A MANUAL FOR USING ENERGY ANALYSIS FOR PLANT SITING

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by

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With an Appendix on

ENERGY ANALYSIS OF ENVIRONMENTAL VALUES

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ABSTRACT

This is an instructional manual for choosing among possible sites for power plants by selecting the one with the least diversion of resources of the environment and of the economy. For each alternative site, changes of embodied energy in flows and storages are estimated in solar equivalent Calories. Then a dollar equivalent is estimated from the ratio of total solar equivalent flows to gross national product. Sample calculations are provided for LaSalle power plant west of Chicago considering alternatives of cooling reservoirs, cooling from a natural water body, and cooling towers.

In order to facilitate calculation, an appendix provides procedures and data for evaluating embodied energy of the environment.

1

INTRODUCTION

Need for an Energy Evaluation

Everyone can probably agree that the location of a power plant or other major technological installation is a decision that should minimize the disturbance of existing values, maximize the contribution of new values, and minimize the costs and resources used. If we recognize that some values are generated by the work of environmental systems and that others are generated by the work of humans and their technological enterprises, the problem of selecting sites and designs to maximize values requires the evaluation of all the useful work affecting the economies of man and nature, directly and indirectly.[1] Since, ultimately, energy flows are responsible for all kinds of work, energy evaluation may be used to consider which alternative sites and designs generate the most useful work for the energies used and, thus, make the greatest contribution to the overall vitality of the combined economy of man and nature. This manual is a guide to embodied energy evaluation of power plant siting. It gives step-by-step procedures for determining which alternative sites and designs provide maximum work for the economy.

Assumptions and Premises

Whereas the manual provides steps toward objective evaluation of the changes in energy flows of nature and human development associated with power plants and their sites, the use of the resulting energy calculations for making decisions involves a basic premise as follows: Systems with the most energy resources can use them to meet all other contingencies so as to survive competition and maximize vitality of the combined economies of man and nature. The primacy of energy in generating work and useful value has long been accepted in specific areas of science and engineering.[2] Appendix A

1. It is commonly recognized that value is generated by the work of natural environmental systems. Although such value is recognized, it is often considered an externality, not amenable to quantified evaluation in most forms of quantitative analysis. Energy analysis attempts to internalize the environmental values in a more nearly unified quantitative analysis of the combined system of man and nature. Therefore, this form of analysis may do more than economic analysis to facilitate the fulfillment of the National Environmental Policy Act requirement to "insure that presently unquantified environmental amenities and values may be given appropriate consideration in decision making along with economic and technical considerations." For more detailed discussion, see Appendix D, part 1.

2. The basic premise of energy analysis, that "systems with the most energy resources can use them to meet all other contingencies so as to survive competition and maximize vitality of the combined economies of man and nature," is similar to the basic premise of economic analysis, which may be stated in a similar form: systems with the most labor and/or capital resources available can use them to meet all other contingencies so as to survive competition and maximize vitality. Only two differences stand out: (1) the indicator that is quantified (energy resources instead of labor and capital) and (2) the boundaries of the system of concern (the combined economies of man and nature instead of the separate economy of man). For more detailed discussion, see Appendix D, part 2.

introduces energy analysis and its relation to the economy. Included as Appendix B is a comparison with economic cost-benefit analysis.

Evaluation of Overall Economy in Units of Embodied Energy

Inherent in the nature of energy are different concentrations and energy types that are often placed in a scale of quality according to the quantity of energy required of one to generate another. The amount of energy of one type required to develop a storage or flow of a second energy type is the amount of embodied energy of the first kind in the second. For example, solar energy is very low quality, because many Calories are required to generate a few Calories of wood, even fewer of coal, even fewer of electricity, etc. For another example, including the embodied energy in equipment, almost 4 Calories of coal are required to generate a Calorie of electricity.[3] Appendix C is a more elaborate explanation of embodied energy and energy quality.

In order to place energy flows and storages on a basis whereby the resources required to develop the flows and storages can be compared, all energy flows are converted into energy equivalents of the same type using tables of energy transformation ratios. An energy transformation ratio is the energy of one type required to generate energy of another under competitive conditions with the process of transformation loaded for maximum power.[4]

Embodied energy in solar equivalents, coal equivalents, or electrical equivalents can be added and subtracted to determine the overall balance of gains or losses when a plant is built or a system is changed.[5] Table 1 contains energy transformation ratios, which were calculated in Appendix E.

3. The concept of energy quality enables the analyst to account for the previous indirect as well as direct requirements of energy flow. Such total energy flow requirements are analogous to cost in economic analysis. Because the calculation of those energy requirements is based on a set of processes operating at optimum energy efficiency, the energy quality calculations are assumed to identify the total energy cost that is in balance with maximum utility. For more detailed discussion, see Appendix D, part 3.

4. Some of the base data needed to compile the tables of energy transformation ratios have been only broadly approximated thus far. In addition, in some cases there is an element of uncertainty as to whether or not the energy transformation process being observed meets the requirement of operating under competitive conditions in which there is the best possible efficiency consistent with maximum power loading. Consequently, some of the energy transformation ratios identified in the tables may not yet be highly accurate. Although intermediate findings of the energy analysis procedure (i.e., embodied energy values of individual flows) will vary in direct proportion to the energy transformation ratios used, the final results often are not sensitive to changes of the ratios. That is true because, in many cases, the embodied energy flows being evaluated are in several different calculations based on different energy transformation ratios. Therefore, often one calculation will serve as a check on another. Also, it often occurs that the total difference between the embodied energy gains and losses being compared is much greater than could be attributed to any base data inaccuracies. For more detailed discussion, see Appendix D, part 3.

5. Although it is appropriate to compare embodied energy values when they are all expressed in common equivalents, it is often inaccurate to algebraically sum all such values indiscriminately because those values may double count the same embodied energy. Care has been taken in the development of this manual to avoid such counting. Some uncertainty remains concerning possible double counting of storages and related flows. In addition, any user who may expand the parameters considered in the manual should be aware of the double counting issue. For more detailed discussion, see Appendix D, part 6.

Table 1a. Energy Transformation Ratios in Solar Calories per Calorie of Environmental Flow and Storage (Details on this table are given in Appendix E).

Name of Item	Energy Transformation Ratio (ETR), Solar Cal/Cal
Sun	1.0
Wind	56.7
Heat	
Vertical exchange	12.9
Horizontal advection	5.3
Vapor	
Vertical exchange	55.9
Horizontal advection	55.9
Rain	
Kinetic potential	2.38×10^5
Gravitational potential over land (875 m)	4.00×10^3
Chemical potential of rain over land	6.90×10^3
Chemical potential of nitrogen over land	2.91×10^9
Chemical potential of phosphorus over land	2.61×10^{10}
Chemical potential of acid rain over land	1.09×10^9
Tide	
Physical potential of tide	11.56×10^3
Chemical free energy of tidal inflow	6.9×10^3
Chemical free energy of tidal outflow	6.9×10^3
Wave	1.16×10^4
Sand	
Chemical potential in sand flux	4.6×10^5
Elevated potential in sedimentation	1.77×10^{14}
Stream	
Physical energy in stream flow	1.06×10^4

Table 1a. (continued).

Name of Item	Energy Transformation Ratio (ETR), Solar Cal/Cal
Chemical potential of water in stream	3.57×10^4
Chemical potential energy in sediments in streams	0.88×10^6
Physical potential energy in materials in stream flow	2.33×10^7
Catastrophic	
Earthquake	3.98×10^6
Hurricanes	1.11×10^3
Tornado	2.61×10^{10}
Floods	4.00×10^5
Species	
Algae	7×10^{29}
Microinvertebrates	7×10^{26}
Vascular plants seeds	9×10^{27}
Insects	7×10^{24}
Vertebrates	4.6×10^{21}
Human exchange	4.5×10^3–5.1×10^5
Money flow	---
Land uplift	
Potential energy	1.5×10^{12}
Chemical potential energy	
Granite	10.19×10^7
Basalt	2.08×10^7
Shale	5.22×10^7
Limestone	0.77×10^6
Sandstone	2.83×10^7
Wood biomass	2.89×10^3
Soil	11.9×10^4
Species	4.6×10^{21}–7.0×10^{29}
Human assets	30.3×10^3–171×10^3
Uplifted land	1.50×10^{12}
Chemical potential in rock	0.77×10^6–10.19×10^7
Physical potential in land form	1.50×10^{12}

Table 1b. Other Energy Transformation Ratios.*

Name of Item	Global Solar Cal/Cal
Fissionable uranium fuel	306
Typical aquatic gross primary production	200
Typical terrestrial gross primary production	340
Coal	6,800
Gasoline	11,492
Electric power	27,200
Average human service in U.S.	887,000
Fertilizer (with phosphate)	1,990,000

*For calculations see Table E1b.

Ultimately, the size and vitality of the combined economy of nature and man depends on the amounts of energy flowing, and this may be evaluated by summing the energies as expressed in embodied energy of one type.[5] More on the concept of embodied energy is given in Appendices A and C.

Evaluating Maximum Power in a Power Plant Situation

If a decision has already been made to build a plant, this implies that the addition of the plant will help maximize power of the combined economies of man and nature in the area served by the power.[6] Whereas energy analysis of this larger area could help such decisions, this manual begins with the assumption that there is a need for the power. It assumes an electrical power output and associated good utilization of the power.

For purposes of siting the plant, the region's power is maximized by retaining as much as possible of the energy flows of the existing landscape and human activities in addition to the new energy flows. This manual, therefore, provides the procedure for estimating for each alternative site the energy embodied in production and the interruptions of production in environmental processes and economic processes using fuels, goods, and services.[7]

6. It is assumed when considering all system components, any system with more power than can be developed by alternatives is the system that can meet all other contingencies so as to survive competition and maximize vitality. As explained in Text Note 2 above, although the energy analysis indicator of success is physical rather than monetary, the goal is essentially the same as in economic analysis. For more detailed discussion, see Appendix D, part 2.
7. The manual's energy analysis procedure may not yet account for all possible factors of concern in making power plant-siting decisions. Rather, the analysis is an attempt to combine evaluations of some of the relevant factors in meaningful and comparable terms. The major thrust of the manual is to account for environmental amenities and values in such a way that they may more easily be given consideration in decision making directly along with many other economic and technical considerations. However, advocates of the method believe other factors of concern that may be identified can be analyzed similarily and given embodied energy values.

2

PROCEDURE FOR EVALUATING CHANGES IN EMBODIED ENERGY

The evaluations of plant siting may be visualized in Fig. 1, which shows local systems of environmental resources, existing land and water uses, and the existing local human economy. Also shown is the new installation to be sited and its newly generated connections to the environmental systems and to the surrounding human economy. This economy runs ultimately on distant resources of fuels and environment, where products and services are drawn to the area through investment. All the pathways in the diagram are accompanied by flows of energy and embodied energy and these may be calculated.[8] They include storages of accumulated assets in soils, forests, human settlements, and technology, which may also be evaluated for the embodied energy stored. The flows that are positive contributions to value are those that contribute to the maximum overall flow of power in the web.[9]

Adding a plant increases the overall power flow of the system, providing the new power flows do not displace more useful power flows in preexisting systems, either at the site or by diverting more energy flows elsewhere in the economy. In this manual the increase ΔA in Fig. 1 is assumed. A plant is sited better when it displaces the local system least (minimizes decrease of ΔB, ΔS, ΔF_1, and ΔC_1) and uses less resources elsewhere, leaving them to generate other values. In other words, ΔA_2, ΔC_2, and ΔF_2 are minimum in the best alternative, and these are zero in Table of changes.[10]

Therefore, the procedure for making decisions involves calculating the change in energy flows between the preplant condition and the alternatives, including the energy flows diverted elsewhere in the economy at a distance. The best alternative for the economy is the plant that adds the new work and displaces the least.[11] A final summation of the effects of alternatives is a summation of the positive and negative changes in the embodied energy flows of the combined system of the economy of nature and man

8. As noted in Text Note 4, there are elements of uncertainty in the calculations of embodied energies in some of the flows identified in the diagram. For the most part, the uncertainty is due to questions of confidence in the base data used in calculating energy transformation ratios. In addition, there has been some controversy over definition of boundaries in accounting for the embodied energies. For more detailed discussion, see Appendix D, parts 3 and 4.

9. As explained in Text Notes 2, 3, and 6, maximizing the flow of power is assumed to account for the same factors of value as are intended in economic theory. A different metric is used in the analysis because the economic one is regarded as less practical as a measure of external resources values. For more detailed discussion, see Appendix D, parts 2, 3, and 5.
10. See Text Note 7.
11. Ibid.

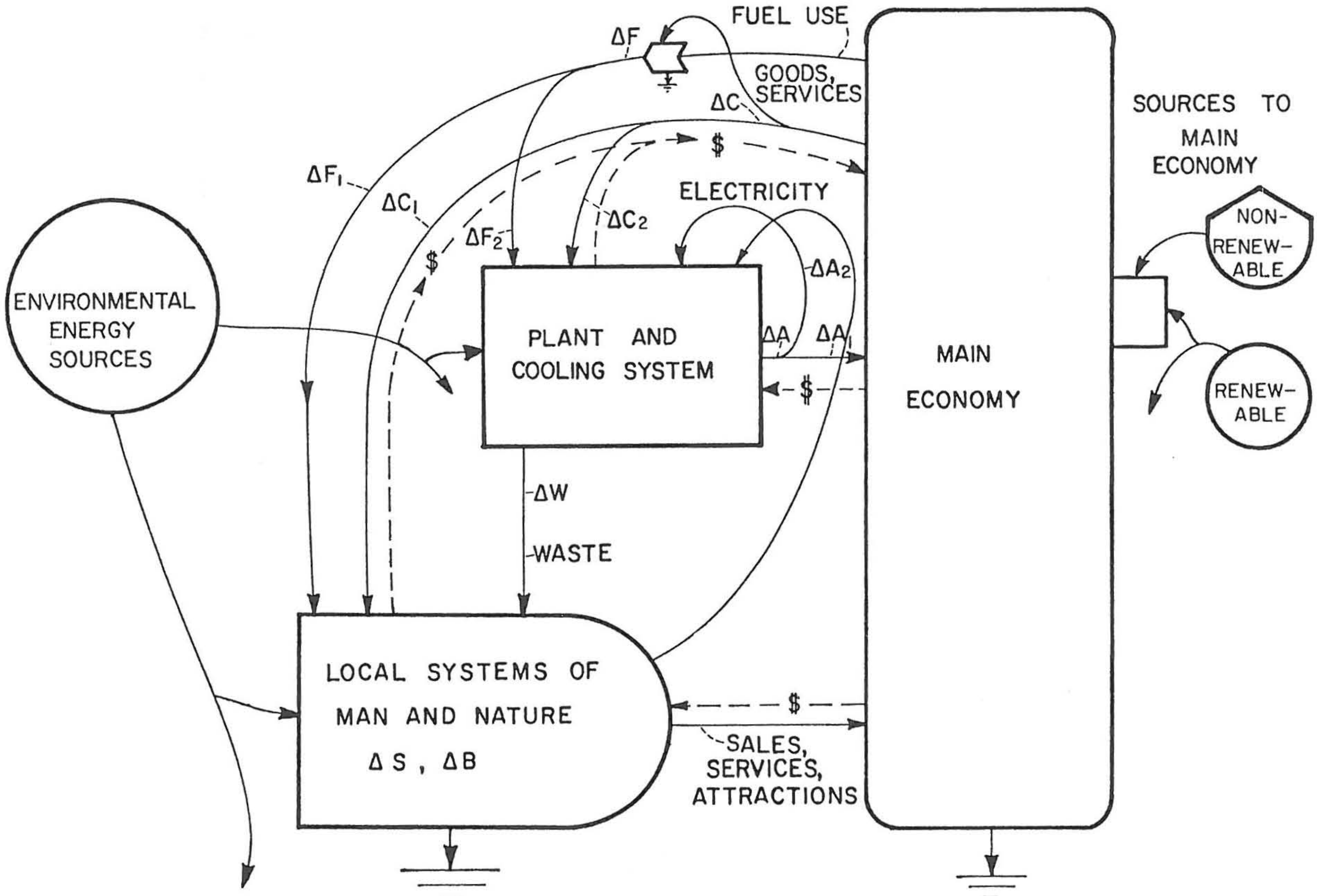

Figure 1. Categories of change in energy flow before and after the construction of a power plant (see Table 2).

that are affected by the new plant.[12] Table 2 has the main categories of evaluation.

Table 2. Categories for Calculating the Changes in Energy Flows Due to the Construction of a Power Plant.

Flows or Storages (letters in Fig. 1)	Items of Change	Change in Embodied Energy Cal/yr
A	Power Plant Productive Contribution	±
B	Changes in Environmental Production	-
S	Changes in Environmental Resources (storages)	-
C	Changes in Goods and Services from Main Economy	-
F	Changes in Fuel and Raw Materials from Main Economy	-
W	Changes Related to Environmental Technology and Waste	-

A longer procedure is to evaluate all energy flows first and then the changes. It is more expeditious, however, to identify and evaluate only the changes. For the long procedure, see Section 5 and Appendix E.

Expressing Embodied Energies in Dollar Equivalents

There is an average total energy flow supporting the nation's whole economy of man and nature,[13] which is the sum of the environmental energies, the fuels, and the embodied energies in foreign imports minus exports. These may be totaled in units of energy of the same type such as coal or solar equivalents[14] (see Fig. 2). It is the use of all the energies that drives money in circulation.[15] An average ratio of dollars to energy can be calculated using the ratio of total energy to GNP (in embodied units of one type). This ratio is useful in giving perspective to the evaluations done in units of embodied energy. Multiplying energy of alternatives by the dollar energy ratio for the appropriate year gives an estimate of the effect on the economy of the energy difference among alternatives.[16]

Often those new to energy evaluation ask, Why not make evaluations in dollars initially? The reason direct dollar evaluation is incomplete is that the many external environmental energy inputs, such as sun, wind, rain, soil, tides,

12. In calculating the final summation of effects, it is important to review the individual values to check for any potential double counting. See Text Note 5. For more detailed discussion, also see Appendix D, part 6.

13. Evaluation of the combined system of man and nature as a single unified economy is fundamentally different from traditional economic benefit-cost evaluations, in which the systems of man and nature have always been evaluated independently. For more detailed discussion, also see Appendix D, part 7.
14. See Text Note 5.
15. The assumption that it is the use of all the energies that drives money in circulation has been an issue of some controversy. Considerable supportive theory and evidence exists, indicating that there is a consistent relationship between monetary value developed and the total, or embodied, energy flow of the man/nature system used in achieving that value. For more detailed discussion, see Appendix D, part 8.
16. Given the assumption that it is the use of all energies that drives money in circulation, it is often appropriate to use the total energy-to-GNP ratio to estimate the effect on the economy due to energy changes. However, it is inappropriate to use the ratio indiscriminately for converting values between monetary and energy terms. In particular, its use is inappropriate for converting from money flow that is not measured at final demand to embodied energy flow. It is used for services (labor) and high-quality goods such as machinery as in examples in Tables 4-6. For more detailed discussion, see Appendix D, part 8.

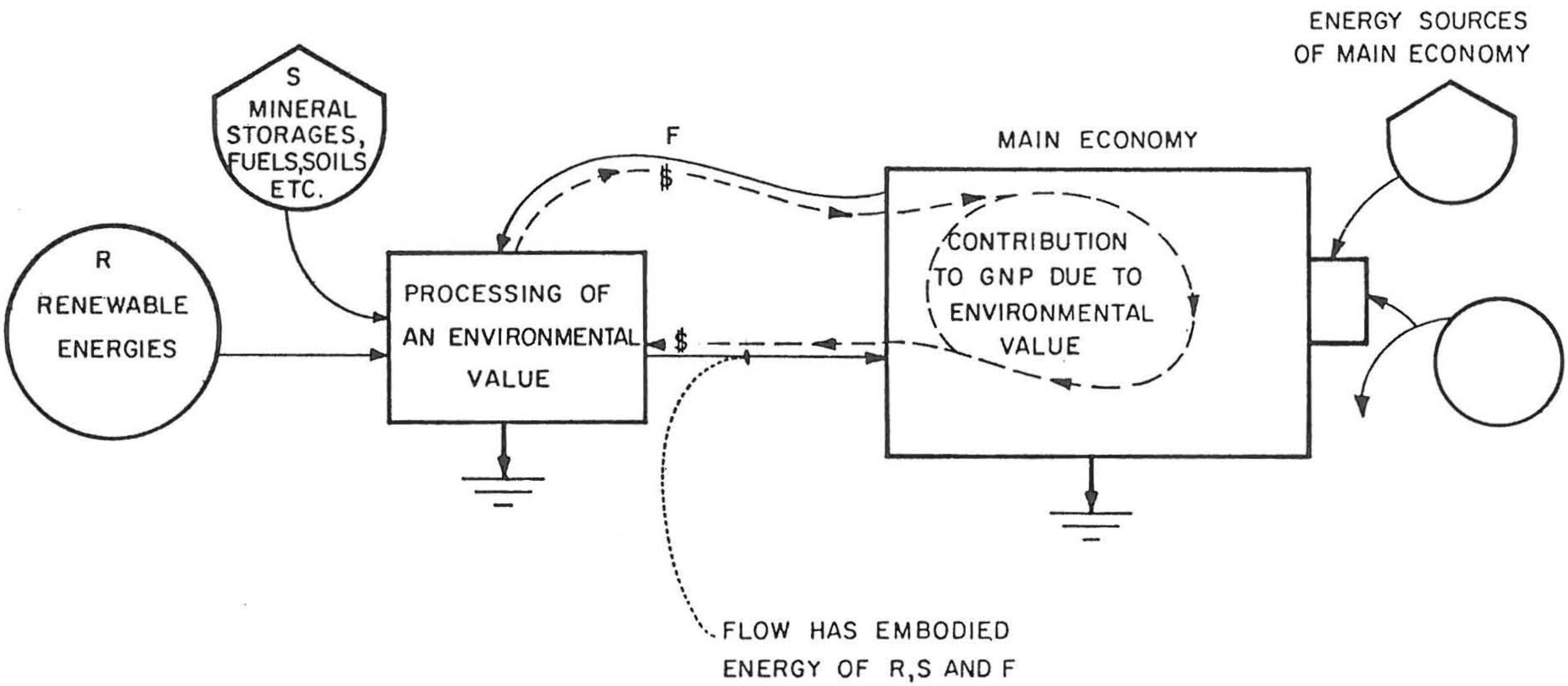

Figure 2. Embodied energy of external environmental inflows (R and S) ultimately drives a much larger dollar circulation in the main economy than is recognized at point of initial processing.

waves, geological process, chemical mineral supply, land forming, vegetation, etc., supply their products without receiving money so that their eventual contribution and effect on the economy is not recognized at the point where the products enter the economy (see Fig. 2). Here prices underestimate the ultimate effect on dollar flow.

