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ENERGY ANALYSIS EVALUATION OF COASTAL ALTERNATIVES

Howard T. Odum

Environmental Engineering Sciences and Center for Wetlands, University of Florida, Gainesville, U.S.A.
(Participating from summer residence at the International Institute for Applied Systems Analysis, Laxenburg, Austria)

INTRODUCTION

This paper summarizes an embodied energy analysis procedure for evaluating the environmental contributions to the economy. It provides a way to compare the economic contributions of natural systems and those proposed in development projects. Since economic vitality depends on work of the environment as well as on the work by humans, measures of work applicable to both are needed to guide development in the coastal zone. The need for a measure of value to be applied to alterative environmental usages is increasingly expressed in public affairs. See, for example, resolutions of this congress on coastal engineering and ecology.

Whereas dollars are being used to measure the contributions of goods and services from the human economy to a coastal zone, it is generally recognized inside and outside economics that the expenditures made to people for their services in processing environmental products do not adequately measure the contributions of the environment to the economy. Since nature's coastal process and the endeavors of humans are both contributing work, an energy method that measures work contributions measures both on the same basis.

Although the concept is simple, there is one complexity that makes the calculations more difficult. Energies of different type do not do equivalent work per unit energy used. Energy types which have more effect generally require more work of other types to be used in the transformations by which they are formed. All kinds of energy have to be expressed in equivalent units of one type of energy.

The energy of one type required to generate energy of other types is the energy embodied in those flows. The embodied solar energy required to deliver a joule of wind, tide, fuel, or human service are all different. In general the energy flows with more embodied energy are those with greater effect per joule. The energy types that require more and have greater effect are said to be of higher quality.

In the embodied energy analysis procedure for environmental evaluation the works of nature and those of the hyman economy are all expressed in embodied solar equivalent joules. The system of humanity and nature which generates more total embodied energy generates more real economy. By chosing alternatives which have the most embodied energy contributions, guidance is provided for coastal planning.

PROCEDURE

The following steps are the procedure used for evaluating environmental contributions to an economy on the same basis as human generated goods and service:

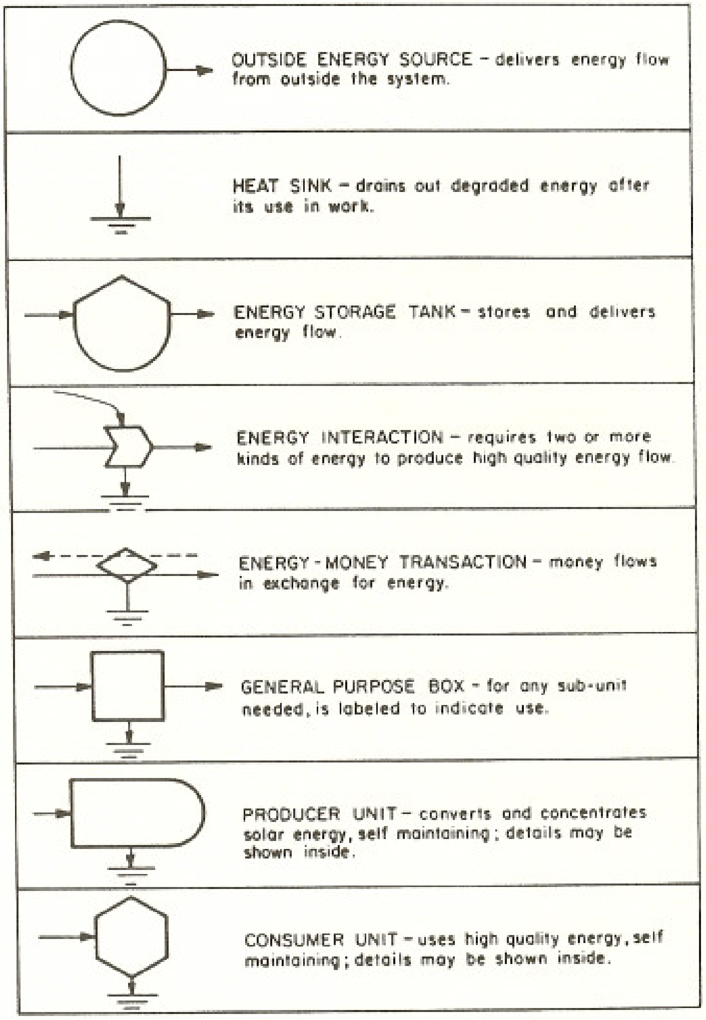
Energy diagram. With information from knowledgeable people draw a systems diagra using energy language. The symbols of the energy language (Figure 1) are not ne and are probably already familiar to many. The symbols are summarized in thei verbal context in Figure 1. Complete explanations with energy and mathematica contexts were given in a recent book (Odum, 1983).
The area diagrammed should be larger than the problems of most concern and includ driving functions from larger areas. For example, to consider evaluations of a estuary of The Netherlands where field trips of this conference were taken, th Zeeland regional district might be diagrammed. The diagram in Figure 2 of the Zeeland area includes many of the estuarine processes, economic activities, and problems of the area.

Aggregated subsystem diagram. With the help of the overview diagram of the regional system in which the problem of interest is embedded, make a second diagram o the processes and subsystems to be evaluated. For example, Figure 3 has processe affecting an estuary in which storm surge structures are being considered. A da is one alternative that eliminates tidal influence; another more costly alternative allows the tide to inflow except during storms when giant gates are closed.
This diagram has pathways to be evaluated. The larger realm diagrammed in Figure helps in determining if the main inflows of embodied energy of nature and from th economy were included. Perhaps readers in examining the two diagrams may recogniz missing pathways that should be included. Part of the power of the energy system is in visual comprehension of complex systems relationships derived from specialists. The importance of each pathway is not really known until its embodied energy is evaluated.

