctly, available energy or "exergy") cost of goods and services. The second is ecological footprint analysis, which estimates the biologically productive land or water areas required (directly or indirectly) to meet various consumption patterns. We also briefly discuss the use of the concept of "emergy" for estimating energy costs and valuation.

Energy and Material Flows Analysis

Energy from the sun drives plant productivity as well as climate and hydrologic cycles, nutrient cycles, ocean currents, weathering and soil formation. Thus a study of energy and material flows in ecosystems relates very directly to the production of ecosystem services. Ecologists have long utilized studies of the flow of energy and materials (e.g., nitrogen, phosphorus) through ecosystems as a way of describing key relationships and understanding the functioning of those ecosystems. Early studies of energy flow in aquatic (e.g., Lindeman 1941) and terrestrial (e.g., Golley 1960) systems illustrated how energy moved through food chains. Ground-breaking analyses of the cycling of critical nutrients in lakes (e.g., Hutchinson 1947) and forests (e.g., Likens and Borman 1977) set the stage for many subsequent analyses and established the field of biogeochemistry. Studies of energy and materials flows can be especially useful for understanding how changes to an ecosystem, such as an increased or decreased level of pollution, may alter the system and the services it provides. For instance, increases or decreases in the inputs of nitrogen to a forest from acidic deposition may impact forest productivity, species composition, and nitrogen runoff in streams and rivers (e.g., Johnson and Lindberg 1991). Larsson, et al. (1994) used energy and material flows to demonstrate the dependence of a renewable resource such as commercial shrimp farming on the services generated by marine and agricultural ecosystems. The committee seconds the view expressed by the NRC (2004) that analyses such as these can provide very valuable information about ecological services and how the flow of services might change in response to specific stressors.

The energy and environmental events of the 1960s and 1970s prompted a number of economists, ecologists, and physicists to examine the energy and material flows underlying the economic process (Boulding 1966, Georgescu-Roegen 1971, 1973). Ecologists noted the importance of energy in the structure and evolutionary dynamics of ecological and economic systems (Lotka 1922, Odum and Pinkerton 1955, Odum 1971). The integration of the first law of thermodynamics with the economic system was first made explicit in the context of an economic general equilibrium model by Ayres and Kneese (1969) and subsequently by Mäler (1974). It is also a feature of a series of linear models developed after 1966 (Cumberland 1966, Victor 1972, Lipnowski 1976). All reflect the recognition that the earth is a thermodynamically closed (but not isolated) system, with energy from the sun crossing the boundaries and maintaining the structure and function of the earth system. A closed system must satisfy the conservation of mass condition. Ayres (1978) described some of the important implications of the laws of thermodynamics for the economic production process, noting that both manufactured and human capital require materials and energy for their own production and maintenance (Costanza 1980).

A key feature of energy flow analysis is the recognition of the importance of energy quality, namely, that a kcal of one energy form (e.g., electricity) may produce more useful work than a kcal of another (e.g., oil). Estimating total energy consumption for an economy is therefore not a straightforward matter because not all fuels are of the same quality, that is, they vary in their available energy, degree of organization, or ability to do work. This effort to incorporate energy quality is often referred to as "second law analysis."

Embodied Energy Analysis

As noted, methods have been developed that seek to use energy and material flows information to determine values associated with different systems or changes in those systems. One such method is embodied energy analysis. The embodied energy method assesses the direct and indirect energy costs of economic and ecological goods and services. It uses input-output tables to determine the direct and indirect energy inputs used to produce these goods and services. Although there is no stated Agency policy to use or develop supplemental valuation methodologies in this area, there is substantial Agency interest in how Energy and Material Flow methods might aid decision making. Recent efforts to explore the utility of such methods, mostly at the regional or local level, are underway (Bastianoni et al., 2005, Campbell 2001, 2004, Lu, et al. 2006).

Some ecologists and physical scientists have used estimates of embodied energy to implement an energy theory of value either to complement or replace the standard neoclassical theory of subjective utility-based value (Soddy 1922, Odum 1971, 1983, Slesser 1973, Gilliland 1975, Costanza 1980, Cleveland, et al. 1984, Hall, et al. 1992). The energy theory of value is based on thermodynamic principles, where solar energy is recognized to be the only primary or external input to the thermodynamically closed global ecosystem. At the global scale, the traditional primary factors of production (labor, manufactured capital, and natural capital) are viewed as intermediate factors (Costanza 1980).

There has been ongoing debate about the validity of an energy theory of value (Brown and Herendeen 1996). Some believe that it is the only reasonably successful attempt to operationalize a general biophysical theory of value that does not hinge completely on consumer preferences (see also Patterson 2002). Neoclassical economists, on the other hand, have criticized the energy theory of value as an attempt to define a concept of value that does not directly reflect consumer preferences regarding the good being valued (see Heuttner 1976). This criticism is, on the one hand, axiomatic, since a major purpose of an energy theory of value is to establish a theory of value not completely determined by individual preferences. On the other hand, techniques for calculating embodied energy utilize economic input-output tables. These tables summarize production interdependencies, but they are not completely independent of consumer preferences, which helped to structure the production interdependencies over time. Neoclassical economists also question the primary status of energy, because in any concrete, short-term situation the scarcity and prices of the conventionally-defined inputs of manufactured capital, labor, and technology are also important. While not denying the importance of these short-term considerations, energy theorists take a broader, more evolutionary perspective, recognizing that these factors are intermediate and that production relationships adapt over time.