The prices of some environmental inflows, such as hydroelectric potential, wood, coal, phosphate fertilizer, etc., reflect only the money used to process the product and are much less than the dollars that ultimatly circulate within the economy as those products are passed along with further transformations and uses.[17] Therefore, to determine the ultimate effect on dollar flow, the energies must be evaluated directly and then their proportionate part of the whole energy budget must be used to determine their proportionate effects on the economy of man.[18]

Another advantage of the energy evaluation is that it is independent of the shifting value of money due to inflation.[19] The dollar-energy ratio does change with inflation as shown in Fig. 3.

Details of Procedure

Still referring to Fig. 1, a more detailed list of categories for evaluating embodied energy is given in Table 3 with the appropriate headings for change in actual energies, energy transformation ratios (from tables), and the changes in embodied solar Calories per year in the final column. Data and methods for calculating energy transformation ratios and embodied energy are given in the manual in Appendix E. First is the added embodied energy of the electric power or other plant contribution. Second are changes in environmental production. A land use map, before and after each alternative, is constructed and helps to identify the changes in environmental and agricultural productivity and losses of soil and wood storages, etc. The first group of items, by evaluating plant production, integrates the various environmental energies interacting, such as wind, sun, rain, soil, etc. In addition, productive processes not involving the biological components are also evaluated, such as some geologic work.[20]

17. Note that most of these environmental inflows carrying embodied energy do not contribute directly to final demand. Each must first be transformed in a series of processes, each with attendant conversion dispersal of actual energy before reaching final demand. It is the money flows that accompany that conversion dispersal that are not always adequately reflected in the original price. For more detailed discussion, see Appendix D, part 8.

18. Energy analysis tools are offered to help achieve the same evaluations that market pricing might eventually achieve. A basic difference is that energy analysis bases evaluations on the physical laws of nature instead of on human perceptions, which are what determine economic markets. Consequently, energy analysis may be used to evaluate resource flows even before we have perceived markets for those flows. For more detailed discussion see Appendix D, part 9.

19. Although energy calculations are mainly independent of the shifting value of money due to inflation, questions are often raised as to whether these numbers are independent of all value change associated with the change of time. In particular, is it appropriate to discount energy values according to some real discount rate? There is no concensus on this question. By one view an energy storage now can facilitate more energy in the future through stimulus to growth, but the increase is evaluated by the further energy added.

20. As noted in Text Note 5, it is important to be aware of the potential to double count embodied energy evaluated for such processes as plant production and geologic work. The embodied energy value may double count to the extent that the time period of concern in each evaluation overlaps.

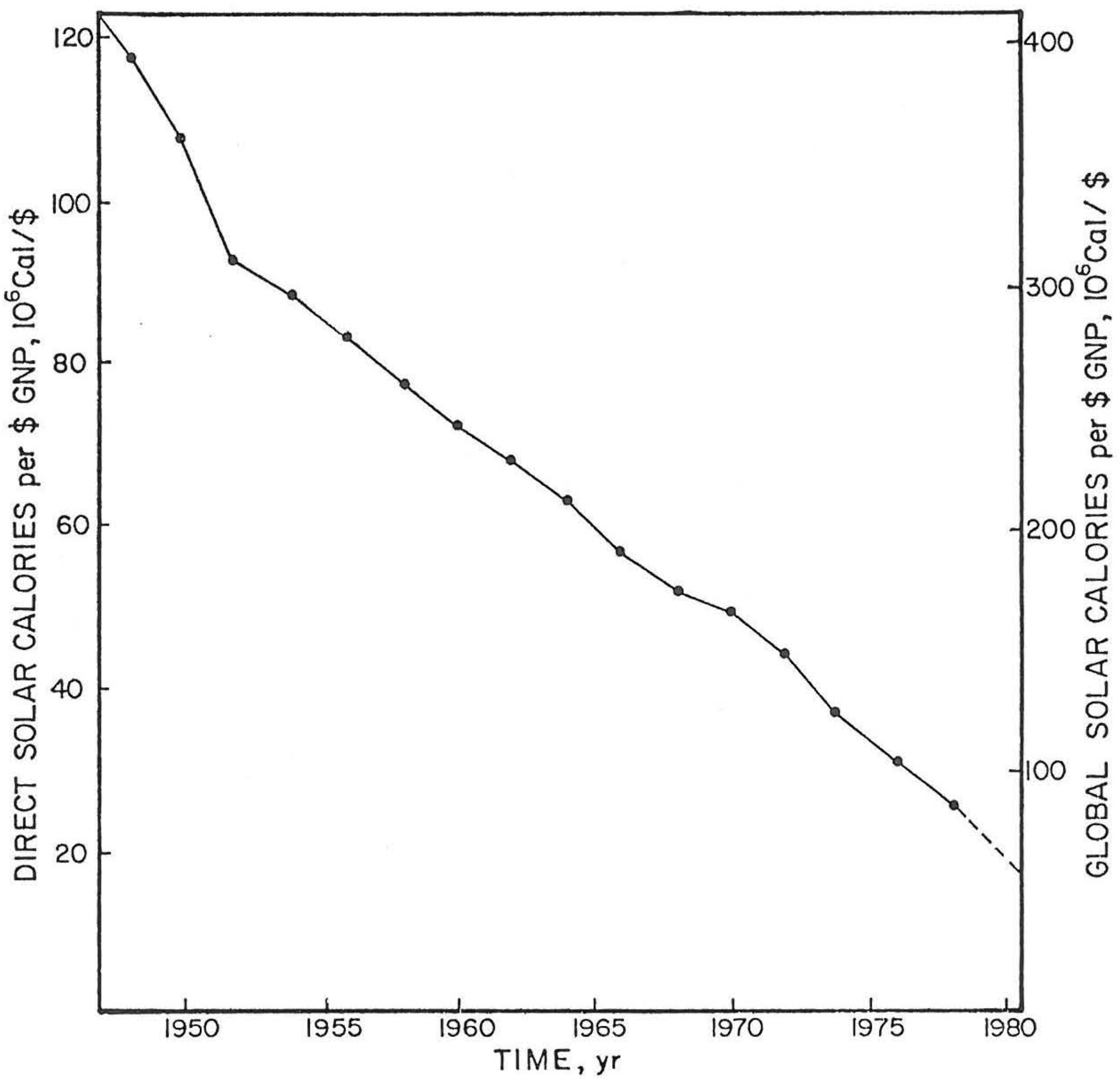

Figure 3. Ratio of embodied solar energy flow to GNP for years preceding the present. Energy flows used include U.S. solar energy plus U.S. fuel use, the latter multiplied by 2000 Cal SE/Cal CE (see Table E2).[21]

Table 3. Categories for Calculating the Changes in Energy Flows due to Construction of a Power Plant.

Flow or Storage (letter in Fig. 1)	Items of Change	Change in Actual Energy Cal/yr	Energy Transformation Ratio	Change in Embodied Energy Solar Cal/yr
ΔA	Power Plant Productive Contribution			
ΔA_1	Net electric power generated			
ΔA_2	Electricity fed back into use			
ΔB	Changes in Environmental Production			
ΔB_1	Production of natural systems			
ΔB_2	Agricultural production			
ΔB_3	Other productive land			
ΔS	Change in Stored Resources			
ΔS_1	Plant biomass			
ΔS_2	Soil			
ΔS_3	Local assets			
ΔC	Changes in Inputs from Main Economy			
ΔC_1	Goods and services to local system			
ΔC_2	Goods and services to plant and cooling system			
ΔF	Changes in Fuels and Raw Material from Main Economy			
ΔF_1	Fuels and raw materials to local system			
ΔF_2	Fuels and raw material to plant and cooling system			
ΔW	Changes Related to Environmental Technology and Wastes			
ΔW_1	Entrainment loss			
ΔW_2	Entrapment loss			
ΔW_3	Heat impact on aquatic systems			
ΔW_4	Chemical impact on aquatic systems			
Algebraic Summation of Differences from Preplant Situation				

Positive increases are contributions to the power and economy of the area and its surroundings. These include ΔA_1, ΔB_1, ΔC_1, and ΔF_1 (see Fig. 1). Negative changes reduce the power of the system or divert more resource for a process than would be required for an alternative. The following are negative: increases in ΔA_2, decreases in ΔB_1, decreases in ΔS, increases of ΔC_2 and ΔF_2 for the same power production, and increases in ΔW.

Next are the energies that are brought in by human development, either as embodied energy of raw materials, fuels, or goods and services.

Another group concerns environmental damages, wastes, and impacts.[22] These may be negative effects, but not necessarily. If environmental technology, such as cooling towers, is used then the energy embodied in these cooling towers is a diversion from other productive activity to the extent that the embodied energy of the technology is greater than the protection it affords. This shows up as higher diversion of energy from the economy.

Global Solar Equivalents

The solar energy supporting processes on land is not just the direct solar energy but the solar energy embodied in the winds, rains, waves, and part of the geologic work converged to the land by the biosphere. In this manual the ratio of global solar energy to direct solar energy was taken as 3.4.[23]

21. In this report the ratio of direct solar energy to coal energy was assumed as 2000 solar Cal/coal Cal, a rounded number suggested as a correct magnitude based on examples of concentration and conversion of plant produce to electricity and indirectly to coal using a factor of 4. A statistical study of many examples will be needed to determine the ratio more accurately. See also computation in footnote 23.
22. The energy embodied in these environmental damages, wastes, and impacts may also double count against other embodied energy flows evaluated in association with other environmental processes, such as plant production, geologic work, etc. As noted in Text Note 20, the calculated embodied energy values may double count to the extent that the time periods of concern in each calculation overlap.
23. The ratio of global area to land area. However, when funds and data are available a more accurate number needs to be calculated that partitions the solar energy absorbed on land to the total with due consideration of albedos, etc.

Production contributions may either be evaluated by summing the input embodied energies in global solar equivalents, in goods and services, in fertilizer, etc., or if these inputs have been related to production previously, one may multiply the actual energy of the production by the energy transformation ratio previously calculated. In the examples below both procedures are used. Either one but not both[24] are included in final summations, since counting both would be counting the same energy twice.

24. Energy transformation ratios for agriculture are in much confusion because some authors are using actual energy instead of embodied energy; others omit embodied energy in goods and services; others omit environmental embodied energy in fertilizer (Slesser 1978; Slesser and Lewis 1979; Fluck and Baird 1980).

3

DRAWING A COMPLEX ENERGY MODEL DIAGRAM

Whereas overall broad categories to be evaluated are given in Fig. 1 and Table 2, a more detailed impact inventory should be made as part of the analysis both to establish what has been considered and to document that some important aspect has not been omitted. A more detailed energy diagram is made showing all kinds of land use, human activities, economic sectors in the area, etc. This more complex diagram will be different for each area, although it will have the general structure of Fig. 1. See for example in Fig. 4 a diagram of the LaSalle site west of Chicago, Illinois. Energy analysis symbols as used in this manual are described in Appendix A.

Those making a complex overview diagram may obtain general instructions on the symbols and their use from reference texts (Odum and Odum 1981; Hall and Day 1977). One decides first on the boundary of the system to be included within the square frame of the system diagram. Next, circles for each source are placed around the outside in order of energy quality, with sunlight on the left and human goods and services of high quality on the far right. The basic productive processes of plants and agriculture are drawn on the left where they receive energy flows of interaction of sun, wind, rain, nutrients, etc. The products, services, attractions, etc., of these flow to consumers within the area or to the outside economy. Storages with long time constants (longer than a year), such as the soil, forest timber, water storages, capital assets, waste storages, etc., are included. The productive and interactive processes are shown with the interaction symbol, which receives inflows from two or more types of energy.

Appendix F summarizes an eleven-step methodology for developing energy circuit models of complex systems of man and nature, which may be helpful to those interested in constructing their own models (Alexander et al. 1980). The steps may be summarized as follows:

1. mapping the general area of interest;
2. identifying the system boundary;
3. identifying energy flows across the boundary;
4. organizing the major system components;
5. identifying interactions between subsystems and sources;
6. connecting the group symbols with external sources;
7. diagraming the subsystems;
8. evaluating the model;
9. translating energy circuit diagrams to differential equations;
10. simulating the energy circuit model;
11. validation of the model.

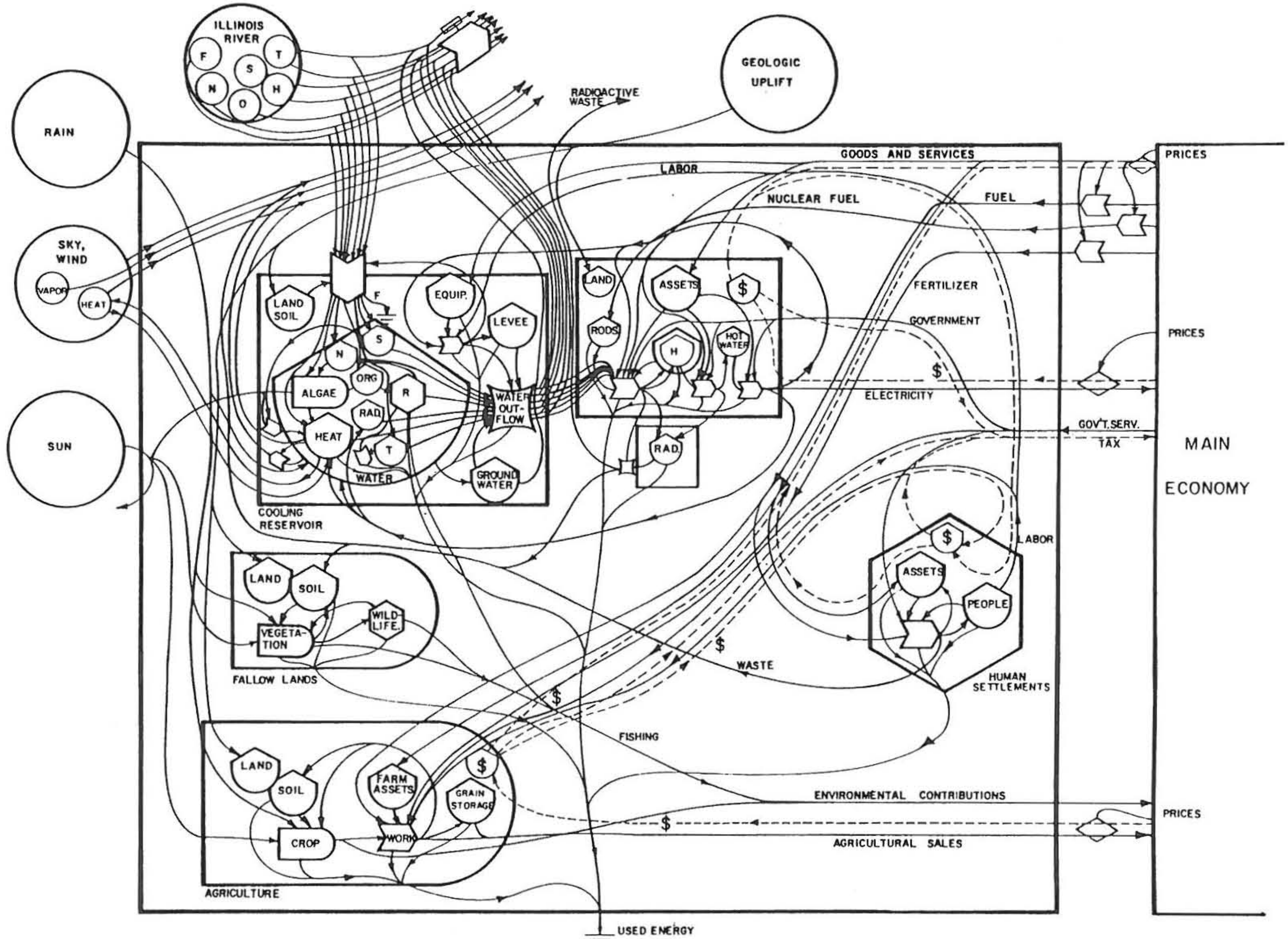

Figure 4. Complex energy diagram of LaSalle County nuclear power plant, cooling lake, and surroundings. See Appendix A for explanation of symbols. Radioactive releases are expected to be within acceptable NRC limits.

4

CASE HISTORY: SAMPLE CALCULATION FOR A POWER PLANT AT LASALLE COUNTY, ILLINOIS, AND ITS COOLING ALTERNATIVES

Procedures for evaluating site alternatives with energy methods are illustrated by an example, LaSalle County Station in Illinois. Seventy-five miles west of Chicago a nuclear power plant is being constructed to go on line in 1980 (Fig. 5). The power plant was built on fertile farmland, and cooling was arranged with an artificial reservoir impoundment that displaced farming activity. For this example, changes in energy flow and storage were estimated for the plant as built compared with the initial pattern of landscape and economic use. Then the changes in energy flow and storage were estimated for the plant as if it had used a cooling tower in place of the impoundment. Third, the differences in energy flow and storage were estimated as if the plant had been built on the shores of a large lake, using the lake for once-through cooling.

Complex Energy Diagram for LaSalle County Station

Figure 4 is a complex energy diagram used to inventory energy sources, environmental processes, and economic activities. The main component blocks of the diagram are the ones in the simplified Fig. 1. Details of important storages and productive processes are shown within. Starting with energy sources on the left, notice the sun's role in driving productivity of agricultural production, natural production of fallow lands, and the photosynthetic production within the reservoir. The Illinois River flowing nearby is shown carrying salts, nutrients, heavy metals, and organic toxins. This water is processed through the reservoir and circulated to and returned from the power plant before being returned to the river somewhat more concentrated due to evaporation. The former economic activity is the supply of fertilizer, goods and services to farming, the processing of grain products, and the export of the agricultural products to the main economy on the right in the diagram. Human settlements are shown as part of the agricultural communities, and, after the plant was constructed, supplying people and goods and services to the power plant operations. Other flows include taxes to government and control and other services from government. Wind is important in the photosynthetic productivity, in wave actions in the reservoir, and in dispersal of stack exhausts. The complex diagram was developed first to inventory everything about the system of the plant and its environment before and after construction. The diagram helped document what was recognized and considered in the evaluation and what was understood to be involved in aggregated flows and storages in the simpler diagram (Fig. 1).

Tables Evaluating Energy Change

Referring to the aggregated diagram in Fig. 1, tables were made of the energy changes associ-

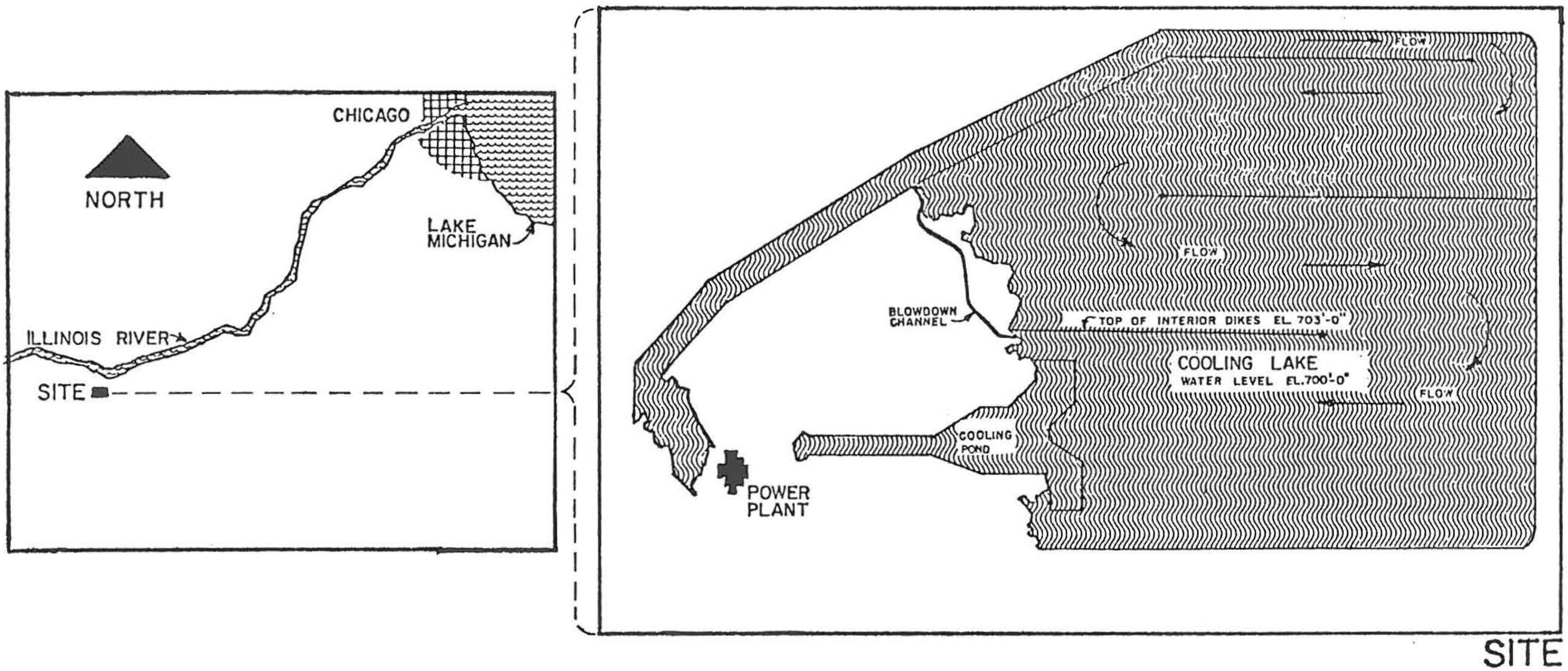

Figure 5. Location and overview of LaSalle Site (Commonwealth Edison Company 1977; NRC 1978).

ated with each of the alternatives. Table 4 has the energy changes associated with the power plant as constructed using the reservoir over agricultural land; Table 5 has the energy changes associated with the alternative using cooling towers; Table 6 has the energy changes associated with the alternative of putting the plant on a large lake. In each table the changes are those in the diagram in Fig. 1, and in more detail in Fig. 4. In each, the actual energies were calculated, the change in energy determined, and then multiplied by the energy transformation ratio to express the flow or storage in embodied solar energy. The details of each calculation are given in footnotes to the tables.