Evaluating actual energy. Energy flows and storages of interest are next evaluate using a tabular format (Table 1). In the left column actual energy flow is calculated in joules per time. Most types of energy calculations were set up for convenience in formula form in "cookbook" lists (Odum and colleagues; Odum and Odum 1983). The calculations of actual energy are given in footnotes, cross-reference to the lines in the energy evaluation table.
Most of the values of actual energy flow in the table are of a different energ quality. It is incorrect to compare energy flows of different quality as measure of work or contribution to the economy.

Energy tranformation ratio. In column two of the evaluation table (Table 1 fo example) are given the energy transformation ratios between solar embodied energ and the type of energy in that line. These energy transformation ratios were obtained by analyzing the global energy system or smaller systems that have had lon periods of successful competition. Table 2 gives some of the energy transformatio ratios used in coastal evaluations and the way they were calculated.

In recent years we have been recalculating these ratios as better data becam available or as additional inputs to each kind of tranformation were recognized Changing one ratio often changes others that were calculated with it. Since th maximum energy transformation efficiency possible in a process is probably



OUTSIDE ENERGY SOURCE – delivers energy flow from outside the system.

HEAT SINK – drains out degraded energy after its use in work.

ENERGY STORAGE TANK – stores and delivers energy flow.

ENERGY INTERACTION – requires two or more kinds of energy to produce high quality energy flow.

ENERGY-MONEY TRANSACTION – money flows in exchange for energy.

GENERAL PURPOSE BOX – for any sub-unit needed, is labeled to indicate use.

PRODUCER UNIT – converts and concentrates solar energy, self maintaining; details may be shown inside.

CONSUMER UNIT – uses high quality energy, self maintaining; details may be shown inside.

Fig. 1. Symbols of the energy systems language.

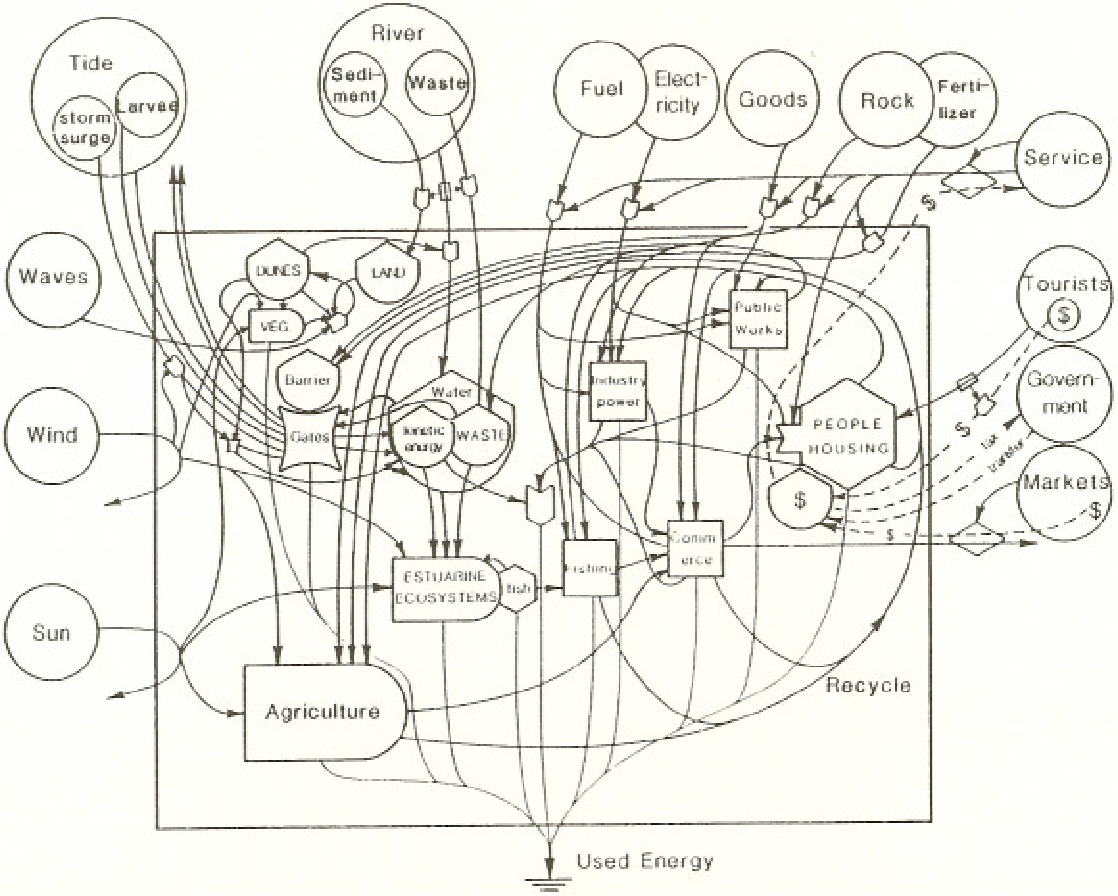


Fig. 2. Energy systems diagram of the Zeeland region of The Netherlands.