As noted, the energy theory of value (like the labor theory of value developed by classical economists) is inherently based on relative production costs, i.e., it yields a measure of (direct plus indirect) energy cost. The question arises as to when these energy-based production cost estimates can provide a measure of value. This is similar (but not identical) to the question that arises in the context of replacement costs based on the standard economic concept of opportunity cost (see Chapter **Error! Reference source not found.** and more detailed discussion of replacement costs in the Appendix below). In economic systems, marginal cost and price will be equal in a perfectly competitive equilibrium. This means that, in the absence of other market distortions, an estimate of marginal cost can provide a proxy for the value of an additional unit of production. Similarly, an estimate of production cost can provide a proxy for value, but only under certain circumstances (see discussion in section on replacement cost). For example, the aggregate individuals must be willing to incur these costs rather than forego the good or service. One difference between replacement and production costs is that while replacement costs are hypothetical, production costs have already been incurred, implying that aggregate individuals were willing to incur the costs, thus satisfying this condition. To the extent that the necessary conditions are met, energy costs can provide information about the value of the associated goods or services as defined by the energy theory of value.

Costanza, et al. (1989) provide an example of wetlands valuation that uses both a conventional WTP approach and a simplified energy analysis approach based on the gross primary productivity (GPP) of coastal wetlands in Louisiana. The energy analysis valuation technique compared total biological productivity of a wetland versus an adjacent open water ecosystem. Primary plant production, which supports the production of economically valuable products such as fish and wildlife, was converted to a monetary value based on the cost to society to replace this energy source with fossil fuel as measured by the overall energy efficiency of economic production. While the results of the WTP- and GPP-based methods were fairly consistent, the authors note that the GPP approach probably represented an upper bound and "may overestimate their value if some of the wetland products and services are not useful (directly or indirectly) to society" (Costanza, et al. 1989, p 341). However, it should be noted that the basic assumptions underlying an energy theory of value imply that there is no reason to expect measures based on energy cost to be the same as preference or WTP-based measures of value.

<u>Ecological Footprint Analysis</u>

The ecological footprint (EF) method is a variation of energy and material flow analysis that converts the impacts to units of land or water rather than energy or dollars. The

EF for a particular population is defined as the total "area of productive land and water ecosystems required to produce the resources that the population consumes and assimilate the wastes that the population produces, wherever on Earth that land and water may be located" (Rees 2000). While usually discussed in the context of the footprint of specific human populations, this concept can also be applied to non-human populations. For example, a portion of the southern Chesapeake Bay has been set aside as a blue crab sanctuary since large numbers of the organisms spawn in this area relative to elsewhere (Virginia Marine Resources Commission, Newport News, VA). In the context of human societies, input-output methods (see previous discussion) are used to estimate direct and indirect land requirements.

Although there are ongoing debates about specific methods for calculating the ecological footprint (Costanza 2000, Herendeen 2000, Simmons, et al. 2000), the ecological footprint is an effective device for presenting current total human resource use in a way that communicates easily to a broad range of people (http://www.footprintnetwork.org/). In terms of valuing ecosystem services, the ecological footprint concept is most useful as an index of the quantity of ecosystem services consumed (expressed in units of a standardized land area) for various consumption patterns. This measurement, however, does not directly convert to a monetary measure of the value of ecological services. It does, however, allow a relative comparison of one footprint to another based on areas or sizes involved. Under this approach, ceteris paribus, a population that has a smaller footprint is viewed as more sustainable. On the other hand, a larger footprint implies a larger biocapacity supporting a given population and a larger required contribution of ecosystem services to maintain that population in its current state.

Emergy Analysis

Emergy analysis shares many of the same goals and assumptions as embodied energy analysis. For example, solar emergy is defined as "the available solar energy used up directly and indirectly to make a service or product" (Odum 1996). Emergy analysis differs from embodied energy analysis and ecological footprint analysis in terms of the method used to estimate the energy required. While embodied energy and footprint analysis use methods based on input-output (a well-developed set of methods for this type of accounting), emergy analysis uses different methods (See recent work by Ukidwe and Bakshi, in press).

Emergy analysis starts with the creation of an energy flow diagram. The "Solar Transformity" is then defined as "the solar emergy required to make one Joule of a service or product" (Odum 1996). This is calculated by dividing any flow in the diagram by the total solar energy input. Odum and coworkers have thus calculated the emergy of the earth's main processes, such as the total surface wind, rain water in streams, the sedimentary cycle, and waves absorbed on shore, to be that of the total emergy input to the earth (Odum 1996). Each of these processes is assigned the total value of incoming sunlight because they are considered co-products of the global geological cycle and cannot be produced independently with less amount of the total emergy.

However, emergy has encountered considerable resistance and criticism, particularly from economists, physicists, and engineers (Hau and Baksi 2004, Ayres 1998, Cleveland, et al. 2000, Mansson and McGlade 1993, Spreng 1988). Consequently, the emergy approach has only been used by a small circle of researchers, although some work at EPA is ongoing (U.S. Environmental Protection Agency 2005). Emergy's accounting method does not produce an estimate of the energy cost of goods and services, but rather "the relative equivalence between energies of different kinds in terms of a universal quality factor." This concept is difficult to understand and to apply in a standard accounting framework. Although the committee as a whole did not study the debate over emergy in detail, the committee believes that substantial questions exist regarding the appropriateness and usefulness of emergy as a method for valuing ecological systems and services**.**

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