Comparing Alternatives

The cooling alternatives are now compared in Table 7. "Total Production Change" is the algebraic summation of all calculated changes in energy flow. The first column is without changes in storages in biomass, soil, and existing assets; the second column includes loss of storages. The totals omitting storages would provide the steady state, long-range comparison, if such items as decommissioning and reconstruction were also included.

The alternative with the greatest net increase in productivity is identified from this comparison of energy flow. The alternative with the largest productivity increase contributes the most net environmental and economic work. Construction of the plant on a large lake, using once-through cooling, is therefore the most favorable alternative, with a total productivity increase of 26322 x 10^{13} solar Cal/yr. This assumes there are no institutional restrictions. The use of an artificial cooling lake is the poorest alternative, with an increase of 24968 x 10^{13} solar Cal/yr. The difference in production increase between the most and least favorable alternative is 1354 x 10^{13} solar Cal/yr, or 5.4% of the present system.

Then, as done in the last column in Table 7, the dollar equivalents of embodied energy are given using the ratio of total embodied energy to total dollar flow in GNP for 1980. This is an estimation of the ultimate impact on the economy of the energy flows estimated and is done to give perspective to those used to thinking in terms of money. By these results an increase in values of up to 199 million dollars per year is possible.

The items in the table have a large range of magnitude. Inspection helps to recognize factors of greater importance for consideration in planning. In the LaSalle example, major factors are value of soil, on-going agriculture, costs of cooling towers, and diverted electricity.

Table 4. Embodied Energy Evaluation of Changes due to Construction and Operation of LaSalle County Station with Cooling Reservoir.

Flow or Storage (letter in Fig. 1)		Items of Change	Change in Actual Energy Cal/yr 10^9	ETR, Energy Transformation Ratio Solar Cal/Cal 10^3	Change in Embodied Energy Solar Cal/yr 10^{13}	Footnote
ΔA		Power Plant Productive Contribution	+ 9,720	27.2	+26,438	1
ΔB		Environmental Production Changes by Land Uses				2
		Gross production of forest, marsh, and old field	+ 22.0	0.34	+ 0.75	2.1
		Agricultural production	---	---	---	2.2
		Gross production of other managed vegetation	+ 23.1	0.34	+ 0.79	2.3
		Gross production of lake	+ 41.2	0.20	+ 0.82	2.4
ΔS		Changes in Stored Resources				3
		Wood biomass	- 0.233	2.89	- 0.067	3.1
		Soil	- 37.7	119	- 449	3.2
		Farm assets	- 1.28*	6.8	- 0.87	3.3
ΔC		Changes in Inputs from Main Economy				4
	ΔC_1	Fertilizer	- 5.05	1990.0	- 1005	4.1
		Machinery	- 1.29*	6.8	- 0.88	4.2
		Labor	- 0.015	887	- 1.33	4.3
		Commodities	- 0.743	67.0	- 4.98	4.4
	ΔC_2	Operation and maintenance greater than alternative	0	6.8	0	4.5
		Capital investment greater than alternative	- 5	6.8	- 3.4	4.6
ΔF		Changes in Fuels and Other Energy				5
	ΔF_1	Liquid fuel	- 2.44	11.5	- 2.81	5.1
		Electricity from outside	- 0.947	27.2	- 2.58	5.2
		Nuclear fuel goods and services more than alternative	0	6.8	0	5.3
	ΔF_2	Nuclear fuel more than alternative	0	0.306	0	5.4
ΔW		Changes Related to Environmental Technology and Wastes				6
		Entrainment	- 0.00981	75.5	- 0.0741	6.1
		Entrapment	- 0.00112	85.0	- 0.0095	6.2
		Heat impact on primary production	- 0.0502	0.20	- 0.0010	6.3
		Chemical impact	- 0.44056	35.7	- 1.57	6.4
Algebraic Summation					+24,968	

*Calculated from cost of goods and services, converted to Calories using average energy-dollar ratio for that year (Fig. 3 and Table E2).

Footnotes to Table 4

1. Power plant productive contribution - ΔA

The primary benefits of LSCS operation will be the annual production of 11.3 billion KWH of electric power (Nuclear Regulatory Commission [NRC] 1978, Table 10.1)

$$\Delta A = +(11.3 \times 10^9 \text{ KWH/yr})(860 \text{ Cal/KWH})$$
$$= +\ 9.72 \times 10^{12} \text{ Cal/yr}$$
$$ETR = 27.2 \times 10^3 \text{ solar Cal/Cal (Table 1b)}$$

2. Environmental production changes by land uses - ΔB (Energy transformation ratios in footnote 2.b)

	Before			After			Change
	Area-acres (footnote 2.a)	Prod x 10^7 Cal/acre·yr (footnote 2.b)	Total prod x 10^{10} Cal/yr	Area acres	Prod x 10^7 Cal/acre·yr	Total Prod x 10^{10} Cal/yr	10^{10} Cal/yr
2.1 Natural systems							
Forest	265	7.40	1.96	215	7.40	1.59	
Marsh	37	3.40	0.13	24	3.40	0.08	
Old field	0	2.56	0	1022	2.56	2.62	
Subtotal			2.09			4.29	+ 2.20
2.2 Agriculture							
Crops	3059	9.87	30.19	0	9.87	0	
Fallow	475	1.86	0.88	0	1.86	0	
Subtotal			31.07			0	-31.07*
2.3 Other managed							
Homesites	49	4.94	0.24	0	4.94	0	
Structures, cleared	0	0	0	49	0	0	
Managed vegetation	0	4.94	0	517	4.94	2.55	
Subtotal			0.24			2.55	+ 2.31
2.4 Lake	0	2.00	0	2058	2.00	4.12	+ 4.12

*This change was omitted from summation. Instead changes in inputs to agriculture were calculated; (see ΔC's and ΔF's).

2.a. Acreages of vegetation and land use subsystems (from Figs. 6 and 7).

Preplant		With Plant	
Plant Site (3061)			
Soybeans	1450	Lake	2058
Corn	971	Managed vegetation	517
Hay	161	Old field	466
Oats	146	Structures	20
Pasture	13		
Fallow	267		
Forest	0		
Marsh	13		
Homesites	40		
Pipeline Corridor (697)			
Soybeans	75	Old field	458
Corn	111	Forest	215
Hay	16	Marsh	24
Oats	0		
Pasture	0		
Fallow	197		
Forest	265		
Marsh	24		
Homesites	9		

Preplant		With Plant	
Railroad spur and tower bases (127)			
Soybeans	65	Old field	98
Corn	39	Right of way	29
Hay	6		
Oats	6		
Pasture	0		
Fallow	11		
Forest	0		
Marsh	0		
Total (3885)			
Agriculture	3059	Lake	2058
Fallow	475	Old field	1022
Forest	265	Managed vegetation	517
Homesites	49	Forest	215
Marsh	37	Structures, right of way	49
		Marsh	24

2.b. Gross primary productivity of land uses. Productivities in 10^7 Cal/acre·yr.*

System	Gross Primary Productivity, 10^7 Cal/acre·yr	Note
Forest	7.40	1
Marsh	3.40	2
Lake	2.00	3
Old field	2.56	4

2.b. (Continued).

System	Gross Primary Productivity, 10^7 Cal/acre·yr	Note
Crops	9.87	5
Fallow	1.86	6
Homesites	4.94	7
Structures, cleared	0	8
Managed vegetation	4.94	9

*Energy transformation ratios:

Natural systems = 340 global solar Cal/Cal for terrestrial, 200 for aquatic (Table 1b).
Agriculture = 3833 solar Cal/Cal, an average of 2175 solar Cal/Cal for corn (Table E1a) and 5491 solar Cal/Cal for soybeans (Swaney 1978);
Managed vegetation and homesites = 340 solar Cal/Cal (assumed equal to natural systems).

1. Forest - From Smith 1980 (after Burgess and O'Neill 1976)
   $(2150 \text{ g C/m}^2\cdot\text{yr})(8.5 \text{ Cal/g C})(4047 \text{ m}^2/\text{acre}) = 7.40 \times 10^7 \text{ Cal/acre}\cdot\text{yr}$
2. Marsh - From Odum 1971
   $(8400 \text{ Cal/m}^2\cdot\text{yr})(4047 \text{ m}^2/\text{acre}) = 3.40 \times 10^7 \text{ Cal/acre}\cdot\text{yr}$
3. Lake - After Wetzel 1975, estimate for moderately eutrophic lake
   $(4.93 \times 10^3 \text{ Cal/m}^2\cdot\text{yr})(4047 \text{ m}^2/\text{acre}) = 2.00 \times 10^7 \text{ Cal/acre}\cdot\text{yr}$
4. Old field - After Whittaker 1975, average over 40 yr
   $(6.326 \times 10^3 \text{ Cal/m}^2\cdot\text{yr})(4047 \text{ m}^2/\text{acre}) = 2.56 \times 10^7 \text{ Cal/acre}\cdot\text{yr}$
5. Crops - From Odum 1971, value for fuel subsidized agriculture (alfalfa) is 24,400 $\text{Cal/m}^2\cdot\text{yr}$
   $(24{,}400 \text{ Cal/m}^2\cdot\text{yr})(4047 \text{ m}^2/\text{acre}) = 9.87 \times 10^7 \text{ Cal/acre}\cdot\text{yr}$
6. Fallow - Generally only fallow for 2-4 yr at most. From Whittaker 1975, productivity of old field at 1.5 yr is
   $(4.6 \times 10^3 \text{ Cal/m}^2\cdot\text{yr})(4047 \text{ m}^2/\text{acre}) = 1.86 \times 10^7 \text{ Cal/acre}\cdot\text{yr}$
7. Homesites - Same as managed vegetation (Note 9)
   $4.94 \times 10^7 \text{ Cal/acre}\cdot\text{yr}$
8. Structures, cleared
   No productivity
9. Managed vegetation - Considered as planted, fertilized, selectively herbicided, mowed grass, estimate approximately 0.5 productivity of alfalfa
   $(24{,}400 \text{ Cal/m}^2\cdot\text{yr})(0.5)(4047 \text{ m}^2/\text{acre}) = 4.94 \times 10^7 \text{ Cal/acre}\cdot\text{yr}$

3. Changes in stored resources - ΔS

Prorate losses over 40 yr.

3.1 Wood biomass

50 acres of trees lost in pipeline corridor (see 2.a)

forest biomass = 4.6×10^4 Cal/m^2 - Missouri Oak Hickory (Appendix E, Table E32)

(50 acres)(4047 m^2/acre)(4.6×10^4 Cal/m^2)(1/40 yr) = 2.33×10^8 Cal/yr

ETR = 2.89×10^3 solar Cal/Cal (Table 1)

3.2 Soil

Soil under lake scraped to clay, basically lost as farmland

1.81×10^5 Cal/m^2 = soil energy content (Appendix E, Table E38)

(1.81×10^5 Cal/m^2)(2058 acres)(4047 m^2/acre)(1/40 yr) = 3.77×10^{10} Cal/yr

ETR = 11.9×10^4 solar Cal/Cal (Table 1)

3.3 Farm assets

Assets = 4.14×10^3 Cal/m^2 (from Appendix E, Table E38)

Land lost to agriculture = 3059 acres (see 2.a)

(4.14×10^3 Cal/m^2)(4047 m^2/acre)(3059 acres)(1/40 yr) = 1.28×10^9 Cal/yr

ETR = 6.8×10^3 solar Cal/Cal (Table 1)

4. Changes in inputs from main economy - ΔC

(Agriculture values and ETR's from Tables E1 and E37)

4.1 Fertilizer

Decrease: (4.15×10^2 Cal/m$^2\cdot$yr)(4047 m^2/acre)(3059 acres) = 5.14×10^9 Cal/yr

Increase: estimate 10% of corn rate, used only on managed vegetation

(0.10)(4.15×10^2 Cal/m$^2\cdot$yr)(4047 m^2/acre)(517 acres) = 8.68×10^7 Cal/yr

Net decrease: 5.05×10^9 Cal/yr

ETR = 1.99×10^6 solar Cal/Cal (Table 1b)

4.2 Machinery

(1.04×10^2 Cal/m$^2\cdot$yr)(4047 m^2/acre)(3059 acres) = 1.29×10^9 Cal/yr

ETR = 6.8×10^3 solar Cal/Cal

4.3 Labor

(1.21 Cal/m$^2\cdot$yr)(4047 m^2/acre)(3059 acres) = 1.50×10^7 Cal/yr

ETR = 8.87×10^5 solar Cal/Cal (Table 1b)

4.4 Commodities

$(0.6 \times 10^2\ Cal/m^2 \cdot yr)(4047\ m^2/acre)(3059\ acres) = 7.43 \times 10^8\ Cal/yr$

ETR = 6.7×10^4 solar Cal/Cal (Table E37, footnote 18d)

4.5 Operation and maintenance

Machinery, labor, commodities estimated from operational costs of power plant (nonfuel) (NRC 1978) and prorated decommissioning costs. This value is then converted using 12,500 Cal/$ (Fig. 3 and Table E2)

$(\$34 \times 10^6/yr + \$0.88 \times 10^6/yr)(12.5 \times 10^3\ Cal/\$) = 4.36 \times 10^{11}\ Cal/yr$

ETR = 6.8×10^3 solar Cal/Cal (Appendix E, Table E37)

This alternative least and was taken as zero change

4.6 Capital investment

From Atomic Energy Commission (AEC) 1973, estimated cost of plant with 4480-acre lake is $\$542.9 \times 10^6$. From AEC 1973, cost of 4480-acre lake is $\$48.4 \times 10^6$. Cost of plant minus cooling is therefore

$(\$542.9 \times 10^6) - (\$48.4 \times 10^6) = \$494.5 \times 10^6$

From AEC 1973, the relative cost of cooling systems translated to constant dollars is:

Reservoir	0.85
Cooling tower	1.00
Once-through	0.54

From AEC 1973, cost of cooling tower system is $\$33.5 \times 10^6$. Using this system as a base, total capital investments for the three alternatives are (in 1973 $):

Reservoir	$(\$494.5 \times 10^6) + (0.85)(\$33.5 \times 10^6) = \$523.0 \times 10^6$
Cooling tower	$(\$494.5 \times 10^6) + (1.00)(\$33.5 \times 10^6) = \$528.0 \times 10^6$
Once-through	$(\$494.5 \times 10^6) + (0.54)(\$33.5 \times 10^6) = \$512.6 \times 10^6$

For cooling reservoir, total prorated capital investment is therefore

$(\$523.0 \times 10^6)(19.6 \times 10^3\ Cal\ FF/\$)(1/40\ yr) = 2.56 \times 10^{11}\ Cal/yr$

ETR = 6.8×10^3 solar Cal/Cal (Appendix E, Table E37)

Difference between this value and minimum case appears in table.

5. Change in fuels and other energy - ΔF

5.1 Liquid fuel

Value for fuel used in agriculture = $1.97 \times 10^2\ Cal/m^2 \cdot yr$ (Appendix E, Table E37)

$(1.97 \times 10^2\ Cal/m^2 \cdot yr)(4047\ m^2/acre)(3059\ acres) = 2.44 \times 10^9\ Cal/yr$

ETR = 11.5×10^3 (Table 1b)

5.2 Electricity

Electricity used in agriculture = $7.65 \times 10^1\ Cal/m^2 \cdot yr$ (Appendix E, Table E37)

$(7.65 \times 10^1\ Cal/m^2 \cdot yr)(4047\ m^2/acre)(3059\ acres) = 9.47 \times 10^8\ Cal/yr$

ETR = 27.2×10^3 solar Cal/Cal (Table 1b)

5.3 Nuclear fuels goods and services

Cost of nuclear fuel is $\$61 \times 10^6$/yr (NRC 1978)

($\$61 \times 10^6$/yr)($12.5 \times 10^3$ Cal/\$) = 7.63×10^{11} Cal/yr (coal equivalents)

ETR = 6800 solar Cal/Cal (Table 1b)

This alternative least and was taken as zero change.

5.4 Nuclear fuel energy

(109 Cal uranium used/1.95 Cal electricity produced)(9720×10^9 Cal electricity produced) = $543{,}323 \times 10^9$ Cal/yr

ETR = 306 solar Cal/uranium Cal (Table 1b)

This alternative least and was taken as minimum (zero change).

6. Changes related to environmental technology and wastes - ΔW

6.1 Entrainment

Entrainment mortality for zooplankton (Kemp et al. 1977)

$P_E = N \times m \times M \times K \times R \times Q$ (in heat Calories)

where, N = numerical density (individual/m^3)

m = mass per individual (kg/individual) = 0.68×10^{-8} kg/individual

M = metabolism per mass (Cal/kg·day) = 500 Cal/kg·day

K = entrainment mortality

R = loss of metabolism (days to replace) = 10 day

Q = daily circulating water flow (m^3/day)

For LSCS plant:

Zooplankton population density varies among sampling periods, stations, and years. The average density of copepoda in the Illinois River (NRC 1978, Table 2.11) in 1976 was N = 5705 number/m^3

Assume all carried to lake in makeup line are lost to river, therefore, replace entrainment mortality by removal factor - 1.0, but some are also supplied to river in blowdown water from lake. Also assume density in lake equal to density in river (a reasonable assumption, as 4 unit/liter typical lake value) (see Wetzel 1975).

Some zooplankton from lake to river will be killed by entrainment (30%).

When LSCS plant is in full operation (Commonwealth Edison Company [CEC] 1977; ER-OLS, Table 3.3-1), the intake makeup water flow and blowdown water flow will be 92.5 cfs and 51.1 cfs, respectively.

Thus, $P_E = N \times m \times M \times K \times R \times Q$

$P_E = (2.83 \times 10^{-2}\ m^3/ft^3)(3.15 \times 10^7\ s/yr)(5.705 \times 10^3\ unit/m^3)(0.68 \times 10^{-8}\ kg/unit)(5 \times 10^2\ Cal/kg{\cdot}day)(1.0\ kill)(10\ day)$
$(92.5\ cfs - [0.7][51.1\ cfs])$

$= 9.81 \times 10^6$ Cal/yr

Energy transformation ratio (Kemp et al. 1977)

ETR = 11.1 CE Cal/Cal x 6,800 global solar Cal/Cal

= 7.55×10^4 solar Cal/Cal

6.2 Entrapment

Qualitative information in CEC, ER-OLS 2.2.1.9 indicate low quality, low diversity of fish populations. No quantitative data on fish populations in appropriate section of river available. Use data from Kemp et al. (1977), adjust for lower flow rate.

fish lost (Kemp et al. 1977) = $(2.00 \times 10^7$ Cal/yr)

circulation rate (Kemp et al. 1977) = $(3.4 \times 10^6\ m^3/day)(35.31\ ft^3/m^3)(1\ day/8.64 \times 10^4\ s) = 1{,}390$ cfs

fish lost = $(2.00 \times 10^7$ Cal/yr)(78 cfs/1390 cfs) = 1.122×10^6 Cal/yr

ETR (Kemp et al. 1977) = 25 CE Cal/Cal

adjust to 12.5:1 for lower quality fish = (12.5 CE/Cal)(6800 global solar Cal/CE Cal = 8.5×10^4 solar Cal/Cal

6.3 Heat impact

Maximum area of plume (3°F excess isotherm) = 4.1 acre (NRC 1978, Fig. 5.1). Estimate average temperature increase in 3°F excess isotherm as 5°F (NRC 1978, Fig. 5.1). A possible decrease in metabolism of 50% for affected area (Kemp et al. 1977). Average primary productivity (NRC 1978)

$$= \left(\frac{0.74 + 149.49 + 8.51 + 312.94}{4}\right) \text{mg C/m}^3\cdot\text{hr} = 117.92 \text{ mg C/m}^3\cdot\text{hr}$$

$(117.92\ mg\ C/m^3\cdot hr)(1\ g/1000\ mg)(9.0\ Cal/g)(12\ hr/day)(365\ day/yr)(1.30\ m^3/m^2)(4047\ m^2/acre) = 2.45 \times 10^7$ Cal/acre·yr

$(2.45 \times 10^7$ Cal/acre·yr)(4.1 acres)(0.50) = 5.02×10^7 Cal/yr

ETR = 200 solar Cal/Cal (Table 1b)

6.4 Chemical impact

Energy of loss of purity (increase in dissolved solids) is the Gibbs free energy

$$\Delta F = nRT \ln \frac{\text{purity of water without plant}}{\text{purity of water with plant}}$$

Purity of river water without power plant = 1 - concentration of dissolved solids = 1 - 444 mg/l = 0.9995560 (NRC 1978)

Purity of discharge water = 739 mg/l (NRC 1978)

Average river water temperature = 56°F (286.3°K) (NRC 1978)

Average river flow without plant is 10,750 cfs (NRC 1978)

Average plant makeup water is 92.5 cfs (NRC 1978)

Average plant discharge water is 53.1 cfs (NRC 1978)

River flow downstream of plant, not including plant discharge will be 10,750 cfs - 92.5 cfs = 10,657.5 cfs

River flow downstream of plant, with plant discharge will be 10,657.5 cfs + 53.1 cfs = 10,710.6 cfs

Total dissolved solids downstream of plant will be:

$$\frac{(10{,}657.5 \text{ cfs})(444 \text{ mg/l}) + (53.1 \text{ cfs})(739 \text{ mg/l})}{10{,}710.6 \text{ cfs}} = 445.45 \text{ mg/l}$$

Purity downstream of plant = $(10^6 - 445.45\ mg/l)(10^{-6}\ l/mg) = 0.99955454$ g/g

River flow downstream = $(10{,}710.6\ ft^3/s)(1 \times 10^3\ g/l)(28.32\ l/ft^3)(3.1416 \times 10^7\ s/yr) = 9.5292 \times 10^{15}$ g/yr

$$\Delta F = \frac{(1.99 \times 10^{-3}\ \text{Cal}/^\circ\text{K}\cdot\text{mole})(286.3^\circ\text{K})}{18\ \text{g/mole}}\ \ln \frac{0.99955600}{0.99955454} = 4.62325 \times 10^{-8}\ \text{Cal/g}$$

Energy loss from loss of purity will be $(9.5292 \times 10^{15}$ g/yr$)(4.62325 \times 10^{-8}$ Cal/g$) = 4.4056 \times 10^{8}$ Cal/yr

ETR for river water purity = 3.57×10^{4} solar Cal/Cal (Table 1)