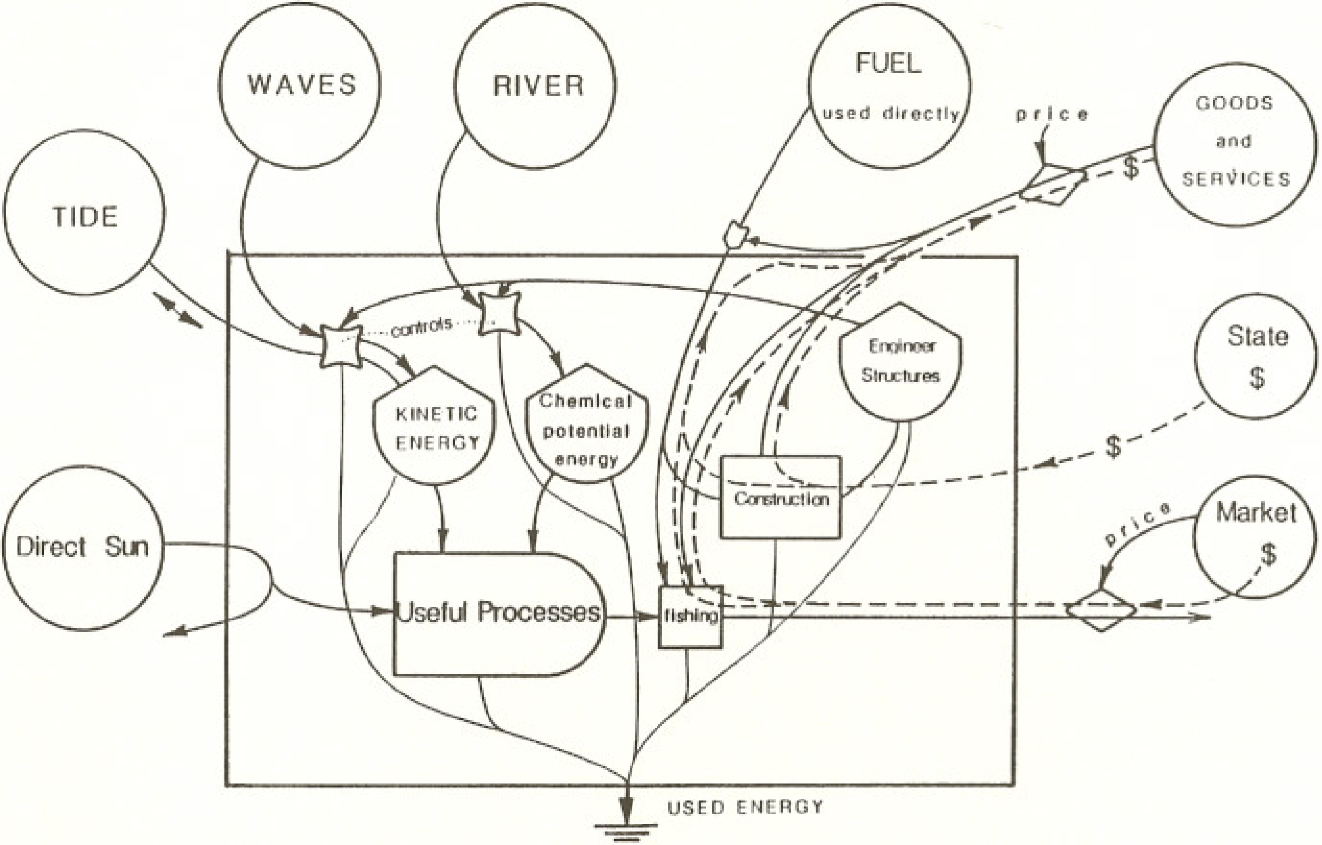


Fig. 3. Some energy flows in a fictitious estuary in which storm gates are under construction. See Table 1.

thermodynamic property, with more tedious work these ratios may eventually stabilize as they approach the correct values.

TABLE 1. Examples of energy evaluation of some flows in a fictitious estuary* with coastal engineering construction. See Figure 2.

Item Number and Footnote	Item	Actual Energy J/y	Energy Transformation Ratio # SEJ/J	Embodied Solar Equivalents E18 SEJ/y	Dollar Equivalents (1980 U.S.)+ E6 $/y
1	Direct sunlight	1.34 E18	1	1.34	0.6
2	Tide absorbed	7.1 E15	2.4 E4	170	77
3	Chemical potential of river inflow	4.9 E15	4.1 E4	200	91
4	Waves	1.71 E15	2.6 E4	44.4	20
5	Fishery yield	2.7 E13	2.7 E6	73	33
6	Direct fuel use in construction	3.8 E14	6.6 E4	25	11
7	Goods and services in construction	--	2.2 E12 SEJ/$	66	30

Footnotes to Table 1:

* For simplicity in showing methods with sample calculations a rectangular estuary is assumed, 40 km by 8 km (3.2 E8 m^2); estuary mouth is 8 km wide.

\# Energy transformation ratios from Table 1.

\+ Items in colums 3 divided by 2.2 E13 SEJ/$; see Table 1.

1. DIRECT SUNLIGHT
(3.2 E8 m^2)(1 E6 kcal/m^2/y)(4186 J/kcal)
= 1.34 E18 J/y

2. TIDE ABSORBED IN ESTUARY
(area elevated)(0.5)(tides/yr)(height squared)(density)(gravity) =
(3.2 E8 m^2)(0.5)(706/yr)(2.5 m)^2)(1.0253 E3 kg/m^3)(9.8 m/sec^2) = 7.1 E15 SEJ/y
0.5 x height is center of gravity

3. CHEMICAL POTENTIAL ENERGY IN RIVER
(volume flow)(density)(G) =
where G = Gibbs free energy of river water relative to sea water

$$G = \frac{(8.33\ \mathrm{J/mole/deg})(300^{\circ}\mathrm{C})}{(18\ \mathrm{g/mole})} \quad \log_e \frac{(1\mathrm{E}6 - S)}{(965{,}000)}\ \mathrm{J/g}$$

where S is dissolved solids in parts per million: 600 ppm

$$G = (138.8\ \mathrm{J/g})\ \log_e \frac{(1\mathrm{E}6 - S)}{(965{,}000)} = 4.9\ \mathrm{J/g}$$

(1E9 m^3/yr)(1E6 g/m^3)(G J/g) = 4.9 E15 J/y

4. OCEAN WAVES ABSORBED
(shore length)(1.8 density)(gravity)(height squared)(velocity) =
(8000 m)(1/8)(1.025 E3 kg/m^3)(9.8 m/sec^2)(1 m^2)(5.4 m/sec)(3.154 E7 sec/y)
where velocity is square root of gd = (9.8 m/sec^2)(3 m deep) $^{1/2}$
= 5.4 m/sec = 1.71 E15 J/y

5. FISHERY YIELDS. Assume fishery yield, 4 g dry/m^2/y
(4 g/m^2/y)(3.2 E8 m^2)(5 kcal/g)(4186 J/kcal) = 2.7 E13 J/y

6. MOTOR FUELS
5% of construction cost for motor fuel at $25/barrel;

6 E6 barrels (bbl) of oil used directly in construction of gates that last 100 years.

$$\frac{(6\ \mathrm{E6\ bbl})(6.3\ \mathrm{E9\ J/bbl})}{(100\ \mathrm{years})} = 3.8\ \mathrm{E14\ J/y}$$

7. GOODS AND SERVICES
Assume $3 E9 1980 U.S. $ is the extra cost of putting storm gates in the entrance dam so that tide can continue to enter estuary in ordinary weather. Gates last 100 years.

$$\frac{(\$3\ \mathrm{E9})(2.2\ \mathrm{E12\ SEJ/\$})}{100\ \mathrm{y}} = 6.6\ \mathrm{E19\ SEJ/y}$$

TABLE 2. Energy transformation ratios for between solar insolation and various types of energy flow.

Footnote		Solar Equivalent Joules per Joule	Means of Calculation
1	Direct sunlight	1	By definition
2	Tide	2.4 E4	Assumed equal that for geopotential energy of rivers based on world web
3	Waves	2.6 E4	From world energy web
4	Chemical potential of river inflow	4.1 E4	From world hydrologic cycle
5	Fishery yield	2.7 E6	Analysis of Chrystal River estuary in Florida
6	Liquid fuel	6.6 E4	Analysis of a wood power plant and oil-electric equivalents
		Solar Equivalent joules per U.S. Dollar	
7	Goods and Services	2.2 E12	Ratio of total solar equivalents used in The Netherlands to gross national product

Footnotes for Table 2:

1. Includes all wave lengths absorbed by earth.
2. Embodied solar energy in land processes includes solar energy absorbed (3.93 E24 SEJ/y) and the solar equivalents of deep heat sources driving the crustal processes (4.06 E24 SEJ/y); 8.0 E24 SEJ/y. The part of deep heat flow not attributable to radioactivity or flow up from mantle is assumed to be from the solar-driven biosphere hydrologic work, sedimentary cycle, etc. This establishes the deep heat equivalents of solar insolation. See Appendices A1-A3, (Odum and colleagues, 1983). Total global annual energy basis in solar equivalent joules is 8.0 E24 SEJ/y.
   Physical energy in stream flow.
   Global runoff, 39.6 E3 $\mathrm{km}^3/\mathrm{yr}$ (Todd 1970); average elevation, 875 m

$(39.6\ E3\ km^3/yr)(1\ E12\ kg/km^3)(9.8\ m/sec^2)(875\ m) = 3.395\ E20\ J/y$

$$\text{ETR: } \frac{8.0\ E24\ SEJ/yr}{3.4\ E20\ J/yr} = 2.36\ E4\ SEJ/J$$

3. Wave energy absorbed at shore estimated as the energy of average wave coming ashore (Kinsman 1965) multiplied by facing shorelines.

$(1.68\ E8\ kcal/m/yr)(4.39\ E8\ m)(4186\ J/kcal) = 3.09\ E20\ J/yr$

$$\text{ETR: } \frac{8.0\ E24\ SEJ/yr}{3.09\ E20\ J/yr} = 25889\ SEJ/J$$

4. Chemical potential energy in rivers.

Rivers represent concentration over water dispersed as rain. A transformation ratio for world average river is given: global runoff, 39.6 E3 km^3/y, typical dissolved solids, 150 ppm.

Gibbs free energy per gram water:

$$= \frac{(8.33\ J/mole/deg)(300^{o}C)}{(19\ g/mole)} = \log_e \frac{(999{,}850)}{(965{,}000)}$$

$(3.96\ E19\ cm^3/y)(0.99985\ g/cm^3)(4.92\ J/g) = 1.948\ E20\ J\ Water/y$

$$\text{ETR: } \frac{(8.0\ E24\ SEJ/y)}{(1.948\ E20\ J\ water/y)} = 4.11\ E4\ SEJ/J\ \text{river water}$$

$$\text{ETR: } \frac{8.0\ E24\ SEJ/yr}{5.187\ E20\ J/yr} = 15423\ SEJ/J$$

5. Fishery yield.

At Crystal River, Florida, Kemp, Homer and McKellar (1975) evaluated energy transfers in food chains and found about 5.1 grams organic net production of larger edible shrimp, crabs, and fishes per square meter per year. At 5 kilocalories per gram dry weight and 4185 J/kcal, the steady fishery yield is:

$(5.1\ g/m^2/y)(5\ kcal/g)(4185\ J/kcal) = 1.07\ E5\ fish\ J/y.$

The energy inputs to this estuarine area include the direct sunlight, the rain and runoff, and the tidal energy absorbed. These are:

Direct solar energy: $(4200\ kcal/m^2/d)(4186\ J/kcal)(365\ d/y)$
$= 6.4\ E9$ solar J/y;

Tidal energy (0.91 m tidal range): $(0.91\ m)(0.5)(706)$
$(0.91\ m)(1.0253\ E3\ kg/m^3)(9.8\ m/sec^2) = 2.94\ E6$ tidal $J/m^2/y$.