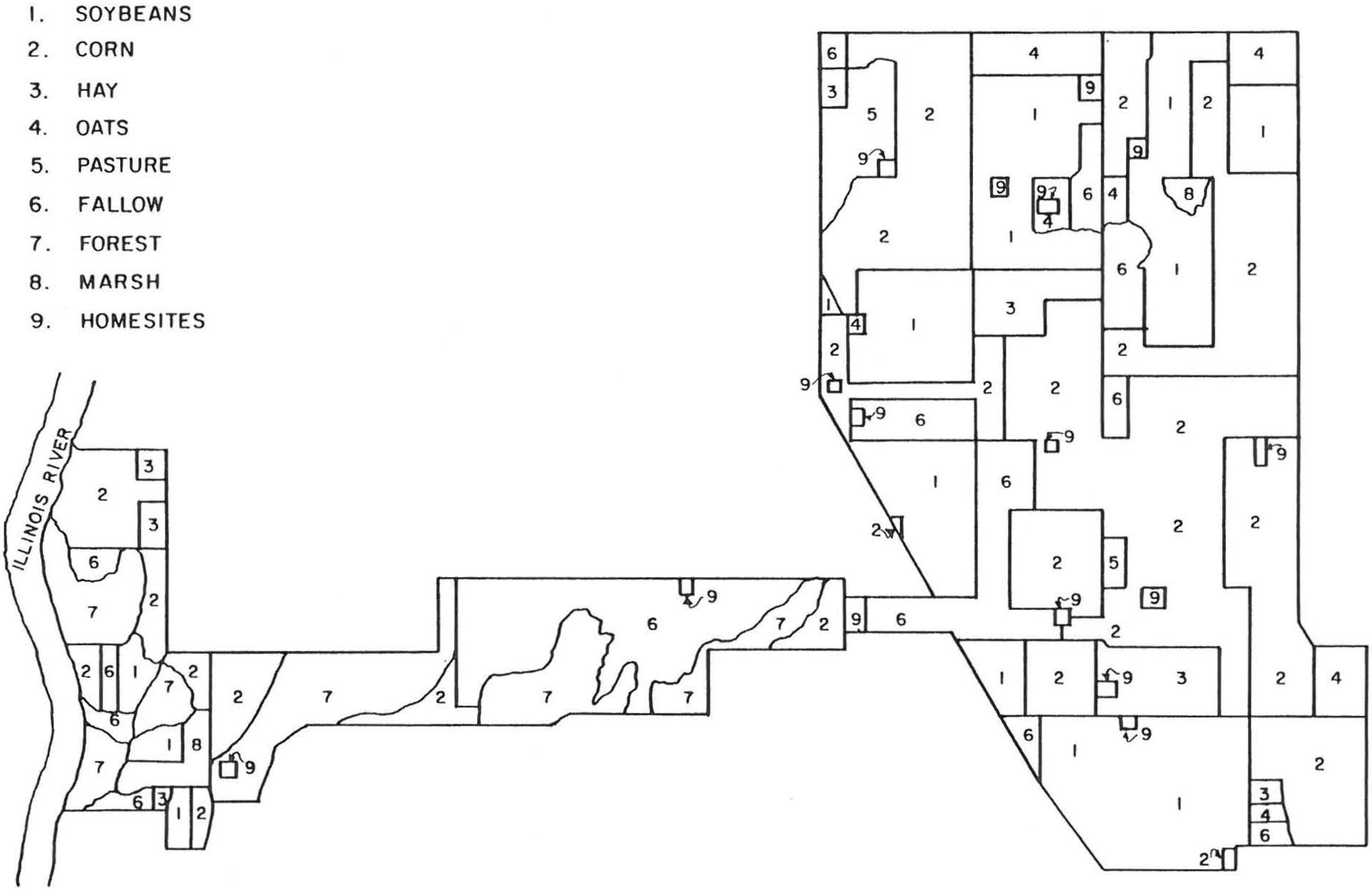

Figure 6. Vegetation and land use for energetic subsystem classification. LaSalle County station, plant site, and pipeline corridor—before construction (after Commonwealth Edison Company 1977, Fig. 2.2-3; United States Geological Survey aerial photographs 1967).

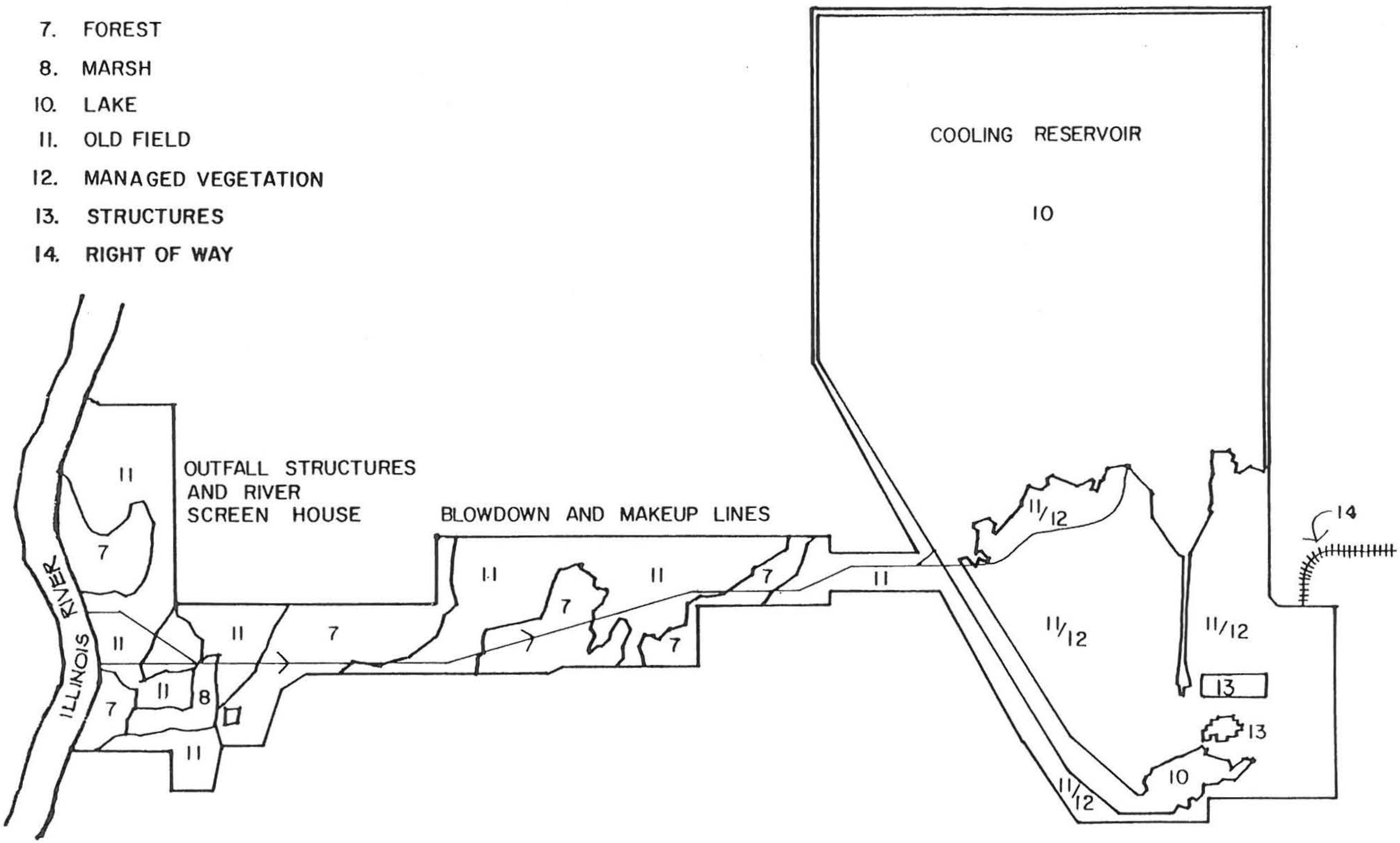

Figure 7. Vegetation and land use for energetic subsystem classification. LaSalle County station, plant site, and pipeline corridor—after construction (after United States Geological Survey aerial photographs 1978; information in NRC 1978; Atomic Energy Commission 1973; Commonwealth Edison Company 1977, Fig. 2.1-4; and text).

Table 5. Embodied Energy Evaluation of Changes due to Construction and Operation of LaSalle County Station Assuming Cooling Towers.*

Flow or Storage (letter in Fig. 1)		Items of Change		Change in Actual Energy Cal/yr 10^9	ETR, Energy Transformation Ratio Solar Cal/Cal 10^3		Change in Embodied Energy Solar Cal/yr 10^{13}	Footnote
ΔA		Power Plant Productive Contribution	+	9,864	27.2	+	26,830	1.1
	ΔA_2	Electricity to Operate Cooling Towers	-	144	27.2	-	392	1.2
ΔB		Environmental Production Changes by Land Uses						2
		Gross production of forest, marsh, and old field	-	47.4	0.34	-	1.61	2.1
		Agricultural production		---	---		---	2.2
		Gross production of other vegetation	+	15.8	0.34	+	0.54	2.3
ΔS		Changes in Stored Resources						3
		Wood biomass	-	2.98	2.89	-	0.861	3.1
		Soil	-	1.83	119	-	21.8	3.2
		Farm assets	-	0.268	6.8	-	0.182	3.3
ΔC		Changes in Inputs from Main Economy						4
	ΔC_1	Fertilizer	-	1.02	1,990	-	203	4.1
		Machinery	-	0.269	6.8	-	0.183	4.2
		Labor	-	0.00313	887	-	0.278	4.3
		Commodities	-	0.155	67	-	1.04	4.4
	ΔC_2	Operation and maintenance greater than alternative	-	13	6.8	-	8.8	4.5
		Capital investment greater than alternative	-	12	6.8	-	8.2	4.6
ΔF		Changes in Fuels and Other Energy						5
	ΔF_1	Liquid fuel	-	0.510	11.5	-	0.586	5.1
		Electricity	-	0.198	27.2	-	0.539	5.2
	ΔF_2	Nuclear fuel goods and services more than alternative	-	11	6.8	-	7.48	5.3
		Nuclear fuel more than alternative	-	8,041	0.306	-	246	5.4
ΔW		Changes Related to Environmental Technology and Wastes						6
		Entrainment	-	0.0130	75.5	-	0.098	6.1
		Entrapment	-	0.00214	85	-	0.0182	6.2
		Heat impact	-	0.0959	0.20	-	0.0019	6.3
		Chemical impact	-	1.100	35.7	-	3.93	6.4
Algebraic Summation						+	25,934	

*For symmetry of calculation with other alternatives, capacity was added for cooling towers so electric yield is the same.

Footnotes to Table 5

Energy transformation ratios from Table 4

1.1 Power plant productive contribution - ΔA

$\Delta A = 9.72 \times 10^{12}$ Cal/yr (from Table 4, footnote 1) plus cooling tower electricity, 0.144×10^{12} Cal/yr

ETR = 27.2×10^3 solar Cal/Cal

1.2 Cooling towers will consume \$4 x 10^6 of \$270 x 10^6 production (AEC 1973)

$$\frac{\$4 \times 10^6}{\$270 \times 10^6} = (0.0148)$$

$(0.0148)(9.72 \times 10^{12}$ Cal/yr$) = 1.44 \times 10^{11}$ Cal/yr

ETR = 27.2×10^3 solar Cal/Cal

2. Environmental production changes by land uses - ΔB

1280 acres needed (AEC 1973, Table XI-1), estimate 50% from forest, 50% from agriculture (from Fig. 5), 25% of total to be managed vegetation

Productivity values from Table 4, footnote 2.b.

2.1 Forest

(640 acres)(7.40×10^7 Cal/acre·yr) = 4.74×10^{10} Cal/yr

ETR = 0.34×10^3 solar Cal/Cal

2.2 Agriculture

(640 acres)(9.87×10^7 Cal/acre·yr) = 6.32×10^{10} Cal/yr

Not included in summation; inputs to agriculture were included instead.

2.3 Managed vegetation

(320 acres)(4.94×10^7 Cal/acre·yr) = 1.58×10^{10} Cal/yr

ETR = 0.34×10^3 solar Cal/Cal

3. Changes in stored resources - ΔS

Prorate losses over 40 yr.

3.1 Wood biomass

From above, 640 acres forest lost

Forest biomass (footnote 3.1, Table 4) = 4.6×10^4 Cal/m^2

(640 acres)(4.6×10^4 Cal/m^2)(4047 m^2/acre)(1/40 yr) = 2.98×10^9 Cal/yr

ETR = 2.89×10^3 solar Cal/Cal

3.2 Soil

Only soil lost is actual plant, cooling tower, and other hard surfaces, estimate at 100 acres

Soil value (from footnote 3.2, Table 4) = 1.81×10^5 Cal/m^2

(100 acres)(1.81×10^5 Cal/m^2)(4047 m^2/acre)(1/40 yr) = 1.83×10^9 Cal/yr

ETR = 11.9×10^4 solar Cal/Cal

3.3 Farm assets

Assets (from footnote 3.3, Table 4) = 4.14×10^3 Cal/m^2

Land lost to agriculture = 640 acres (from above)

(640 acres)(4047 m^2/acre)(4.14×10^3 Cal/m^2)(1/40 yr) = 2.68×10^8 Cal/yr

ETR = 6.8×10^3 solar Cal/Cal

4. Changes in input from main economy - ΔC (values from footnote 4, Table 4)

4.1 Fertilizer

Decrease: (4.15×10^2 Cal/$m^2 \cdot$yr)(4047 m^2/acre)(640 acres) = 1.07×10^9 Cal/yr

Increase: 10% of corn rate, on managed vegetation

(0.10)(4.15×10^2 Cal/$m^2 \cdot$yr)(4047 m^2/acre)(320) = 5.37×10^7 Cal/yr

Net decrease: (5.37×10^7 Cal/yr) - (1.07×10^9 Cal/yr) = -1.02×10^9 Cal/yr

ETR = 1990×10^3 solar Cal/Cal

4.2 Machinery

(1.04×10^2 Cal/$m^2 \cdot$yr)(4047 m^2/acre)(640 acres) = -2.69×10^8 Cal/yr

ETR = 6.8×10^3 solar Cal/Cal

4.3 Labor

(1.21 Cal/$m^2 \cdot$yr)(4047 m^2/acre)(640 acres) = -3.13×10^6 Cal/yr

ETR = 8.87×10^5 solar Cal/Cal

4.4 Commodities

(0.6×10^2 Cal/$m^2 \cdot$yr)(4047 m^2/acre)(640 acres) = 1.55×10^8 Cal/yr

ETR = 6.7×10^4 solar Cal/Cal

4.5 Operation and maintenance

Estimates as in footnote 4.5, Table 4. From AEC (1973) capability loss and excess operating and maintenance is $12,840,000.

(19.6×10^3 Cal/\$)(\$12,840,000)(1/40 yr) = 6.29×10^9 Cal/yr more

(4.36×10^{11} Cal/yr) + (6.29×10^9 Cal/yr) = 4.42×10^{11} Cal/yr; increased 1.0148 for greater capacity = 4.49×10^{11} Cal/yr

Difference from alternate in footnote 4.5, Table 4, (4.49 - 4.36) $\times 10^{11}$ Cal/yr = 0.13×10^{11} Cal/yr

ETR = 6.8×10^3 solar Cal/Cal (Table 1)

4.6 Capital investment

From footnote 4.6, Table 4, capital investment for plant with cooling towers is $\$528.0 \times 10^6$ (1973 \$). Capital investment is therefore:

$(\$528.0 \times 10^6)(19.6 \times 10^3$ Cal FF/\$)(1/40 yr) = 2.59×10^{11} Cal/yr; increased 1.0148 for greater capacity = 2.63×10^{11} Cal/yr

Difference from lowest alternative in footnote 4.6, Table 6, $(2.63 - 2.51) \times 10^{11}$ Cal/yr = 0.12×10^{11} Cal/yr

ETR = 6.8×10^3 solar Cal/Cal

5. Changes in fuels and other energy - ΔF

5.1 Liquid fuel

From footnote 5.1, Table 4, fuel = 1.97×10^2 Cal/$m^2 \cdot$yr)

$(1.97 \times 10^2$ Cal/$m^2 \cdot$yr)(4047 m^2/acre)(640 acres) = 5.10×10^8 Cal/yr

ETR = 11.5×10^3 solar Cal/Cal

5.2 Electricity

From footnote 5.2, Table 4, electricity = 7.65×10^1 Cal/$m^2 \cdot$yr

$(7.65 \times 10^1$ Cal/$m^2 \cdot$yr)(4047 m^2/acre)(640 acres) = 1.98×10^8 Cal/yr

ETR = 27.2×10^3 solar Cal/Cal

5.3 Nuclear fuel good and services

From Table 4, 7.63×10^{11} Cal/yr plus 1.48% for cooling towers (footnote 1.2) = 7.74×10^{11} Cal/yr (coal equivalent); difference from alternative $(7.74 - 7.63) \times 10^{11}$ Cal/yr = 11×10^9 Cal/yr

ETR = 6.8×10^3 solar Cal/Cal

5.4 Nuclear fuel

$543{,}323 \times 10^9$ Cal/yr (Table 4) plus 1.48% for cooling towers (footnote 1.2) = $551{,}364 \times 10^9$ Cal/yr; difference from alternative $(551{,}364 - 543{,}323) \times 10^9$ Cal/yr = 8041×10^9 Cal/yr

ETR = 306 solar Cal/uranium Cal

6. Changes related to environmental technology and wastes - ΔW

6.1 Entrainment

Estimate proportional to makeup

Cooling lake makeup = 92.5 cfs (NRC 1978, Fig. 3.1)

Cooling tower makeup = 121 cfs (AEC 1974)

Cooling lake entrainment (from Table 4, footnote 6.1) = 9.81×10^6 Cal/yr

Increased 1.0148 for greater capacity

$$(9.81 \times 10^6 \text{ Cal/yr})\left(\frac{121 \text{ cfs}}{92.5 \text{ cfs}}\right)(1.0148) = 1.30 \times 10^7 \text{ Cal/yr}$$

ETR = 75.5×10^3 solar Cal/Cal

6.2 Entrapment

Estimate proportional to blowdown (value from footnote 6.2, Table 4; blowdown values from NRC 1978 and AEC 1974); increased 1.0148 for greater capacity $(1.12 \times 10^6$ Cal/yr)(100 cfs/53.1 cfs) (1.0148) = 2.14×10^6 Cal/yr

ETR = 8.5×10^4 solar Cal/Cal

6.3 Heat impact

Calculations as in Table 4, assume impact proportional to blowdown; increased 1.0148 for greater capacity

$(5.02 \times 10^7 \text{ Cal/yr})(100 \text{ cfs}/53.1 \text{ cfs})(1.0148) = 9.59 \times 10^7 \text{ Cal/yr}$

ETR = 200 solar Cal/Cal

6.4 Chemical impact

For cooling tower example, data for Commonwealth Edison's Byron plant is used (AEC 1974)

Energy of loss of purity (increase in dissolved solids) is the Gibbs free energy

$$\Delta F = nRT \ln \frac{\text{purity of water without plant}}{\text{purity of water with plant}}$$

Purity of river water without plant = 1 - concentration of dissolved solids = 1 - 444 mg/l = 0.99955600 (NRC 1978)

Dissolved solids of discharge water will be approximately 4 times the TDS in the makeup water (AEC 1974), so

(4)(444 mg/l) = 1,776 mg/l

Average river water temperature = 56°F (286.3°K) (NRC 1978)

Average river flow without plant is 10,750 cfs (NRC 1978)

Average plant makeup water is 121 cfs (AEC 1974)

Average plant discharge water is 28.90 cfs (AEC 1974)

River flow downstream of plant, not including plant discharge, will be 10,750 cfs - 121 cfs = 10,629 cfs

River flow downstream of plant, with plant discharge will be 10,629 cfs + 28.90 cfs = 10,657.9 cfs.

Total dissolved solids downstream of plant will be

$$\frac{(10{,}629 \text{ cfs})(444 \text{ mg/l}) + (28.90 \text{ cfs})(1{,}776 \text{ mg/l})}{10{,}657.9 \text{ cfs}} = 447.61 \text{ mg/l}$$

Purity downstream of plant = 1 - 447.61 mg/l = 0.99955239

River flow downstream = $(10{,}657.9 \text{ ft}^3/\text{s})(1 \times 10^3 \text{ g/l})(28.32 \text{ l/ft}^3)(3.1416 \times 10^7 \text{ s/yr}) = 9.4823 \times 10^{15} \text{ g/yr}$

$$\Delta F = \frac{(1.99 \times 10^{-3} \text{ Cal/°K·mole})(286.3\text{°K})}{18 \text{ g/mole}} \ln \frac{0.99955600}{0.99955239} = 1.14315 \times 10^{-7} \text{ Cal/g}$$

Energy loss from loss of purity will be (increased 1.0148 for greater capacity)

$(9.4823 \times 10^{15} \text{ g/yr})(1.14315 \times 10^{-7} \text{ Cal/g})(1.0148) = 1.100 \times 10^9 \text{ Cal/yr}$

ETR = 3.57×10^4 solar Cal/Cal (from Table 1)

Table 6. Embodied Energy Evaluation of Changes due to Construction and Operation of LaSalle County Station with Once-Through Cooling.

Flow or Storage (letter in Fig. 1)		Items of Change	Change in Actual Energy Cal/yr 10^9	ETR, Energy Transformation Ratio Solar Cal/Cal 10^3	Change in Embodied Energy Solar Cal/yr 10^{13}	Footnote
ΔA		Power Plant Productive Contribution	+ 9,720	27.2	+26,438	1
ΔB		Environmental Production Changes by Land Uses				2
		Gross production of forest, marsh, and old field	- 23.7	0.34	- 0.81	2.1
		Agricultural production	---	---	---	2.2
		Gross production of other vegetation	+ 7.90	0.34	+ 0.269	2.3
ΔS		Changes in Stored Resources				3
		Wood biomass	- 1.49	2.89	- 0.431	3.1
		Soil	- 0.897	119	- 10.67	3.2
		Farm assets	- 0.134	6.8	- 0.091	3.3
ΔC		Changes in Inputs from Main Economy				4
	ΔC_1	Fertilizer	- 0.510	1,990	- 101.5	4.1
		Machinery	- 0.135	6.8	- 0.092	4.2
		Labor	- 0.00157	887	- 0.139	4.3
		Commodities	- 0.0777	67	- 0.521	4.4
	ΔC_2	Operation and maintenance	0	6.8	0	4.5
		Capital investment	0	6.8	0	4.6
ΔF		Changes in Fuels and Other Energy				5
	ΔF_1	Liquid fuel	- 0.255	11.5	- 0.293	5.1
		Electricity	- 0.0991	27.2	- 0.270	5.2
	ΔF_2	Nuclear fuel goods and services	0	6.8	0	5.3
		Nuclear fuel	0	0.306	0	5.4
ΔW		Changes Related to Environmental Technology and Wastes				6
		Entrainment	- 0.148	75.5	- 1.117	6.1
		Entrapment	- 0.0412	85.0	- 0.350	6.2
		Heat impact	- 3.01	0.20	- 0.060	6.3
		Chemical impact	---	---	---	
Algebraic Summation					+26,322	

Footnotes to Table 6

Energy transformation ratios from Table 4

1. Power plant productive contribution - ΔA
   $\Delta A = 9.72 \times 10^{12}$ Cal/yr (from Table 4, footnote 1)
   ETR = 27.2×10^{3} solar Cal/Cal

2. Environmental production changes by land uses - ΔB
   Estimate 50% as much land needed as for cooling tower option = 640 acres. As in Table 5, assume 50% from forest, 50% from agriculture, 25% of total to be managed vegetation. Productivity values from Table 4, footnote 2.b.

2.1 Forest
(320 acres)(7.40×10^{7} Cal/acre·yr) = 2.37×10^{10} Cal/yr
ETR = 0.34×10^{3} solar Cal/Cal

2.2 Agriculture
(320 acres)(9.87×10^{7} Cal/acre·yr) = 3.16×10^{10} Cal/yr
Not included in summation; inputs to agriculture were included instead.

2.3 Managed vegetation
(160 acres)(4.94×10^{7} Cal/acre·yr) = 0.79×10^{10} Cal/yr
ETR = 0.34×10^{3} solar Cal/Cal

3. Changes in stored resources - ΔS
   Prorate over 40 yr

3.1 Wood biomass
From above, 320 acres lost
Forest biomass (footnote 3.1, Table 4) = 4.6×10^{4} Cal/m^2
(320 acres)(4.6×10^{4} Cal/m^2)(4047 m^2/acre)(1/40 yr) = 1.49×10^{9} Cal/yr
ETR = 2.89×10^{3} solar Cal/Cal

3.2 Soil
Only soil lost is for plant and other hard surfaces, estimate 49 acres
Soil value (from footnote 3.2, Table 4) = 1.81×10^{5} Cal/m^2
(49 acres)(1.81×10^{5} Cal/m^2)(4047 m^2/acre)(1/40 yr) = 8.97×10^{8} Cal/yr
ETR = 119×10^{3} solar Cal/Cal

3.3 Farm assets

Assets (from footnote 3.3, Table 4) = 4.14×10^3 Cal/m^2

land lost to agriculture = 320 acres (above)

(320 acres)(4.14×10^3 Cal/m^2)(4047 m^2/acre)(1/40 yr) = 1.34×10^8 Cal/yr

ETR = 6.8×10^3 solar Cal/Cal

4. Changes in inputs from main economy - Δ C

Values from footnote 4, Table 4

4.1 Fertilizer

Decrease: (4.15×10^2 Cal/$m^2 \cdot$yr)(4047 m^2/acre)(320 acres) = 5.37×10^8 Cal/yr

Increase: 10% of corn rate, on managed vegetation

(0.10)(4.15×10^2 Cal/$m^2 \cdot$yr)(4047 m^2/acre)(160 acres) = 2.69×10^7 Cal/yr

Net decrease: (2.68×10^7 Cal/yr) - (5.37×10^8 Cal/yr) = -5.10×10^8 Cal/yr

ETR = 1990×10^3 solar Cal/Cal

4.2 Machinery

(1.04×10^2 Cal/$m^2 \cdot$yr)(4047 m^2/acre)(320 acres) = -1.35×10^8 Cal/yr

ETR = 6.8×10^3 solar Cal/Cal

4.3 Labor

(1.21 Cal/$m^2 \cdot$yr)(4047 m^2/acre)(320 acres) = -1.57×10^6 Cal/yr

ETR = 8.87×10^5 solar Cal/Cal

4.4 Commodities

(0.6×10^2 Cal/$m^2 \cdot$yr)(4047 m^2/acre)(320 acres) = 7.77×10^7 Cal/yr

ETR = 6.7×10^4 solar Cal/Cal

4.5 Operation and maintenance

Estimates as in footnote 4.5, Table 4

From Table 4, operation and maintenance cost = 4.36×10^{11} Cal/yr same as for reference case

ETR = 6.8×10^3 solar Cal/Cal

4.6 Capital investment

From footnote 4.6, Table 4, capital investment for plant with once-through cooling is \$512.6 x 10^6 (1973 \$). Capital investment is therefore:

(\$512.6 x 10^6)(19.6×10^3 Cal FF/\$)(1/40 yr) = 2.51×10^{11} Cal/yr

ETR $\mp$ 6.8×10^3 solar Cal/Cal (Appendix E, Table E37)

5. Changes in fuels and other energy - ΔF

5.1 Liquid fuel

From footnote 5.1, Table 4, fuel = 1.97×10^2 Cal/$m^2 \cdot$yr

(1.97×10^2 Cal/$m^2 \cdot$yr)(4047 m^2/acre)(320 acres) = 2.55×10^8 Cal/yr

ETR = 11.5×10^3 solar Cal/Cal

5.2 Electricity

From Table 4, footnote 5.2, electricity = 7.65×10^1 Cal/$m^2 \cdot$yr

(7.65×10^1 Cal/$m^2 \cdot$yr)(4047 m^2/acre)(320 acres) = 9.91×10^7 Cal/yr

ETR = 27.2×10^3 solar Cal/Cal

5.3 Nuclear fuel goods and services

From Table 4, 7.63×10^{11} Cal/yr

ETR = 6.8×10^3 solar Cal/Cal

5.4 Nuclear fuel

543,323 x 10^9 Cal/yr (Table 4)

ETR = 306 solar Cal/uranium Cal

6. Changes related to environmental technology and wastes - ΔW

6.1 Entrainment

Calculation as in footnote 6.1, Table 4

Water through plant = 2862 cfs (NRC 1978, Fig. 3.1)

Mortality = 30%

(2862 cfs)(0.30)(5705 units/m^3)(0.68×10^{-8} kg/unit)(500 Cal/kg·day)(10 day)(2.83×10^{-2} m^3/ft^3)(3.15×10^7 s/yr)

= 1.48×10^8 Cal/yr

ETR = 75.5×10^3 solar Cal/Cal

6.2 Entrapment

Calculation as in footnote 6.2, Table 4, assume proportional to flow

(2.00×10^7 Cal/yr)(2862 cfs/1390 cfs) = 4.12×10^7 Cal/yr

ETR = 85.0×10^3 solar Cal/Cal

6.3 Heat impact

Calculation as in footnote 6.3, Table 4, assume impact proportional to blowdown

(5.58×10^7 Cal/yr)(2862 cfs/53.1 cfs) = 3.01×10^9 Cal/yr

ETR = 200 solar Cal/Cal

6.4 Chemical impact

No change in dissolved solids expected with once-through cooling

Table 7. Comparison of Annual Energy Contributions and Dollar Equivalents for Cooling Alternatives.

Alternative	Source	Total Production Change Solar Cal x 10^{13}/yr: Without Storages	Total Production Change Solar Cal x 10^{13}/yr: With Storages	1980 $ Equivalent§ x 10^6/yr	Difference Between Existing Plant x 10^6 $/yr
Existing plant with reservoir	Table 4	25,418	24,968	3,672	-
Plant with cooling towers	Table 5	25,957	25,934	3,814	+142
Plant on large lake, once-through cooling	Table 6	26,333†	26,322	3,871	+199

§Production including storage losses divided by U.S. global solar energy-dollar ratio (68 x 10^6 Cal/$) from Fig. 2.
†Alternative with greatest increase in productivity.

5

EVALUATING ALL ENERGY FLOWS

Given in Appendix E is a manual for evaluating any or all energy flows at a proposed site. As an example, energy flows are calculated for the LaSalle plant site area before construction when its pattern was agriculture, human settlements, and economic activity. For energy evaluation of alternative choices only those properties expected to change need to be evaluated. The more complete evaluation gives perspectives concerning the basis of value, showing many major and minor environmental energy flows that are interacting in production. Many of these environmental flows are directly and indirectly generated by the sun's energy, some locally and others elsewhere in the biosphere, as part of the general processes of atmosphere, oceans, and earth cycles. When the embodied energies responsible for many of the flows are calculated, they refer to the same original solar energy in whole or in part. For example, winds, rain, waves, and part of the geological energy of the land cycle are drawn from the main solar heat engine working on the oceans.

Estimating the total energy flow contributing to the area requires a procedure for identifying flows that represent the same original energy so that there is no double counting. One way of doing this is to use the largest of the embodied energies that come from the ocean-atmosphere-biosphere and regard those smaller flows as generated by-products of the same processes. For example an area receiving more rain than average has more embodied energy of the sun as rain than it receives as sun or as wind.

To determine such alternatives as whether to build a power plant or not, energy evaluation of the larger area served by the plant is required, considering energy flows with and without the plant. A larger scale of analysis is required than the size of the alternatives to be evaluated.

Table 1 of Appendix A has been superceded by Table 1 and omitted from this reprint.

APPENDIX A*

Energy Analysis, Energy Quality, and Environment

Howard T. Odum

Energy analysis is the modeling of systems accompanied by an evaluation of the energy flows inherent in the system. It includes a synthesis of parts into whole patterns where energy flow is used as the common unit of measure among parts. In practice, energy analysis starts with a diagram of important flows, structures, storages, and process interactions. Such a diagram is accompanied by numerical evaluation and appropriate tabular documentation. This evaluated energy diagram shows simultaneously energy balances, energy transformations, kinetics, material flows, information flows, and work transformations. From this basic energy diagram, various aggregate calculations and simulations can be carried out. These result in an evaluation of the role parts of the system play in maintaining the vitality of the whole. Energy analysis shows common characteristics among systems of different types and suggests new energy concepts.

The energy flows of one type required to support energy flows in another part of the system define the energy cost of that part, and the energy cost is often a measure of the potential value of the part to the system as a whole. The quality of energy is measured by the Calories of one type that can generate a Calorie of other types, and the ratio suggests which features of the system must have large amplifier effects to justify their accumulated energy cost.

As part of the basic science of energetics and systems, energy analysis diagrams have been used for a half century in many fields to show overall relationships and resources. In recent years, as fossil fuel supplies diminish, overall environmental energy analysis procedures have become of special interest for showing the energy basis of the economy of humanity. This is a description of some of the methods of energy analysis as used both to understand the energetics of man and the biosphere and to evaluate alternative choices in energy use. The paper is divided into four parts. The

*Reprinted from: Martha W. Gilliland, ed., Energy Analysis: A New Public Policy Tool. Westview Press, Boulder, Colorado, 1978, pp. 55–78.

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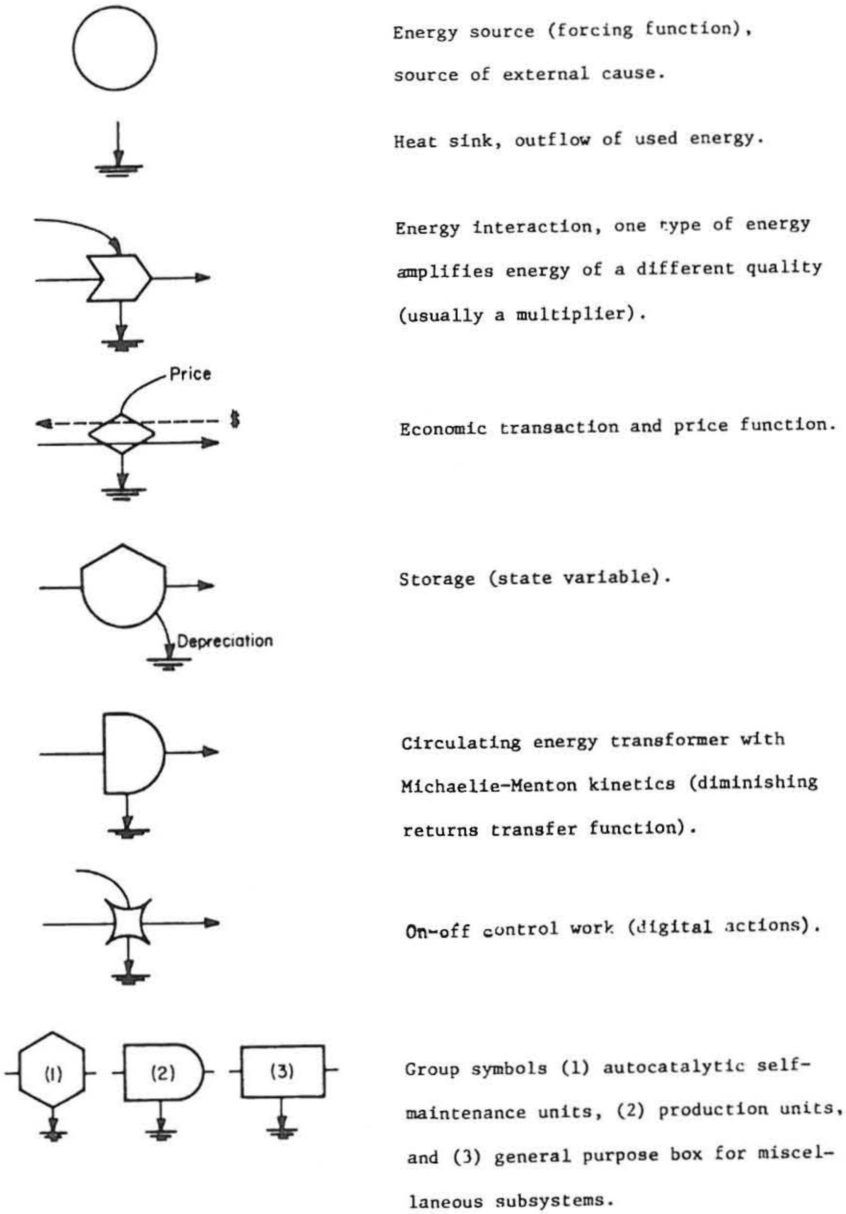

Fig. 1. Energy analysis symbols.

first section includes a description of the basic energy diagram and some of the theory which underlies data preparation. The second section discusses the concept of energy quality, its evaluation, and its significance as a value measure. The third section applies the concept of energy cost and energy quality to real world natural and economic systems. The final section applies these same concepts to some alternatives of special interest in energy policy-making today.

Preparing Energy Analysis Data

Data in several forms are required for a full energy analysis of the system of interest; these data are derived from an evaluation of the heat equivalents of energy flows. Certain theoretical factors which explain the observed patterns of energy flow in many systems aid in data preparation and in diagramming. In this section, the energy symbols used in diagramming are given first along with an example. Second, the evaluated energy flows (as heat equivalents) inherent in the example are given--a first law evaluation. Third, the maximum power theory, which may explain observed patterns of energy flow, is introduced. Fourth, some characteristic webs of energy flow which develop because of the maximum power theory are given. Finally, the concept of energy of equivalent quality is discussed via an energy cost diagram.

Energy Symbols and Diagrams

Although different symbols have been used by different authors diagramming systems for various purposes, the full potential of energy analysis requires that the symbols carry mathematical and energetic meaning simultaneously. For this, the energy analysis symbols in Fig. 1 are available as used and described in many books and papers since 1967 (1). An energy analysis diagram of Silver Springs, Florida, is given in Fig. 2 which shows the flows of energy of many types and in several forms. It indicates how these flows interact as they do work and shows all flows ultimately leaving the system as degraded heat. While Silver Springs is predominately a "natural" system, note that its economic component is included in Fig. 2. As the diagram indicates the work of the natural processes interfaces and attracts the flow of money in tourist-supported developments.

First Law Evaluation; First Law Diagram

The next step after diagramming the system is a numerical evaluation of the energy flows.

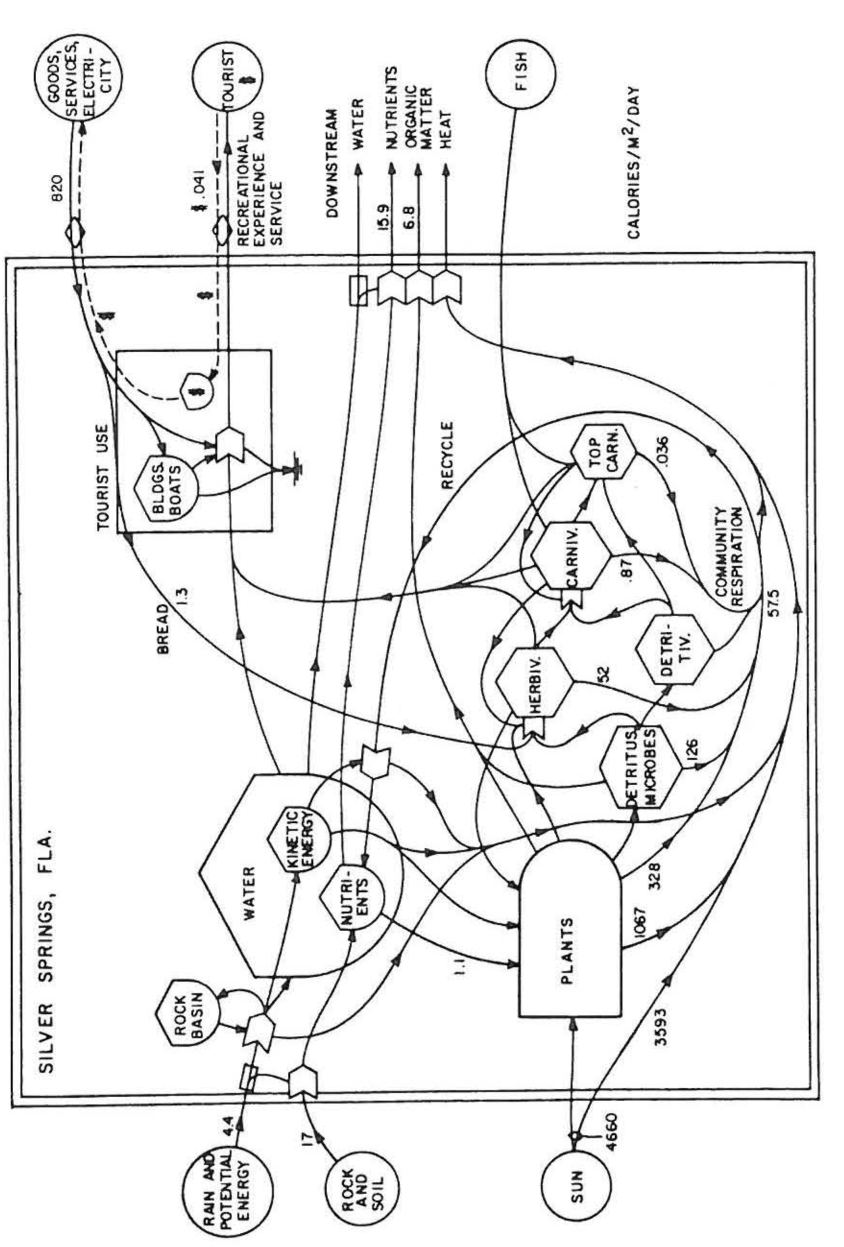

Fig. 2. Silver Springs, Florida, example of an energy analysis diagram evaluated with numerical values of heat equivalents to form a first law diagram (2).

In Fig. 2 the average heat equivalents stored or flowing per time are written on the diagram giving the reader an overview of the pattern of external inflow of resources, the inside storages in structure, the processes, and the feedback control actions. Heat equivalents are the Calories of heat obtained from each form of energy if converted into heat. Since transfer into heat by definition and by the first law is 100%, heat equivalents are the common denominator of all flows. Even flows of material and information have energy accompanying them.

All inflowing Calories must be accounted for in storages or outflows. If the diagram like that in Fig. 2 is in steady state, inflows equal outflows. A heat equivalence diagram is a "first law diagram". There is generally no controversy in concepts about making a first law diagram, although there is ample room for error in getting the pathways and values correct and comprehensive.

Maximum Power Theories

Heat equivalence measures, or first law measures, provide no information about the potential value of the energy for performing some work function. Second law considerations, however, do. More precisely second law considerations in combination with a time measure of energy flow (which allows energy flow per unit time to be maximized) may, in fact, explain why systems develop certain standard organizational designs. The observed patterns of energy flow and transfer in many kinds of systems seem readily explained by the theory of maximum power. This theory, if general, may make possible the restructuring of science to view systems of many kinds as special cases of a few general patterns. The similarity in the design of systems helps the process of energy analysis, since energy diagrams can be drawn more easily when the basic plans for the shapes and configurations of pathways are suspected in advance.

Apparently first clearly stated by Alfred Lotka in 1922 (3), the maximum power principle states that systems which maximize their flows of energy survive in competition. Among the observed properties of real energy webs, which seem to be explained by this principle, are the characteristic patterns in Fig. 3. Here the potential energy in the source is transformed to a new kind of energy represented by the storage. Some of it is degraded in the process and some is transformed into a higher quality form with new characteristics. Some of this stored higher quality energy is fedback in loops to interact with and amplify the incoming flow of low quality energy from the source. Systems develop chains of these storage-feedback units forming discrete

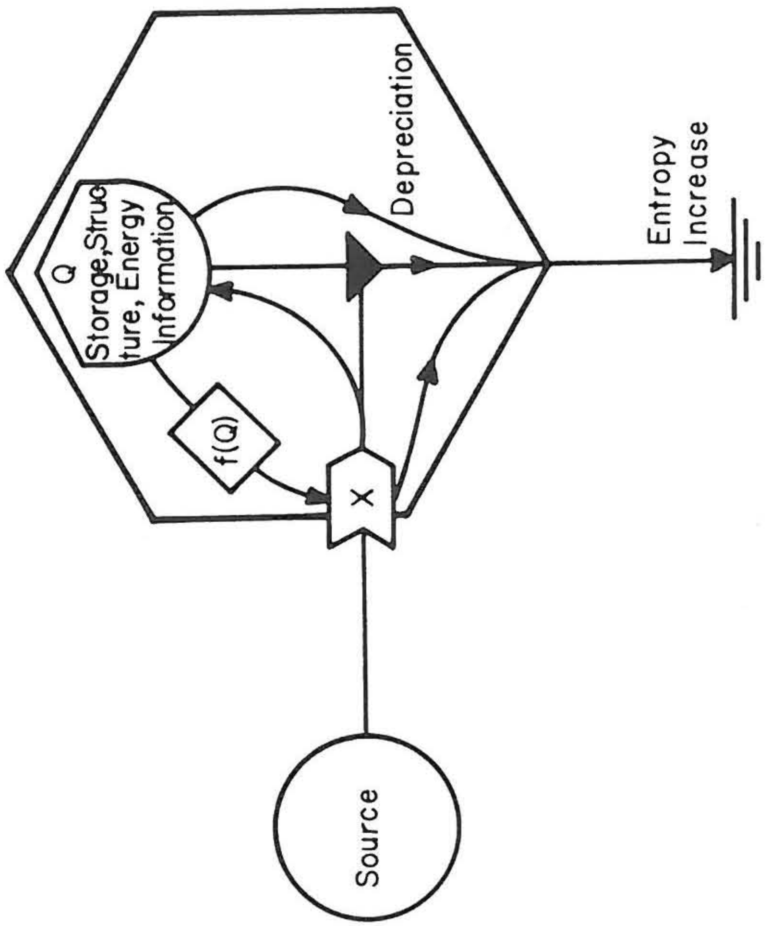

Fig. 3. Typical sub-unit observed in all systems. Note storage, depreciation, feedback, and production (transformation work) process.

energy levels. The transformation of energy from low to high quality via webs of storage-feedback units is apparently what allows power to be maximized in the system.