Freshwater inflow ($3\ m^3/m^2/y$): $(3\ m/y)(4.94\ J/g\ water)$
$(1\ E6\ g\ water/m^3) = 1.48\ E7\ J/m^2/y$.

When these inputs are expressed in solar equivalents by multiplying by energy transformation ratios they become:

Direct sun $(6.4\ E9\ SEJ/m^2/y)(1\ SEJ/J) = 0.64\ E10\ SEJ/m^2/y$
Tide $(2.94\ E6\ J/m^2/y)(2.4\ E4\ SEJ/J) = 7.1\ E10\ SEJ/m^2/y$
Freshwater $(1.48\ E7\ J/m^2/y)(1.5\ E4\ SEJ/J) = 22\ E10\ SEJ/m^2/y$

The input energy supporting the fishes is taken as the sum of tidal and freshwater energies omitting direct solar energy as already included in rain (which includes global solar energy). The energy transformation ratio for the fishes is the ratio of supporting energy in solar equivalents divided by fishery yield energy:

$$\frac{(7.1 + 22)\ E10\ SEJ/m^2/y}{(1.07\ E5\ fish\ J/m^2/y)} = 2.7\ E6\ SEJ/fish\ J$$

6. Liquid fuel.

An energy transformation ratio was obtained between solar energy (direct and indirect) and electricity using analysis of the wood power plant at Jari, Brazil. Then equivalent between oil and electricity were used to obtain solar equivalent of oil. See Appendix A5 (Odum and Odum, 1983).

7. Energy dollar ratio for The Netherlands in 1980

$$\frac{3.7\ \mathrm{E23\ SEJ/y}}{166\ \mathrm{E9\ \$/y}} = 2.23\ \mathrm{E12\ SEJ/U.S.\ \$}$$

from Braat (1983).

Embodied solar equivalents. In the evaluation table (Table 1 for example) the embodied solar energy equivalents of each energy flow are obtained by multiplying the actual energy flows of that type in column 1 by the energy transformation ratios in column 2.
The resulting column 3 of the table has all the flows in embodied energy units of the same quality. These may be compared to see which are larger and thus more important.

Goods and services. Energy is embodied in goods, services, and labor of humans for which money is paid. To evaluate embodied energy the money paid for that service is multiplied by the ratio of embodied solar energy per dollar spent for that nation for that year. To the extent that the prices paid for goods and services represent the share those services are of the total national service, the dollars paid may be used to evaluate the fraction of the total national energy embodied.
To prevent double counting of services, the contribution of the system studied is subtracted from the national energy flow for this purpose. Also, to avoid double counting of services, the services involved in energy transformation ratios used to calculate embodied energy in raw materials, products, fuels, etc. must be subtracted from the estimates of services calculated from total money spent. These corrections to calculations of goods and service to avoid double counting rarely exceed 1%, whereas omitting goods and services may involve errors of 5% to 50%.

Dollar equivalents. Finally, dollar equivalents of the embodied energy are estimated (see column 4 in Table 1 for example). In every country there is a total embodied energy used that represents the reality and buying power of the gross national product (GNP). A ratio of solar embodied energy used per year to GNP (energy/dollar ratio) is calculated for that country in that year.
The energy dollar ratio for a country is obtained by summing all the main energy inputs used by a country including environmental energies, fuels, goods and services with care to avoid double counting. Dollar equivalents are calculated by dividing items in column 3 by the energy/dollar ratio. See the example in column of Table 1. Since dollar magnitudes are often familiar, the last column may provide perspective on importance of each line in the table.

EXAMPLES

Some typical estuarine calculations in Table 1 are examples of the procedure for fictitious rectangular estuary in which storm surg protection is being constructed.

Tidal value. Dollar equivalents are given for embodied energy of tidal energy use in the estuary. The dollar contribution of the tidal work (column 4) is greate than the extra money spent in construction so as to retain tidal access. Whethe this fictitious example actually resembles the situation in Zeeland estuaries remains to be seen after accurate actual data are substituted for the illustrativ numbers used in the example.

Freshwater contribution. Table 1 includes energy of freshwater inflow. The freshwater of river inflows is a large and valuable economic resource. See for example the evaluation of the Rhine by Braat (1983). When proposals are made to divert freshwaters to agricultural use where it evapotranspires as part of its work there, large embodied energies are diverted from estuarine work. Damming an estuary to form a freshwater lake removes the use of the freshwater energy that formerly occurred during interactions with sea water in that basin. Not enough is known about the possible utility of the freshwater work before it was diverted.

Fishery contributions. As in the example in Table 1, the solar embodied energy involved in fishes high in the food chain may be large. Much work of nature is done in converging sunlight, necessary nutrients, etc. into a quality product. When the dollar evaluation is made the contribution to the economy is much higher than the dollars paid to the fishermen. Too often the value of fisheries to an economy has been judged by the money paid for the fishes at the dock. Whereas it has long been known that the contribution to the dollar circulation in the economy is much larger, an easy way of estimating the full economic contribution of products of natural systems was not available.

Contribution of waves. The role of breaking waves in maintaining and cleansing a beach is recognized as one of the reasons for the concentrated economic patterns that develop along beaches. Supplying these services with human work and machines would be prohibitive in cost. An example of calculations evaluating this contribution is included in Table 1.