The objective procedures of energy analysis given here do not require acceptance of the generality of the maximum power principle. However, the possibility that all systems can be easily generalized with these energy principles is responsible for some of the excitement developing in this area of science. Details on the maximum power theories are given elsewhere (1).

Characteristic Webs

Figure 4a shows this web of storage-feedback units found in real systems such as those of the biosphere and the economy of humanity. Note that the flow of energy from a primary source simultaneously generates diverging flows that converge back and interact again. Examining any one storage unit on the diagram suggests that several energy inputs are required to sustain that storage. However, tracing pathways back in the web shows that simultaneous diverging and reconverging pathways provide all inputs, each the by-products of the other. For minimum waste the flows can be adjusted so that no one of the necessary interacting pathways is any more limiting to the storage than another.

When the energy from the source or sources on the left diverge, converge, interact, and loop in the characteristic manner shown, potential energy is degraded and dispersed into the heat sink. It is no longer usable for work. As a result, the pathways on the right have relatively few heat equivalents, although their role as feedback controls may be just as important and essential as the flows with larger heat content on the left. The flows and structures on the right require the flows on the left, and vice versa.

Diagram of Cost Equivalents

After an energy web is drawn and the flows of heat equivalents are evaluated, the diagram shows the manner and extent to which the energy flows within the system depend on the sources of energy. Another copy of the energy diagram can be used to write energy costs on all the pathways. This becomes an energy cost diagram. Figure 4b is an example. It is the same as Fig. 4a but evaluated in energy units of equivalent quality rather than in heat equivalents. The energy cost in solar equivalents of each flow is written on the pathway. Since there is only one source for all flow pathways in this example, all pathways have the same numerical cost value. The values on an energy cost diagram are

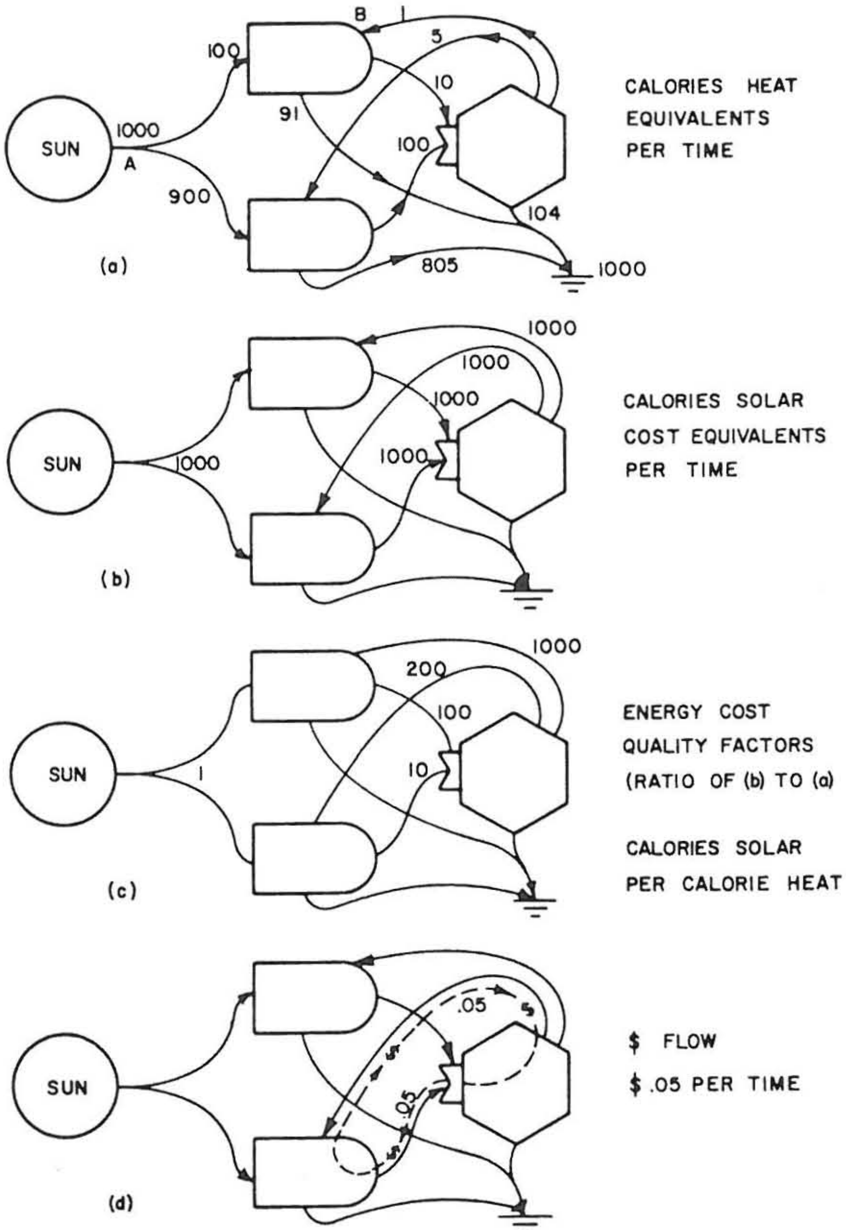

Fig. 4. Typical form of energy web observed. (a) heat equivalent numbers included to form a first law diagram; (b) with solar cost equivalents written on pathways; (c) with solar energy quality factors written on pathways; these numbers were obtained by dividing those in Fig. 4a by those in Fig. 4b; (d) dollar flow.

not additive. Pathways diverging from a production process each have the same cost equivalents. When they reconverge in an interaction process, the output is not the sum of the converging flows. The cost value is that of the flow originally responsible for the interacting flows. In this example, the sun's flow is the cost of all the derived renewable flows.

For several purposes of energy analysis, the equivalent cost diagram is a basic tool for determining which flows are important. In it all numbers are expressed in Calorie equivalents of the same type.

In examples where there are two different outside energy sources, the energy cost equivalents of two interacting flows may be greater than the cost in cases where all flows are mutual by products of one source. In that case, observed energy cost equivalents on the diagram may not be the thermodynamic minimum cost.

Evaluation and Significance of Energy Quality

The discussion above indicated that the heat equivalent of an energy flow does not reflect the energy cost required to sustain the flow. The energy cost of sustaining a flow or a storage is a measure of its energy quality. Many heat equivalents are lost to the heat sink when low quality energy is transformed to high quality energy. The more transformations that occur, the fewer heat equivalents that remain. But, as we have seen, the high quality energy with few heat equivalents is required via feedback to maintain the preceeding transformations. Needed is a means to evaluate this energy quality at each step. This section introduces a method for that evaluation and suggests that energy quality may be a measure of value.

Work and a Scale of Energy Quality Transformation

Maxwell defined work as energy transformation. Represented by Fig. 4a and observed in systems of all kinds are chains of energy transformation in which the Calories of heat equivalence are gradually converted into degraded heat of low quality while upgrading the remaining energy stepwise into higher and higher quality (Fig. 4). For example there are food chains like that in the Silver Springs diagram of Fig. 2. Similar chains occur in the energy transformations of the human industrial economy, in the chains of energy transfer in the earth's processes and the chains of biochemical action in cells, etc.

If a system based on one energy source has been maximized for power transformation with the least waste (as compared to alternative designs), then the ratio of two flows in a web diagram is the efficiency with which one type of energy flow is transformed into another. For example, in Fig. 4a the ratio of B to A is 0.1%. The reciprocal is the number of Calories of one type of energy required to generate another type. In this case, 1000 Calories of flow A are required to generate 1 Calorie of flow B. This energy quality ratio is defined as Q.

$$Q = \frac{\text{Calorie flux of type A}}{\text{Calorie flux of type B}} \quad \text{in Calories per Calorie}$$

If the type of energy which is the input is put in the numerator and the type of energy that results from the transformation is the denominator, then the energy quality ratios are greater than 1. The energy quality idea is simple in chains from single sources. It is simply the energy of one type required to develop energy of another type and is a cost measure of the relative value of two types of energy. The ratio of the two flows of energy in heat equivalents is the energy quality factor for that transformation. It is hypothesized that there is a minimum energy cost for a transformation at maximum power. That cost represents an inherent thermodynamic limit below which no improvement can be made. It is further reasoned that systems that have had a long period of evolution and survival under competition have approached these thermodynamic limits. Thus it is useful to develop tables of energy quality factors by evaluating energy analysis diagrams of long established systems. When there are two sources, energy quality is calculated by expressing one source in quality units of the other type, using energy quality factors relating the two types of energy as independently determined (4). The complex web of varied flows that develops is apparently necessary to maximizing each flow. Cost factors can be given in solar equivalents or in units of some other type of energy. Coal equivalents are often used. An analysis of a system which transforms the energy of the sun into wood and then into heat engines, indicated that 2000 Calories of sun are required to produce 1 Calorie of steam, a Q ratio of 2000 Cal/Cal. Do the geological processes which produce coal from sunlight do better?

Diagram of Energy Quality Ratios

Having drawn a first law diagram and a cost equivalence diagram, numbers for a diagram of energy quality ratios (Q) are obtained by taking the ratio of the cost equivalents to the heat equivalents (as in the example of Fig. 4c). This diagram shows the solar Calorie cost of each Calorie of

other type of energy flow. As one moves further downstream from the energy source, the energy quality ratio increases. Sometimes a table of cost equivalents is used to evaluate the diagram of energy quality factors which is then used with the first law diagram to calculate the diagram of cost equivalents.

Cost and Potential Effect

Procedures thus far have shown how to calculate the energy cost of sustaining some component of a system. But how can the effect of that component on the rest of the system (via its feedback pathways) be evaluated? In other words, what is the value of the pathway to the system? The maximum power theory suggests that the energy cost of a component determines how its feedback flow will interact upstream. For the long selected system, energy costs may have been minimized and energy amplifier effects are similar. In that case, energy cost measures energy effect and, therefore, is a measure of the energy value of the component to the system. In other words, the ultimate potential value of an energy flow is equal to its minimal energy cost, and it may be safe to assume that systems which have existed for long time periods have minimized their energy costs. Furthermore, maximum power theory as well as observed system structures suggests that the development of a web of energy flows which produces many kinds of energy at the same time is the most efficient way to transform energy to higher quality.

For new, developing systems such as some new energy technologies, energy costs may not be minimized as yet. In those cases, present energy costs may exceed their effect. From the maximum power principle, however, it may be postulated that any unit that does not feed back with an amplifier effect that is at least as great as its energy cost may be a liability and will tend to be eliminated.

When humans manipulate the energy flows in the economy, they affect the manner in which feedback flows interact with and amplify the upstream processes. Flows of energy which have high potential value (because of their high inherent energy costs) should be saved for uses with high amplifier effects.

Many new technological mechanisms for energy transformation arranged by man seem simple at first glance. But an energy diagram of those mechanisms (which forces one to identify the sources of energy) indicates that large amounts of high quality energy from a complex web of natural and economic interactions sustains the new mechanism. The new mechanisms may use more energy than natural processes. For example, Kemp (13) analyzed desalination plants and found that the production of 1 calorie of chemical free energy of fresh water required 3.1 calories in energy cost expressed as coal equivalents. This is about 6000 calories of energy cost in solar equivalents and is higher than natural desalination by the sun in world weather processes (3215 cal/cal).

Paradox of the High Energy Cost of Flows of Low Calorie Content

Implicit in this discussion is the fact that the energy cost of maintaining a flow or component increases as the heat calories that flow contains decrease. It is postulated that this concept is general because it is a property of all real energy webs observed. In energy diagrams, such as that given in Fig. 4, the less a flow at the right seems to involve heat equivalent energy, the more heat equivalent energy there is behind it making that flow possible. Flows of valuable materials, information, human service, etc. seem to be low in energy whereas the energy flow that makes them possible may be very large.

Webs of Energy Flow in Nature and in the Economy

This section applies the concepts developed thus far to some examples of real world energy webs. By applying the concepts of energy cost, energy quality, and energy effect as well as the possibility that systems organize themselves into webs which maximize power, a great deal of insight into how real world systems function is possible. First consider the earth's surface and its biosphere where the energy web is mainly based on solar energy. Second, consider energy webs controlled by humans with economic components.

Solar Based Energy Web of the Biosphere and Earth's Surface

Usually the flows of energy in the biosphere are considered in parts as dictated by such discipline boundaries as meteorology, oceanography, and geology. But energy flows across discipline boundaries in the real world. The real world biosphere system operates as a web with all parts working in unison. Fig. 5 represents an attempt to diagram the many kinds of energy transformations and feedbacks that take place in the biosphere as it develops the wind, waves, and rain and its land cycles, chemical transformations and biological productivities. In the process of diagramming the biosphere model, many controversial questions were raised. Before all the pathways can be evaluated with confidence, some of these questions will need detailed analysis and some

require advances in science. Current calculations in heat equivalents are given in Table 2 and on Fig. 5 (a first law diagram). Part of Table 1 was assembled from the ratios found.

The point is that energy analysis models are one way of stating hypotheses for further testing. For example, according to older theories, the uplift of land in mountain building receives energy from the residual temperature gradient between the deep earth and the surface (note the flow from residual deep heat to continents in Fig. 5). An alternative theory, which emerged as Fig. 5 was being developed, is that there is enough energy from the sun going into crustal work to drive most of the uplift cycle. Note (Fig. 5) that energy from the sun becomes part of uplift processes through the hydrological cycle, through chemical potential energy deposited in sediments from photosynthesis and other biosphere activities, and from the heat from radioactive substances that are concentrated into the surface cycle by differential photosynthetic, sedimentary, and geothermal activity.

The heat emerging from the earth as potential energy is about 1.27 calories per square meter per day (12). For a temperature gradient of 300°C (from 600°C to 300°C over a depth of 35 km) the Carnot efficiency with which work could be done is 50%. Such a system, if operating at maximum power, might do mechanical work with 25% efficiency and produce 0.32 calories per square meter per day as mechanical work. Figure 5 shows more than this much work in rivers. The photosynthetic production buried in sediments is large enough to account for a good part of the emerging heat.

Energy Webs Controlled by Humans

Where pathways in a web are controlled by humans, money circulates in closed loops and flows as a counter current to the flow of energy (see Figs. 4d and 6). How and under what circumstances are the money flows and the energy flows related?

In order to examine the relationship of energy and money, we consider four cases: the relationship (i) at the point where energy obtained externally enters a system, (ii) within a circulating money-energy loop internal to a system, (iii) in the overall U.S. economic system, and (iv) in circulating money-energy loops at the end of the system web (the terminal or most down-stream point in the system).

Consider Fig. 6 in examining the point where energy enters the system. Money (the dotted lines on Fig. 6) circulates around the feedback loops involving humans but not around the pathways of the environmental systems nor does it flow out of the system toward the sun or fuels in the

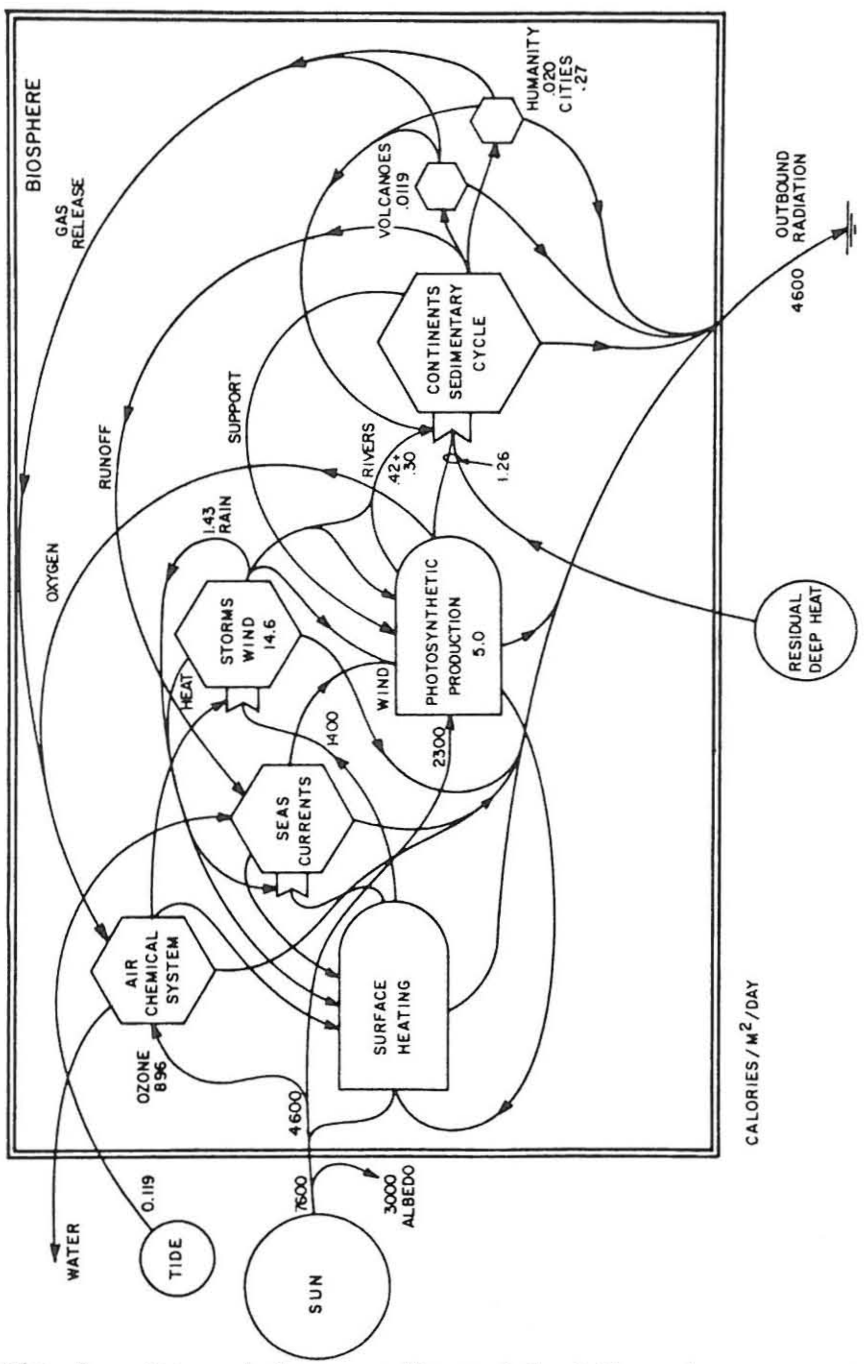

Fig. 5. Aggregated energy flow model of the main processes of the earth's surface and the biosphere. See Table 1 for numbers.

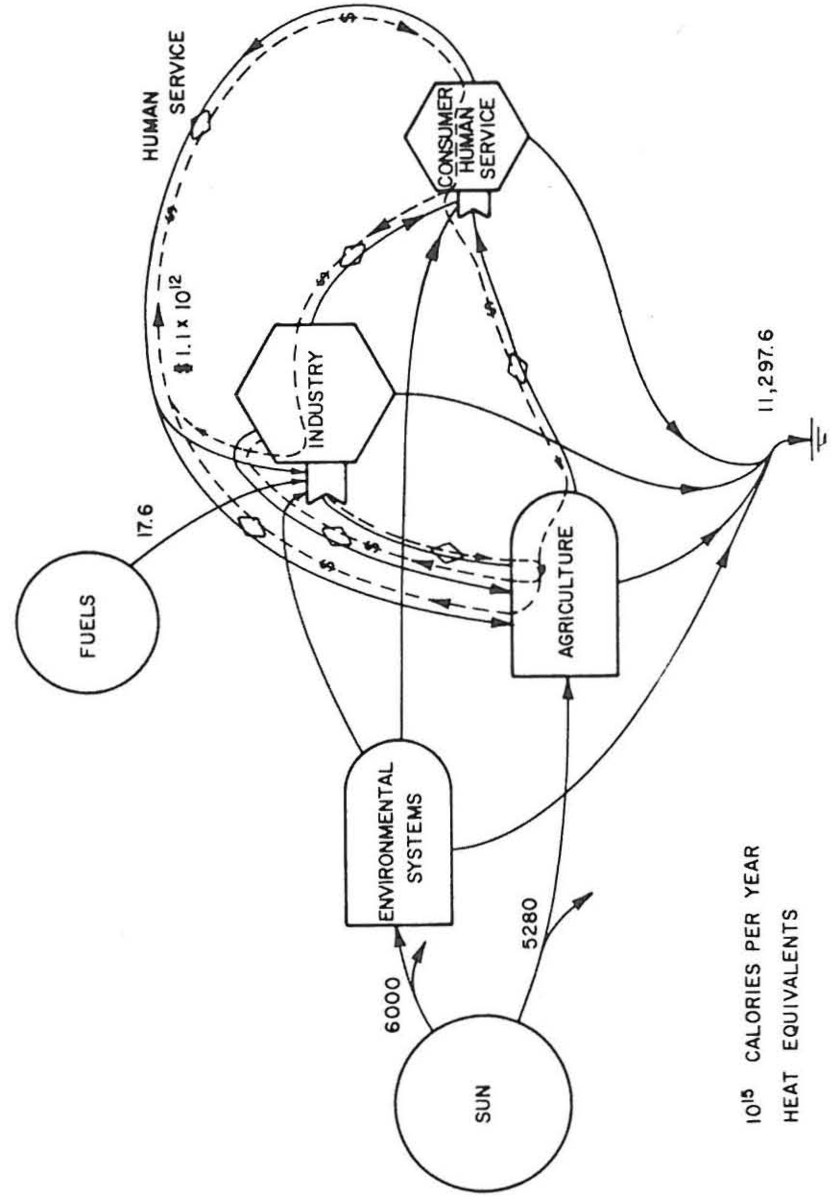

Fig. 6. Energy flow in an aggregated economic model that shows the relationship of human service as high quality feedback in the U.S. Personal income, farm area and fuel use for 1974 (U.S. Statistical Abstract).