Input to the estuary of goods and services. An example of the estimation of embodied energy equivalents of goods and services is included in Table 1. The money spent on construction is multiplied by the energy dollar ratio to obtain the embodied energy in these goods and services. In most of the items in Table 1 energy is calculated first and money equivalents derived from the embodied energy. For goods and services the procedure is reversed. Data on money spent are given, and the embodied energy is inferred from the money. The embodied energy in goods and services is an money-allocated proportion of the energy supporting the Dutch economy most of which is derived from fuels. However, the contribution of the estuarine system to the economy should be subtracted from the national energy dollar ratio calculation that is used to avoid double counting as already mentioned.

Fuels. The fuels embodied in goods and services are those transformed in the economy away from the estuary. Fuels which are utilized within the estuarine system by the boats and construction machinery need to be evaluated separately. This is done in Table 1.

Sunlight and indirect sunlight (wind, rain). The sunlight energy absorbed in the estuarine system is readily calculated from insolation data and area. However, the local sunlight absorbed contributes to the global weather and oceanic system and, vice versa, the global weather and oceanic system contributes inputs of wind and rain to the estuarine area. Usually there is more embodied solar energy incoming to an estuary through wind and rain than there is in direct insolation. The land and its associated estuaries represent a convergence of global earth processes.

Double counting of direct sunlight and the indirect sunlight is avoided by subtracting the direct sunlight from the indirect inputs before adding the two. This is tantamount to using the larger one only.

Others. There are many other inputs to an estuary which may be evaluated such as the energy embodied in species, in particular chemical inflows, in sediment inflows, in other geological sources, etc. Energy tranformation ratios for these have not been studied much yet. These are not included in the examples. Preliminary efforts to evaluate these were given elsewhere (Odum and colleagues, 1983).

Totals. With care to avoid double counting of two inputs with common energy sources, the inputs to an estuary may be summed to determine the total embodied energy and total dollar equivalents. As suggested by the example, estuaries and coastal zones receive more converging energy inputs than most other kinds of areas. They have more embodied energy and more unrecognized role in the economy. Coastal projects that divert well established energy inputs may easily divert part of the basis for economic vitality.

DISCUSSION

For a controversial method still being improved, discussion of its evolution, its criticisms, and its relation to other methods may be appropriate.

Evolution of the Method

The embodied energy method of energy analysis described here evolved through several phases. These are reviewed briefly.

Early students of energy such als Boltzmann (1905), Ostwald (1909), and Lotka (1922), developing concepts at the turn of the century, wrote extensively on the use of energy measures as a general concept of value. In the 1930's scientific efforts to develop an energy theory of value were embraced by non-technical enthousiasts with a public action program that went to extremes, even proposing to do away with money. This movement was called technocracy (Scott, 1933). There was no concept of energy quality differences, all calories being regarded equal. Some opposition to later more sophisticated energy theories of value comes from memories of these inadequate beginnings.

We became impressed with energy as a general measure of utility in the study of energy systems of streams, springs, ponds, forests, etc. in the 1950's. While dealing with public controversies over dredge and fill project in Texas in 1959, ways were sought to adequately represent the value of the rich turtle grass beds so they would no be eliminated by development projects which claimed to be more valuable to the economy than the ecosystems being displaced (Odum, Muehlberg and Kemp, 1959).

Our measurments of the gross photosynthetic productivity of the grass flats and other estuarine ecosystems provided direct measure of the work of nature that was contributing to fisheries, cleansing waters, and other life support functions supporting the economy without much conscious recognition. A dollar equivalent was developed for organic produce based on crops. Then a whole estuary, Corpus Christi Bay, Texas was analyzed as a system. With funds obtained from the Corpus Christi Chamber of Commerce a graduate student from the Bureau of Business Research in Austin was added to the project to evaluate the direct economic uses of the bay. The resulting publication (Anderson, 1960) included nature's work calculated with a dollar equivalent for organic production. We now see this result as an underestimate of nature's contribution because the dollar equivalents calculated from crop prices was much less than the embodied environmental contribution of crops to the economy. Nevertheless the Corpus Christi value study showed the work of the bays to be much more valuable than had been recognized at the time. Also from this work came the recorgnition that money paid for environmental services is a countercurrent loop back to the economy that does not pay nature (Odum, 1967a).

An energy system language was developed in the 1960's, first for ecosystems (Odum 1967a). The diagrams were used to represent the quantitative flows of energy These methods were then applied to agroecosystems, putting flows from nature an those from the economy on the same calorie basis (Odum, 1967b).

The method was expanded to the whole of society and the questions of limited resources with a book (Odum, 1971). A limited concept of energy quality was used i which all forms of energy were converted to organic equivalents. Sunlight wa represented in photosynthetic equivalents, but all organic substances includin coal and oil were evaluated as equivalent calories. Goods and services were evaluated with an energy dollar ratio determined from the ratio fo U.S. fuels to U.S Gross National Product.

Eugene Odum with economist coauthors (Gosselink and colleagues, 1974) summarize several ways of evaluating environmental work of marshes for the economy includin the energy analysis method given in the H.T. Odum's 1981 book.

This paper was strongly assailed by Shabman and Batie (1978) with a rebuttal (Odu and Odum, 1979). The heart of the controversy was the deep difference in concep of value and whether energy is its basis. See section on value that follows.

The energy quality concept was formalized with the energy transformation ratio a its measure (Odum, 1975). Energy transformation ratio from direct sunlight to coa at that time was estimated from calculations of the potential of wood power plant as about 2000 direct solar calories per coal calorie.

By the time an energy analysis summary was prepared for a report of the U.S. Congress (Odum and collegues, 1976), the dollar energy ratio was calculated includin coal equivalents of U.S. sunlight as well as U.S. fuels (Kylstra, 1974). Althoug we had little confidence in the accuracy of this important factor, we standardized its use temporarily so that concepts could be explained consistently in a elementary textbook (Odum and Odum, 1976, 1981).