Table 2. Estimates for environmental energy flows of the biosphere in order of quality. See Fig. 5.

Type of energy	Table footnote	Heat equivalents Calories/m^2/day
Solar energy not including albedo	1	4600.
Solar energy reaching surface including heat reradiation from sky	1	9000.
Evapotranspirational energy flux	1	1400.
Ozone absorption process	2	896.
Wind and storms	3	14.6
Photosynthetic productivity	4	5.0
Potential energy of rivers against gravity over continents	5	0.42
Potential energy of rain purity compared to sea water over land	6	0.30
Tide	7	0.119
Human labor	8	0.020
Volcanic activity	9	0.0119
World fuel consumption	10	0.265
Gravitational work of land uplift	11	5.0×10^{-9}
Seismic activity	12	1.92×10^{-5}

1. Sellars reference (10). 2. 13% of insolation, Ryabchikov (9). 3. Hubbard (8). 4. reference (9).

5. River runoff, 37,000 km^3/yr; average elevation, 875 m (9)

$$[(10^2 cm/m)(3.7 \times 10^4 km^3/yr)(10^{15} cm^3 km^2)(875\ km)(1\ g/cm^3)(10^3 cm/sec^2)(2.38 \times 10^{-11} Cal/erg)] \div [(365\ days/yr)(5.1 \times 10^{14} m^2\ \text{area of earth})].$$

Footnotes to Table 2 (continued)

6. Calories free energy per gram of water = RT ln (100/97.5)

$$\frac{(2\ Cal/deg.\text{-}mole)\ (300\ deg.)\ (0.0154)}{(18\ g/mole)\ (1000\ g\text{-}cal./Cal.)} = 5.1 \times 10^{-4} Cal./g$$

Continental rain, 109,000 km^3 (9).

$$[(109{,}000\ km^3)(10^{15} cm^3/km^3)(1\ g/cm^3)(5.1 \times 10^{-4} Cal/g)] \div [(5.1 \times 10^{14} m^2/earth)(365\ days/yr)] = .30\ Cal./m^2/yr.$$

7. .0058 watts/m^2 (8); unlike other flows, tide is not from sunlight.

8. $$\frac{(4 \times 10^9\ people)\ (2500\ Cal./person/day)}{(5.1 \times 10^{14} m^2/earth)} = 0.02\ Cal/m^2/day$$

9. .00058 watts (8).

10. 1970 3 x U.S. consumption

$$\frac{50 \times 10^{15} Cal/yr}{(5.1 \times 10^{14} m^2/earth)\ (365\ days)} = 0.265$$

11. 3.6 cm uplift per 1000 years (7); 29% of earth surface continental (9)

$$[(10^3 cm/sec^2)(3.6\ cm)(.29\ continental)(3.6\ cm)(2\ g/cm^3)(2.38 \times 10^{-11} Cal/erg)(10^4\ cm^2/m^2)] \div [(365\ days/yr)(1000\ yrs)]$$

12. (1500 x 10^{20} ergs/yr (11)

$$\frac{(1500 \times 10^{20})\ (2.38 \times 10^{-11} Cal./erg)}{(5.1 \times 10^{14} m^2/earth)\ (365\ days/yr)} = 1.92 \times 10^{-5}$$

ground. Clearly, the amount of work (energy effect) that goes with the circulating flow of money depends on those external inflows from the sun and fuels. But the money flow, at the point where external energy flows into the system, buys only the work that is being fed back from the economy that processes the energy. At that point, money does not reflect the eventual effect of the external energy. Therefore, the money flow at that point is not proportional to the amount of energy entering from the external source.

Second, consider the relationship of money to energy within a loop internal to the system. How do economic price mechanisms affect these internal energy flows? By eliminating limiting factors, the price mechanisms of an open market tend to facilitate the maximum flow of power through the whole network. For example, when a commodity becomes scarce and the price rises, more money (and thus more energy) flows through that pathway from upstream; that is, more money flows through the pathway in which the shortage occurs. The result is elimination of the shortage. When a commodity is scarce, obtaining some of that commodity results in more energy effect than under non-scarce conditions (because obtaining the commodity opens a bottleneck of flows). Thus, that commodity is temporarily more valuable and justifies more energy cost. It is well established in economics that money flows into a pathway in response to the marginal effect of that pathway as a limiting factor. More money flows toward the commodity that is limiting output than toward any other commodity involved in producing the output at that time. It appears then that money flows are proportional to energy costs when energy costs and energy effects are equal. Fig. 4 represents such a case. However, in the more usual examples of the present time where the economy is in a transient state and is heavily subsidized by fossil fuels, some energy flows are being used with less energy effect than their energy cost. In these cases, money flow and energy costs are not proportional. Separate money and energy diagrams identify such cases. To show the full facts of systems of energy and economics, a separate diagram of money flow should be included with the first three already mentioned (Fig. 4d).

Third, consider the case of the U.S. economic system. The overall money circulation (real GNP) can be related to the overall rate of energy inflow as a Calorie to dollar ratio. This ratio changes with time and measures overall inflation. The ratio of energy inflow to dollar of GNP decreases with inflation. While one can calculate an energy to dollar ratio where the energy counted is only that of concentrated fuels, a more meaningful ratio includes all sources, solar energy as well as fossil fuels. As indicated by Fig. 6 and others, the money flows depend on solar energy

(as it is processed by the environment) as well as on concentrated fuels. Several questions were raised at the symposium about the possibility of double counting where the ratio of GNP to total energy flow is used to estimate the approximate energy contributions of goods, services, labor, and other inputs to a sector. These questions are addressed in a note (14).

The final case is that of the money-energy relationship at the end or termination of the web. In a system like that of Fig. 6, the high quality pathways at the end of the web (the far right on the diagram) contain a flow of energy which is the convergence of most of the energy interactions. These terminal flows may have nearly the same ratio of energy (in cost equivalents) to dollars as the overall system does. Given data on the flow of dollars in these terminal high quality loops, an estimate of the energy flow (in energy cost equivalents) can be obtained by multiplying by the energy flow/dollar flow ratio for that year.

Among the high quality loops at the high quality end of a web are the feedbacks of human service. These have very high energy quality factors and high amplifier control actions at their work interactions. Energy to dollar ratios are appropriate for estimating the energy cost involved in these feedbacks. The Energy Quality of a medical doctor's service may be as high as 4×10^{12} solar Calories per Calorie.

Considerable controversy exists as to what part of the energy support of humans as consumers is a regular necessary part of the support of the feedback. Maximum power theory and experience in analyzing systems suggests caution in dismissing as unimportant any part of a working and competing system. Because of its high quality and thus high energy cost, human service is the major part of any energy analysis and cannot be omitted.

Evaluating Alternatives

After energy diagrams are prepared and energy quality factors estimated, special calculations can be made to suggest which features of a system or proposed system are energetically important. Examples of such calculations are given in this section for some cases of special interest in energy-environmental policymaking.

Evaluating Net Energy

Net energy is the difference between the yield of energy and the feedback required in a process, where both flows are expressed in Calorie equivalents of the same type. A net energy calculation is made to evaluate a single source to

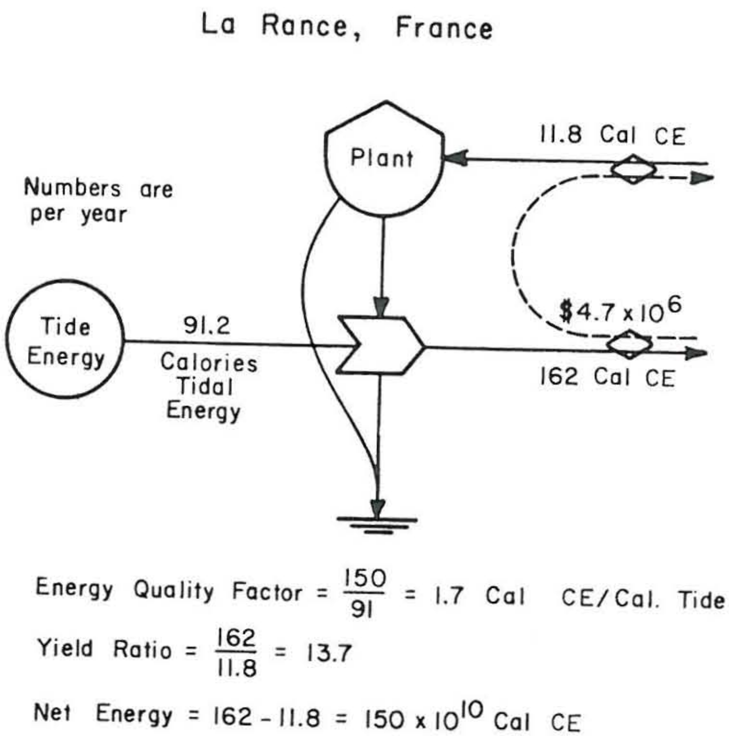

Fig. 7. Example of net energy evaluation of a single source. Tidal energy converted to electricity. Both electricity and feedbacks of goods and services are converted to cost equivalents of the same type (fossil fuels as used in heat engines abbreviated FFE).

determine how important its contribution is. Figure 7 is an example. As in procedures previously described, heat equivalents of the flows are determined first. Then using tables of quality factors, solar or coal cost equivalents are estimated and written on the diagram. The difference between yield and feedback is the net energy (Y-F).

To interpret the importance of the source to the economy, the ratio of the yield to feedback is calculated. High ratios mean that the source can support the development of more activity in the economy downstream to the right. When the yield ratio is small, there is little energy to support activity other than that which supplies the necessary feedback. A system with only one source which has developed a steady state has no net energy since it feeds back energy of equal cost to that delivered (as illustrated by Fig. 4b). Where there are several sources and/or where there is growth with feedbacks not yet fully developed, analysis of a single source (as shown in Fig. 8) can indicate the role of that source in supporting more economic development. A whole system which is in steady state has no net energy; it feeds all of its work from net energy sources back to amplify interactions, subsidizing other sources, and maximizing power (as illustrated by Fig. 6).

The U.S. is running now on many sources with yield ratios of about 6 units yield for 1 fed back.* Sources with higher yield ratios than this are good primary sources and contribute more to the economy. Sources with a lower ratio are being partially sibsidized by the main economy, since they yield less per unit received back than their competitors.

As was indicated earlier the amount of circulating money associated with the production of an energy source does not indicate the energy contribution of that external source. It only affects the overall energy to dollar ratio later. A source need not be a good one (competitive) or have net energy to be economic.

Evaluating Secondary Sources

A secondary source is one that does not yield net energy although it does bring in additional energy to the system

*In calculating the net energy and yield ratios of primary energy sources using the method described here, the energy costs include those associated with concentrated fuels, labor, and solar energy as it is processed by the environment. All of these are necessary inputs and are present in the feedback loops which allow the source to be develop. All must be evaluated in equivalent energy cost units prior to summing.

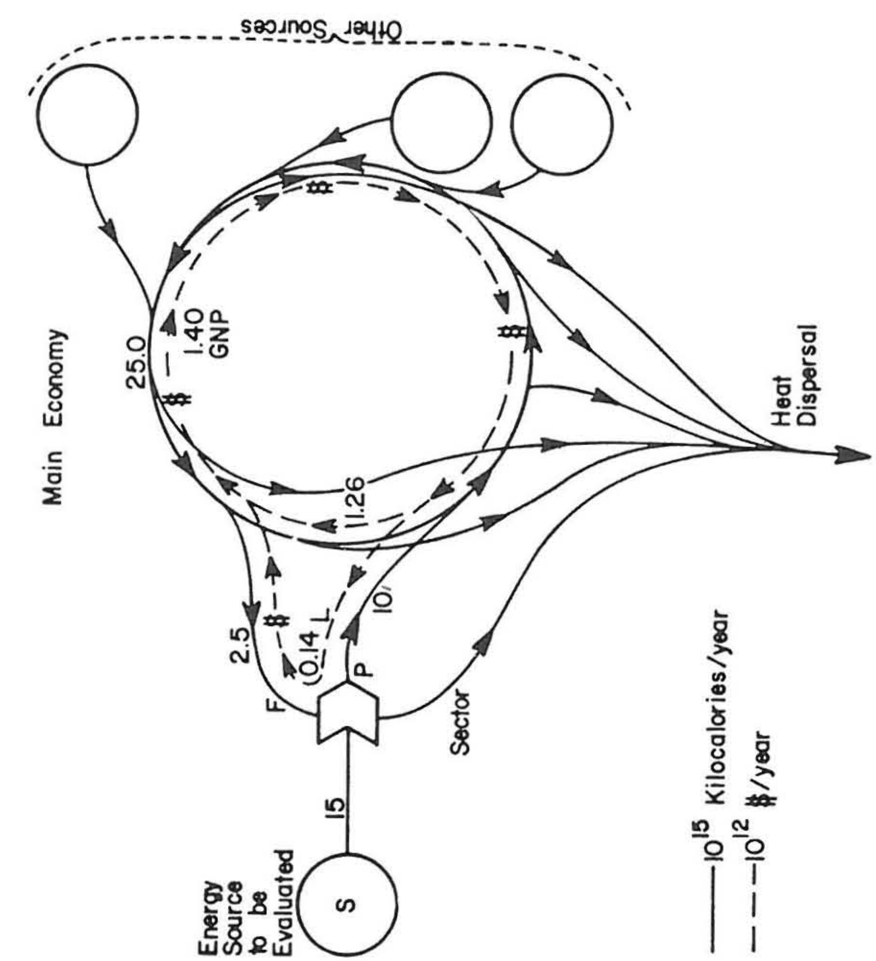

Fig. 8. An example of evaluation of an economic sector and source.

from the outside. A secondary source receives more energy in feedback than it draws from the environment, where both are expressed in Calorie cost equivalents of the same type. However, secondary sources are a major, necessary part of systems that have an excess of high quality energy from one or more primary sources. High quality energy does not generate effects commensurate with its energy costs unless it can interact with large quantities of low quality energy such as sunlight. For example, energy in rivers and fossil fuels must be used in interaction with landscapes and solar energy to generate as much work as these sources cost. The more the high quality energy can be spread out to interact with the solar energy the greater amplifier action it may have. Examples are irrigation, tourism, forestry, and fisheries. All of these depend on high quality fossil fuel sources which feedback, interact, and amplify the solar energy required for crop production, forestry, fisheries, and tourism. But as these systems are now operated, solar energy is a secondary source and the high quality fossil fuels are their primary energy source.

Evaluation of the secondary source interaction with high quality feedback is done in the example given in Fig. 8. Heat equivalents are evaluated first. Then cost equivalents of the same quality are evaluated. Then an investment ratio is calculated. The investment ratio is the ratio of feedback to the flow of new resource, where both are expressed in Calories of the same quality. A source is competitive when high quantities of new external energy are brought in per unit of feedback energy invested to make the process possible. In the U.S. as a whole, a usual ratio of feedback to inflow is 2.5 to 1 (both in energy units of the same quality), 2.5 Calories of energy invested via feedback for each 1 Calorie that investment brings in externally. Ratios lower than this are economic; ratios higher than this tend to be less competitive.

Evaluating Consumer Feedbacks

Some of the higher quality feedback loops of systems, such as human medical and governmental service, feedback their work with little direct interaction with external energy sources. Their contribution to maximizing power in the system is in providing special mechanisms, materials, parts, controls, and information. Evaluating their contribution involves comparison of their energy cost with their energy effect. Energy costs can be obtained from the basic energy diagrams showing the energy flows required to develop feedback. The effect, however, can be determined only by disconnecting the pathway and observing the energy flows with and without the feedback interaction. Often these numbers are found by comparing similar systems which differ in having the concerned pathway. Often simulation models are used. This concept of consumer feedback with consequent amplifier action on the whole system can be illustrated by three examples, one involving no humans and two where humans are essential.

A tropical forest plantation of Cadam trees in Puerto Rico has a productive net yield of photosynthesis 20 g/m^2/day (80 Calories/m^2/day wood equivalents) as a monoculture without many consumers (5). In contrast, a fully developed ecosystem nearby (with fully developed consumers feeding back in an organized manner) showed an increase in this basic primary production. An increase of 7 g/m^2/day (28 Calories/m^2/day), most of which was used by the consumers without any net energy, was measured. The system with consumers contained more energy flow (power) than the same system without consumers. Most of the web of producer-consumer interaction was required to maximize power.

In systems involving human consumers, many think of human consumption as the terminal purpose of an economy. In contrast, human consumers really act as units which feedback services necessary for maximizing power under competition. Agriculture and space heating provide two examples.

Only in primitive subsistence agriculture was crop production a primary energy source that yielded net energy. In subsistence agriculture, yield ratios are about 2 to 1. By the time human activities are coupled back into the system, the yield ratio is closer to 1 to 1. Most industrial agriculture now receives more energy (in the form of fossil fuels) back from the economy than it yields (all energies measured in cost equivalents). Thus industrial agriculture is now a secondary source of energy. It is characterized by ratios of feedback to inflow energy of 2-10 to 1 (yield ratios of 0.1 - 0.5 to 1). When agriculture (or other similar solar technologies) are carried out in tiny areas such as greenhouses, ratios of feedback energy to inflow energy are very high, 1000 to 1 or more (both in Calorie equivalents of the same quality), or yield ratios of 0.001 to 1 or less. Since they take far more energy from the economy than they contribute, such operations are not sources of energy. Rather, these operations are consumer devices that use solar energy to aid the flow of some other kind of energy. For example, greenhouse vegetables could be necessary for the health of human beings on a desert island; the amplifier action would be that of the health differential and the energy cost would be justified because of its effect on human health. The energy effect is to increase the power flow of the entire system (because the human population is healthier and can interact and do more work in other parts of the system).

Neither a gas water heater nor a solar water heater yields net energy. A gas water heater takes 1½ Calories to generate 1 Calorie of hot water. An evaluation of solar water heaters as an energy conservation action (in comparison to natural gas heaters) suggests a savings ratio of 4 Calories per Calorie; the system does still not yield net energy. However, space heating is clearly required for human productivity. It should be viewed as a consumer device which is energy costly, but which is also energy effective via all of the feedback pathways involving human productivity.

In summary, excess energy goes to consumers who feedback with an amplifier effect and make the whole system more effective. Undoubtedly in times of expanding energy, a system, which is already ahead of others in competition for power, generates net energy that goes to consumers but does not immediately feedback to amplify some other flow in the system. The maximum power theory suggests that such unlooped consumer flows are fairly random, but are creative, and after later selection, effective feedback interactions develop. As energy excess decreases and growth slows, those feedbacks with greatest effect will survive; unlooped consumer flows will not. In order to plan for times of decreasing net energy, it is important that we begin evaluating the energy cost and energy effect of the multitude of consumer feedback loops existing in our economy.

Evaluating Energy Conservation Alternatives

Measures proposed to conserve energy can be evaluated on a Calorie per Calorie basis. The feedback of conservation service such as providing housing insulation or improving car efficiencies can be evaluated in Calorie cost. Calorie savings can then be compared to the Calories fedback in the savings effort (where both are expressed in energy equivalents of the same quality). If the ratio of savings to feedback is greater than one there is a net energy contribution. The feedback is usually one of high quality goods and services, and data are usually expressed in dollars. The U.S. Federal Energy Administration has sometimes used the ratio of dollars spent to energy saved. This ratio is about the same as the ratio of energy spent to energy saved, since feedback of high quality goods and services can be evaluated with an energy to dollar ratio.

Evaluating Environmental Impact

The use of energy diagrams and energy analysis for evaluating environmental impact has led to some exciting, if

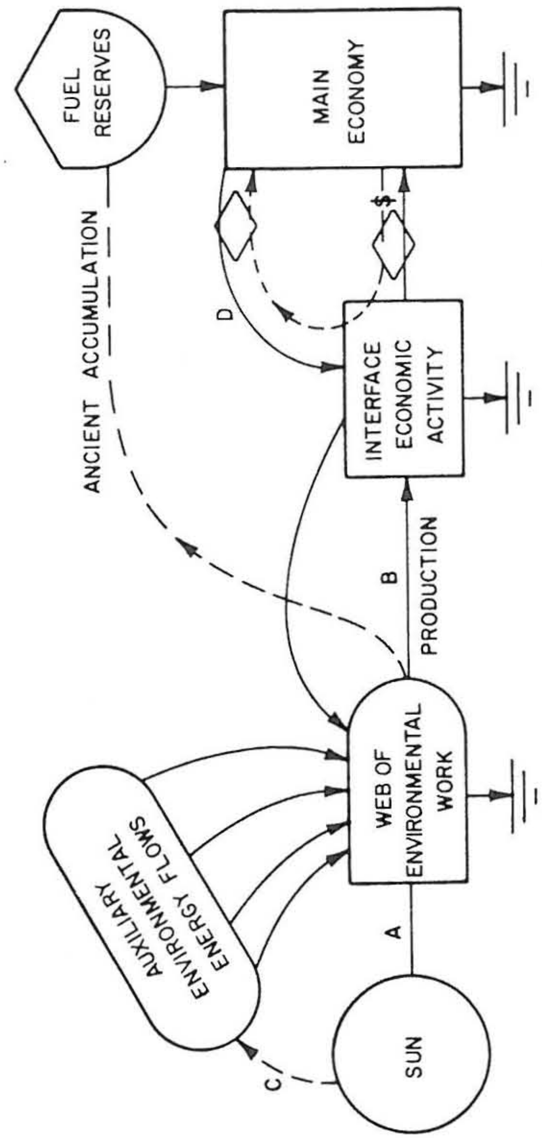

Fig. 9. Summary of energy flows of the environment attracting additional energies of investment and economic development. Cost equivalents are evaluated at A or B and related to actual or potential energy flows attracted at D.

controversial, insights into the appropriate use of environmental control technologies. Environmental control techniques are energy costly. The maximum power principle suggests that their energy effect in maintaining human health (e.g. a flue gas desulfurization system) and in maintaining environmental flows or fisheries (e.g. tertiary sewage treatment plants and cooling towers) ought to be at least equal to their energy cost and should involve external solar energy where possible. The investment ratios of these systems (e.g. the ratio of energy invested in a tertiary sewage treatment plant to the energy flow that investment involves in solar energy interaction) ought to be as low as possible. Our analyses at the University of Florida indicate that some advanced technologies have very high investment ratios. In these cases, the energy flow in the environment that is maintained or even amplified by the technology is too small to justify so much economic investment. Technologies with high investment ratios are poor users of the conservation dollar.