A summary of coastal examples of energy analysis included comparison of variou alternatives for cooling power plants, energy transformations in fish food chains, net energy of tidal power, etc. (Odum and colleagues, 1977). A south Florida project for the Department of the Interior developed energy systems diagrams for th ecosystems, for the region, and energy analysis of regional systems, park, an wetlands (Odum and collegues, 1976). Costanza (1975) found economic developmen spatially correlated with embodied energy of the environment including soil storage. Regan (1977) in 67 Florida counties found high correlations between embodie energy of the environments with their economic growth. These correlations wer direct evidence of the energy basis for economics.

It was recognized that the environmental energies supporting land economies o humanity and nature included more indirect sunlight coming ashore from the ocean as waves, rain, and winds than comes to the land as direct sunlight. New energ transformation ratios were developed with higher contents of indirect embodie solar energy in many other kinds of energy (Odum, 1978).

A sabbatical period in New Zealand was used to do a national overview energy analysis of New Zealand (Odum and Odum, 1980) in which these calculations wer refined.

As part of contracts with the Department of Energy and later with the Nuclear Regulatory Commission a manual of environmental evaluation was developed with cookbook formulae and reference data for the United States (Odum and colleagues, 1980, 1983; Odum and Odum, 1983). The ratio of solar energy to fuels was calculated wit the larger indirect solar energy based on the ratio of the oceanic area to th land area of the globe (6800 indirect solar equivalent joules per joule coal). This report included comments of critics and rebuttals. A graduate text on energ systems included a chapter on the energy analysis theory back of these methods an a chapter on energy systems basis for economics (Odum, 1983).

At the International Institute for Applied Systems Analysis a working paper was generated with overview energy analyses of 11 countries (Odum and Odum, 1983). As part of this a new and higher figure for solar equivalents of fuel was used incorporating the earth energy driving geological processes and a more realistic conversion of solar energy to fuels and electricity based on a real wood power plant at Jari, Brazil. Energy dollar ratios were obtained based on all embodied energies. The procedures used in the IIASA working paper were used in this paper.

Because of the evolution and tightening of both concepts and data, successive papers and books had different transformation ratios. Little wonder that the General Acounting Office (GAO, 1982) in trying to review methods of energy analysis described these methods as inconsistent and turned to other methods. National and international conferences held to resolve the deep differences among different approaches to energy analysis included a National Science Foundation workshop at Stanford in 1976, a Wallenberg conference in Sweden in 1982, and a Gordon Research Conference on Thermodynamic Analysis in 1982, but many aspects were unresolved and many opposing attitudes remained unchanged.

Recent Innovations

The following are some of the recent changes in the energy analysis procedure:

1. Where energy transformation ratios were calculated from the world web operating the biosphere, contributions of the heat sources deep in the earth to the earth cycle were included. The energy driving the web was taken as the sum of the solar energy and deep heat both expressed in solar energy equivalents.
2. The last calculation of the global solar equivalents to coal was based on conversions of rainforest wood to electricity in a wood power plant in operation at Jari, Brazil. This energy transformation ratio, 40,000 SEJ/J, was close to one obtained by assigning part of the global energy sources to coal formation in proportion to coal's fraction of the world land mass.
3. Environmental energy inputs which are mutual byproducts of the global web of the biosphere have a common energy source. To avoid double counting of two byproduct flows, only the larger of the two is counted.
   The embodied energy in its flow includes the same energy embodied in the other. Energy diagrams are drawn to recognize flows of different types which have common sources.
4. Although the double counting error involved in estimating embodied energy in services is usually small, specific procedures that subtract any double counting are now done to improve accuracy.
5. Energy analysis of whole countries have been done so that energy dollar ratios are becoming available to evaluate the energy embodied in goods and services more accurately. A world energy dollar ratio is used for diverse purchases from international markets. It was calculated as the sum of the total renewable energy use and non-renewable energy use of the earth, both expressed in solar equivalents.
6. Distinctions are made between the embodied energy required for net geological uplift and the lesser embodied energy required to drive land uplift and denudation that is in steady state.
7. Embodied energy in top soil formation and erosion is calculated separately from earth formed in the slower process of rock weathering to form clay and its denudation.

Comparisons with Input-Output Approach

Widely used are input-output methods of estimating "embodied energy" (Hannon, 1973; Herendeen, 1981). A matrix algebra procedure is used to assign energy to input-output pathways of a web. Often, only fuel energy inputs were considered. Energy values are actual energies, and differences in energy quality are ignored. When byproduct pathways diverge as in the example of sheep meat and wool coming from the same animal, the input-output procedure divides the embodied energy in the sheep into two parts, even though all of the embodied energy is required to make each product.

In many of the procedures, for reasons of convenience in matrix algebra and because of fear of double counting, the human services from the final demand sector are omitted. Thus service-rich sectors such as medicine, high technology, and communications are evaluated with much of the embodied energy omitted. This produces large distortions in evaluations of what processes require the most energy.

The following list summarizes difficulties in some input-output evaluations:

1. Energy quality differences are not considered.
2. Environmental energy inputs are omitted.
3. Energy is divided up among byproduct flows, though the total individual embodied energy is required for each.
4. Energy is assigned only to dollar flow pathways even though there are energy pathways outside of the money circulation.
5. Energy is assigned to pathways by a matrix inversion procedure on the assumption that energy flows in proportion to the money flow. This procedure is tantamount to assuming a priori that energy flow is proportional to money flow.
6. When energy flow is partitioned among pathways, changing the aggregation of the input-output matrix changes the energy allocations among commodities.
7. Omitting human service pathways omits major embodied energy inputs.
8. Data 10 or 15 years out of date are used on the assumption that the ratio of flows (input-output coefficients) are unchanging over long periods.

These faults in the input-output method seem sufficient to eliminate the approach. Yet defenders of the approach feel the same way about the methods described here.

Comparisons with a Hybrid Approach

Costanza (1980, 1981) trained in both approaches has tried to blend the methods. He used some environmental energies, used energy transformation ratios to evaluate energy quality differences, and used a more complete method so as to include human service. However, the matrix inversion method still partitions energy flow arbitrarily, partitions energy among byproducts, assigns energy differently when a web is aggregated, and gives a degraded outflow energy the same embodied energy as the inflowing energy sources.

Comparison with Process Analysis

Energy analysis of the flows of fuels, electricity, chemicals, etc. in industry is sometimes called process analysis. Suitable network diagrams are drawn of all the flows and interactions. Then actual energies are calculated. Only those flows that are calculable as mechanical work are included. These include chemical potential energy as Gibbs free energy and mechanical work of heat engines. These are all of one quality of energy and thus are comparable as measures of work. Currently used is the word "exergy" meaning available mechanical work.

These procedures are satisfactory as far as they go but they do not include other kinds of energy of other quality that may be involved, some of which have very high embodied energy. For example, services are not included. To broaden the industrial process analysis to be complete, requires use of energy transformation ratios not only for electricity but for all inputs. All system pathways must be evaluated.

Some discussants have distinguished between our energy analysis and process analysis. However, the methods are similar in the first part of the procedure, defining systems with network diagrams, evaluating all pathways in units of actual energy. Our procedure goes beyond these by including environmental energies, energy quality distinctions, and services.

Comparisons with Agricultural Energy Analysis

Some of the most detailed energy analysis has been of agroecosystems (Slesser, 1978; Fluck and Baird, 1980). Most of these evaluate actual energy in sun, fuels, and products. Generally, because of lack of concensus on how to do it, services have not been included. High embodied energies from environmental work in rain, soil, fertilizer, seeds, pesticides, etc. have not been included. Whereas, the published data on actual energy flows are very valuable they are grossly in error in giving perspectives on energy required in modern agriculture. For example, coal equivalent energy in corn production estimated by Pimentel and Pimentel (1979) is underestimated by 8 times (Odum and Odum, 1983). Agricultural energy analysis has usually stopped before including the most important inputs, those with little actual energy but very high embodied energy.

Contrasting Value Concepts

Underlying the strongly worded controversies over the embodied energy concepts are fundamental differences in concepts of value and the limitations of science. At one end of the spectrum of opinion is the premise that all useful entities require real work to maintain their structure and processes against the inexorable depreciation required by the second law of thermodynamics. Therefore anything of value is measurable by the work required. Whereas individual humans may chose to value various items and to value items in short supply more, the human society in its group decisions selects what has been part of successful patterns of institutional survival. Since what succeeded was the pattern that generated the most useful work, work may be used to predict long range values. In this view the human is controlled by the resources and network of the biosphere. In the long run surviving human cultures are forced by energy laws to build a symbiotic systems pattern, helping to manage the biosphere toward maximum power use by the combined system of humanity and nature.

At the opposite end of the spectrum of opinion are those who regard value as without scientific basis, wholly subject to human choice without limit. Human ability and derived technology is regarded as an unlimited quantity that may be assigned as desired to eliminate any resource shortages. No commodity is regarded as a common denominator or essential. Energy is regarded as a substitutable commodity not necessary to value. In this view the human is at the center of the biosphere free to manipulate it without limit.

Many, if not the majority of scientific specialists, have not been concerned with building a science of the larger scale that includes environment, humans, and economics. Many engineers and scientists with pride in the pricision of their realm of concern have been happy to leave the messy looking larger complexity to those with a premise that science is not applicable there. Many scientists would agree. When the first efforts to develop energetics of human affairs were crude, this was taken as evidence for indeterminancy. The situation was similar to that regarding life in the last century. Crude first efforts in biology and chemistry were slow to eliminate vitalism and other beliefs that science did not apply.

The concepts of value carry over into the embodied energy controversy with a different expectation of what is being attempted. Those defending the input-outputapproach seem to have a different concept of embodied energy. Rather than evaluating energy as the basis for economic value, their concept is more one determining the fuels that go with dollars in different processes as a measure of the efficiency of fuel use per dollar.

Future Improvements

What will be required to further tighten the procedures for tracing causal energy transformation through systems webs? Some progress will come from better understanding of the partition of energy flows in networks particularly in geological phases, mineral formation, etc. See papers by Burnett (1981), Gilliland (1982), and Lavine and Butler (1982). Improved energy transformation ratios will evolve. Computer spread-sheet representation of networks may allow easy recalculations of whole systems when one number is changed. Embodied energy calculations of whole can be generated as part of dynamic simulations, thus increasing understanding of embodied energy concept. A mathematics of energy cuasality may be developed. See, for example, initiatives by Patten and colleagues (Patten and Finn, 1979) in tracing causality through webs.

More empirical studies are needed testing the hypothesis that useful amplifier effects of feedbacks from a flow are correlated with the embodied energy of that flow. Such correlations may help demonstrate the close relationships between energy embodied and useful action to maximize power.

That energy flow is the basis for value is a version of the maximum power principle which predicts that surviving designs are those that maximize useful power. Empirical studies that compare the total power of a newly succeeding system over its displaced alternative may help test the generality of the maximum power principle.

In the meantime, for those trained in science and engineering who believe that work is required for value, the energy evaluation method may now be accurate enough for practical use in evaluating environmental contributions to the coastal zone. It may be some time before the majority of those concerned with public policy accept the premise that scientific energy evaluation applies.

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