A better fit of humanity and nature is obtained by coupling the wastes of the economic system to the natural systems through interface ecosystems which can make more use of solar energy. Fig. 9 shows a general format for evaluating such energy interactions with the environment. An example is the recycling of treated sewage into cypress swamps as was carried out in our Florida experiments (Fig. 10). Compare the investment ratios of two alternatives for handling secondary sewage. A tertiary sewage treatment plant might be invoked to remove the nutrients from the effluent prior to its release into a river. The investment ratio for that alternative is 100 to 1 or more. At least 100 Calories of energy are invested in the treatment plant for each Calorie of productivity in the coastal zone involved in the process (all Calories equivalent in quality). The alternative evaluated in the Florida experiment called for cycling the secondary treated sewage directly into a cypress swamp. The wastes were absorbed or transformed and valuable wood growth accelerated. The energy investment in the system (D in Fig. 9) was 11.5×10^6 Calories (coal cost equivalents) per year per acre and represented mainly the cost of pipes and pumps. The energy flow from the swamp (expressed in coal cost equivalents) was 3×10^6 Calories per acre per year (B in Fig. 9). The investment ratio (the ratio of D to B in Fig. 9) is 3.8 to 1, a vast improvement over the 100 to 1 ratio involved in a tertiary sewage treatment plant.

Furthermore, the mining and manufacturing processes required to assemble raw materials into a treatment plant depend themselves on environmental energy flows. We have seen over and over again through these energy diagrams that the

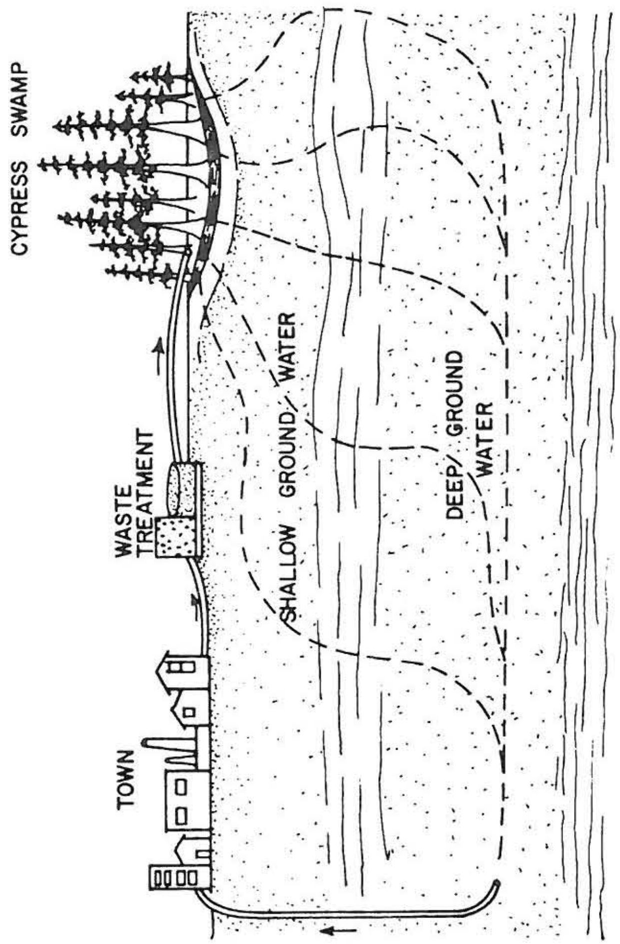

Fig. 10. Example of using a cypress swamp as an interface ecosystem to recycle wastes and maintain a high ratio of useful solar energy to purchased goods and services from the economy (6).

economic processes with which money is associated rarely take place in the absence of environmental processes (based on solar energy). The economic processes both interact with and depend on the environmental ones (e.g. manufacturing depends on the wind to dilute and disperse its air pollutants). The processes of mining and manufacturing utilize and load the cleansing capacities of these environmental flows. For 100 units of energy invested in the tertiary sewage treatment plant about one third is environmental loading elsewhere. (The U.S. energy budget matches 2.5 coal equivalents of fuel energy with one coal equivalent of renewable environmental energy). In the case of the treatment plant, utilization of 33 units (100 x 1/3) is more than the 1.3 units (3.8 x 1/3) required for the recycling system. In addition to being poor investments, the distinct possibility exists that advanced environmental control technologies actually cause more environmental degradation than they alleviate.

Summary

Energy analysis is the basic science of energetics of open systems, which considers laws and principles by which energy flow generates designs of structure and process. A language of energy symbol diagrams helps develop models and organize data for analysis and synthesis. Understanding the contributions of external energy sources and internal mechanisms is aided by preparing diagrams: (i) a first law diagram of heat equivalent flows, (ii) a diagram with energy costs expressed in Calories of the same quality, (iii) a diagram with energy quality factors as related to sunlight or coal and (iv) a diagram with money flows. Energy analysis studies are generating new concepts of energetics, systems organization, power spectra, and the energy basis of economics.

Practical application of energy analysis includes calculations of net energy to evaluate primary sources, calculations of an energy investment ratio to evaluate secondary sources, calculation of energy savings ratios to evaluate energy conservation ideas, and calculation of energy effectiveness ratios to evaluate which consumer roles are competitive.

Because of its generality, energy analysis may be useful as a point of departure in general education of students learning the unity of the world system of humanity, economics, and environment.

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14. Double Counting Questions: Figure 8 shows the flows of energy and money in the general economy. It includes free environmental energies and external fuels from deposits which are also free since their external pathway is not accompanied by money. All Calories must be in cost equivalents (not heat equivalents). The rough proportion is used to estimate the energy feedback (F):

$$\frac{\text{Energy feedback (F)}}{\text{Total energy (T) including environmental inputs}} = \frac{\text{Money flow in Loop (L)}}{\text{Total GNP}}$$

In the example shown this is:

$$\frac{F}{25 \times 10^{15}\text{kcal/yr}} = \frac{0.14 \times 10^{10}\$/\text{yr}}{1.4 \times 10^{12}\$/\text{yr}}$$

$$F = 2.5 \times 10^{15}\text{Kcal/yr}$$

Because some of the energy of sources goes into the economy and back to the sector as goods and services, one must correct for double counting for some purposes. When diagrammed with energy circuit and money flows as shown in Figure 8 there is no question about what is meant and no question about what is the correct answer to the net energy questions.

If the question is: how much of the energy of the main economy is feeding back with feedback F, the answer is 2.5×10^{15}Kcal per year of which 40% was originally from the source S, since source S with 10×10^{15} Calories is 40 percent of the total of 25×10^{15}. If the question is what is the net energy contribution of source S., then one subtracts F from P. In the example $10 - 2.5 = 7.5 \times 10^{15}$Kcal net energy in fossil fuel equivalents. The yield ratio P/F is 10/2.5 or 4/1. In this example the sector is a net producer supporting other sectors.

Suppose the question asked is, "What are the ultimate energy sources for the sector?" In Figure 8, to obtain the total energy basis of the sector one should add the inflow from source (S) to 60% of the feedback (F), since this is the amount of F that is from entirely different sources.

15. The work was supported by the Energy Research and Development Administration through contract E-(40-1)-4398 with the University of Florida and by the National Cooperative Highway Research Program of the National Research Council through a contract with Cornell University.

APPENDIX B

COMPARISON OF ENERGY ANALYSIS AND ECONOMIC COST-BENEFIT PROCEDURES

1. CONCEPTS

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Table B1 presents some of the basic theoretical assumptions of both energy and economic analyses. Related assumptions are shown adjacent to each other so that similarities and differences between the two forms of analysis may be easily identified. The discussion in this appendix may help lead the reader through the comparisons that are outlined in the table.

When comparing alternatives, the goals of economic and energy analyses are generally very similar but have one important procedural difference. The overall end of both forms of analysis is to identify the alternative that provides the system of concern with the most production. However, different procedural goals are pursued as indicators of that end. Economic analysis seeks to identify the alternative that has the minimum total cost or the least use of scarce resources. Thus, in economics the assumption is made that production is maximized for the system when efficiency of resource use is maximized. Energy analysis seeks to identify the alternative that accomplishes the most work or that provides the system with the most energy resources. Thus, although energy analysis seeks maximum production for the system, it does not assume that it is necessarily achieved by maximizing efficiency. Instead, as discussed below, energy analysis gives explicit consideration to time and assumes that an optimum balance of efficiency and speed of resource use will maximize production.

Conceptually, both economic and energy analyses have universally applicable classifications of resources that are assumed to carry value. In economic analysis, resources of value are called scarce resources, which may be land, labor, and/or capital. Any resource may be scarce and may be classified as land, labor, or capital. In energy analysis, the basic resource of value is embodied energy, which is the total of direct and indirect energy flows required to produce a given resource when produced at optimum efficiency for maximum system production. In practice, embodied energy is assumed to be generated largely from past and present solar energy, and all resources carry that embodied energy. Although energy and economic analyses define valuable resources in different ways, both definitions may apply to any resource in the global system.

There is a potentially important difference between economic and energy analyses regarding

Table B1. Comparison of Theoretical Assumptions.

Parameter to be Compared	Economic Analysis	Energy Analysis
Goal of Analysis Procedure	Identify the alternative that has the minimum total cost (including both internal and external costs, i.e., all costs to the total system of concern) or Identify the alternative that causes the least use of scarce resources within the system of concern	Identify the alternative with which the system of concern accomplishes the most work per unit time (power) or Identify the alternative that provides the system of concern with the most energy resources
Resources of value	Scarce resources (summarized as land, labor, and capital available to the system of concern)	Embodied energy (summarized as the minimum total amount of energy required, directly and indirectly, to provide a given product when the system of concern is operating at optimum efficiency for maximum power)
Substitutability of valuable resources in production processes	Scarce resources (land, labor, and capital) may substitute for each other	There is no substitute for embodied energy. System may reorganize to substitute embodied energy of one source for another
Effect of time on value	There is a time component of value operating such that a resource controlled now is usually more valuable for satisfying wants than the same resource controlled later	Numerical values of energy and embodied energy don't change, but energy storages may increase relative competitive position during growth. Speed of energy use affects efficiency of effect
Model for valuing a resource	A system of economic markets with monetary transactions, operating with competition for satisfying wants with the least use of scarce resources	A unified global system of man and nature with energy transformations operating under competitive conditions in which there is the best possible efficiency consistent with system-wide maximum power loadings

Table B1. (Continued)

Parameter to be Compared	Economic Analysis	Energy Analysis
Mechanism for valuation	The market-pricing mechanism, which identifies, for each transaction in the economy, the balance of a resource's marginal cost and its marginal utility	The maximum power mechanism, which identifies, for each type of energy transformation, the total direct and indirect energy requirement when the system is operating under competitive conditions in which there is the best possible efficiency consistent with maximum power loadings. Those conditions represent an optimum balance of efficiency and speed
Boundaries of concern for valuing a resource	A local, regional, national, international, or other economy of man and scarce resources. In practice, evaluations are often limited to the system of markets within that economy and consider effects for an unspecified but usually limited time into the future	A global system of man and nature (i.e., large enough to account for all feedback effects), considering effects as far into the future as they may occur (i.e., allowing for full life-cycle effects)
Value relationship between the cost of a process's inputs and the effect of its outputs	In a free-market economy, money paid for the scarce-resource inputs to a process (i.e., land, labor, and/or capital used in that process) is considered a measure of the value of the cost of the process. Money paid for the outputs of the process may be of different value and is considered a measure reflecting the value of both the cost of the inputs and the utility of the outputs	In surviving competitive systems of energy transformations, the embodied energy in the inputs to a process is considered a measure of the value of the cost of the process. That embodied energy is, by definition, also embodied in the outputs, which may ultimately achieve a different value only if energy transformation efficiencies change in future use of that energy
Interdependence of subsystems within the boundaries of concern	All prices and markets are interdependent	All embodied energies and energy transformations are interdependent
Overlapping of values (potential for double counting)	The monetary value of the product of one process (e.g., sheet steel) may account for at least part of the same value that is accounted for in the monetary value of the product of another process (e.g., automobile) because both cost and utility of the two products overlap	The embodied energy value of the product of one process (e.g., biotic production) may account for at least part of the same value accounted for in the embodied energy value of the product of another process (e.g., soil production) because the energy embodied in the two products may result from different transformations of a common energy flow

the substitutability of valuable resources. In economic analyses, land, labor, and capital may substitute for each other to decrease a given product's cost. Therefore, there may be considerable uncertainty when using economic analysis to assess future values if relative scarcities, and therefore relative values, of land, labor, and capital change in the future. In energy analysis, there is no lower cost substitute for embodied energy because, according to the laws of nature, it is a limiting physical requirement for any given production. Therefore, when projecting future values, energy analysis may provide an extra measure of confidence over economic analysis, in which potential substitutions could drastically alter the projected values.

Although time is considered to have an effect on effect in both economic and energy analyses, calculations of that effect are based on different algorithms. In economic analysis, a resource controlled now usually is considered more valuable than the same resource controlled later. This preference with respect to time is reflected in a discount rate. That rate is the rate of interest that might be with the resource. The rate earned may be quantified explicitly in economic valuations by projecting into the future the trends of recent changes of value with time. Energy accumulations accelerate competitive positions during growth maximizing system power. Also efficiency is less with speed. In some sense this may be considered a substitution of time for energy because speeding up a production process saves time but costs energy. That is due to the phenomenon of the efficiency of energy transformation varying with speed. This algorithm explains a physical reason for time's affecting value. The time component may be made explicit in energy analysis valuations by identifying rates of resource use and associated efficiencies of energy transformation at maximum power loading. That is, energy transformation ratios may vary with time according to the speed with which the system draws on its resource supplies. Thus, in times of increasing rates of growth, embodied energy values would be affected in a similar fashion to economic discounting. However, should growth rates slow toward steady state or even decline, then economic discount rates determined by projection of past trends would suggest a considerably different effect on value than would be indicated by the energy analysis algorithm relating efficiency and speed. That difference may be extremely important when considering values of long-term effects.

There is a particularly important difference between the models used for valuing a resource in economic and energy analyses. The energy analysis model is a unified global system of man and nature with embodied energy being the common unit of all transactions. In contrast, the economic analysis model is a limited system of economic markets with money being the common unit of only scarce-resource transactions. Because there are no economic markets in the natural environment, and consequently no money transactions, natural-environmental contributions to value are external to the model. The value of natural-environmental resources is recognized explicitly in the model only when those resources are considered scarce. Although some value of other natural resources is often recognized, assessment of that value cannot be governed by the market model. Consequently, the economic analysis model applies only to market resources whereas the energy analysis model may apply to any resource.

The mechanisms by which energy and economic analyses assess value are different but may, in certain situations, achieve the same end. In economic analysis, the market-pricing mechanism is used to assess value at the point where cost balances utility. In energy analysis, real situations that are thought to be at or near maximum power are used as a guide in energy transformation ratio calculations to assess value at the point where efficiency and speed of resource use are in optimum balance. The balancing of cost and utility of any resource use is probably homologous to the balancing of efficiency and speed of resource use. Therefore, the two analyses' mechanisms merely may be using different means to assess the same end. However, the energy analysis (maximum power) mechanism is governed by the previously established physical laws of nature whereas the economic analysis (market-pricing) mechanism is governed by current human perceptions of resource scarcity and utility, which define economic markets. Because we are not always fast to perceive the full utility or sometimes even the true global scarcity of certain resources, the energy analysis mechanism may enable us to be more rapidly responsive to certain resource changes. That is one reason why energy analysis is offered as a tool for valuing externalities even if ultimately both forms of analysis were eventually to achieve the same finding.

Similar boundaries of concern for valuing a resource are often defined by both energy and economic analysts. However, in practice, important differences are often evident regarding both spatial and temporal boundaries. The spatial boundaries of economic analyses include man, scarce resources, and the products developed from interactions of man and scarce resources and may be defined as a local, regional, national, international, or other boundary. Economic benefit-cost analyses often assume a national or global boundary; but usually only market transactions within that boundary are evaluated. Thus, often there are nonmarket (e.g., environmental) value changes to be considered that technically may be within the spatial boundaries of concern but nonetheless are external to the economic analysis. (See the above discussions on the models and mechanisms for valuing resources.) When considering the value of environmental resources, energy analysis makes no distinction between the conceptual and the practical spatial boundaries used. The values of both market and nonmarket environmental resources are evaluated within the bounds of a unified global system of man and nature.

When considering temporal boundaries of concern, economic analysis may again be seen to have a discrepancy between concept and practice, a discrepancy that is not evident in energy analysis. The economic market-pricing mechanism, due to its dependence on current human perceptions of future utility, often gives only minimal consideration to long-term value changes even though conceptually economic analyses, including benefit-cost analyses, have open-ended temporal boundaries. In contrast, energy analysis, with evaluations based on the limiting physical requirements of full life-cycle flows in the global system, considers and evaluates value changes regardless of how far into the future they may occur.

The economic relationship between the values of a process's input costs and its output effects has both similarities to and differences from the energetic relationship of those values. In economic analysis, the value of input costs may differ from the value of output effects depending on the utility of the outputs. In energy analysis, the two values may differ depending on the system-wide efficiency of energy transformations during the use of the output energy. That value difference is defined as zero when the system is operating at steady state. That is, the embodied energy requirement may equal the embodied energy effect at steady state because system-wide energy transformation efficiencies remain constant during steady state. Economic and energy analyses differ on this parameter due to the important difference concerning evaluation models, as discussed above. Because the energy analysis model is more comprehensive, including nonmarket (e.g., environmental) resources and resource flows, that model may account for any value of a process's outputs due to their use in those nonmarket processes. The economic analysis model does not account for such value. Thus, to the extent that nonmarket processes account for a different proportion of input costs than of output effects, energy and economic analyses will show different ratios of input value to output value.

In valuing resources and products, both energy and economic analyses recognize the interdependencies of processes within the system of concern. In other words, the complex web of interconnected processes causes at least part of the value developed in the production of any good or service to be at least indirectly dependent on the production of any other good or service. Thus, in economics, all prices and markets are interdependent; and in energy analysis, all embodied energies and energy transformations are interdependent. Such interdependencies within a value system create a potential for double counting values; that potential is discussed below.

Both economic and energy analyses use measures of value that have considerable potential for double counting. That is, the quantification of any given monetary transaction according to price, or of any energy flow according to embodied energy, often accounts for the same value that is accounted for in other monetary transactions or energy flows. Economic analysis accounts for such overlapping of value by separating out the value added portion of each transaction and by measuring aggregate value only at final demand, which is considered 100% value added. Energy analysis accounts for such overlapping of value by calculating aggregate value only for some integrative energy flow, which embodies most or all of the energies from the other flows. For example, the embodied energy value calculated for the energy flow of a system's biotic production is often considered an integrative value in environmental analyses because most of the energy embodied in most other environmental processes is used either directly or indirectly in biotic production. Thus, although energy and economic analyses each use a measure of value that has considerable potential for double counting, they employ somewhat different strategies to avoid such double counting when attempting to calculate system-wide, or aggregate, values.

APPENDIX B
(Continued)

COMPARISON OF ENERGY ANALYSIS AND ECONOMIC COST-BENEFIT PROCEDURES

2. CRITICISM AND REPLY

A referee's comments to the previous section are given below and followed by responses. The referee was concerned that economic analysis and its subset cost-benefit analysis was mischaracterized. This exchange may help show the differences between viewpoints of economic and energy analysts, some of which are semantic. Merging of these fields is to be welcomed since the real systems of concern process both energy and money, both being involved in development of value. One regards value as free to change according to human desire; the other regards value as physically determined ultimately with humans forced by necessity to develop preferences for that which works in their survival—H. T. Odum.

Referee: Cost-benefit analysis is specifically defined to take into account non-monetary aspects. It was developed to overcome the problem that public decisions cannot be made based only on factors that have monetary values attached. How well the principles are applied depends on the practitioner. Clean air, clean water, and protection and wise use of natural resources are all values that can be included in cost-benefit analysis. It is simply not true that natural environmental contributions to value are external to the model. Such statements should be removed, or comments attached before the final report goes out.

Response: Environmental contributions are external to the market pricing model as long as they are not perceived as scarce; thus, the model is dependent upon human perception of scarcity. Energy analysis offers a new scientific method for evaluating externalitites, one that calculates the real basis for existence rather than the fluctuating human-perceived values that are and should be a function of scarcity rather than real contributions to survival. Many results of economic analysis grossly underestimate environmental and resource contributions to a society's pattern of survival and competitive position. Therefore, the economic cost-benefit methods might benefit from incorporation of the new method.

Referee: The discussion incorrectly seems to imply that economic resources must be categorized into land, labor, and capital. This was the classical economic system, but was developed to improve on earlier faulty theories that ignored differences in kinds of resources. There is no such requirement in economic analysis to use these categories. Resources can be classified in any way that gives validity to a study or evaluation. If I were forced to do my evaluation using only one resource, it would be the store of human knowledge. This is what enables wind, water, sun, minerals, etc. to be transformed into resources to be used for our maintenance and pleasure. Considering energy to be the only resource has its counterpart in the 18th-century economic thought when the "labor theory of value" was advanced. All capital was said to be the embodiment of labor. This seems to be the same view expressed in energy analysis that all resources are embodied energy. The problem with single resource evaluations is that they do a poor job of indicating when the use of one resource should be expanded (or contracted) as compared to another resource.

Response: No intent was made to imply that economic analysis uses only land, labor, and capital. Economic analyses have often regarded energy as just another commodity. Energy is not a resource but the property of all resources, including materials and information. The embodied energy (that required) is greater for materials than for fuels and is greatest for information. Energy accompanies everything, but money does not. The human-labor theory of value failed to include work of machines, of nature, and the different quality of work of different types. It was not proportional to physical work or embodied energy.

In the short run, each type of resource may be a limiting factor and must be considered separately whether in arbitrary units or its energy equivalents. In the long run, transfer of energy within systems due to human behavior and self-organizing mechanisms of nature diverts energy from storages to eliminate any limiting factors (a point of possible agreement among viewpoints).

Referee: The goal of energy analysis was stated to identify the alternative that accomplishes the most work. Aside from the definition of work from physics, I don't know what this means. More troubling, what if the most desired good or value is one that requires very little work, say dedicating a natural area to a specific set of uses? Why would we have as a goal the maximum output of work? Work output is only an intermediate step toward achieving goals of society, such as providing for maintenance and pleasure.

Response: Work was defined by Maxwell as energy transformation. The definition of work from physics is correct for comparisons among flows of the same type of work. Work involving more than one kind of energy requires that energy of one type necessary to generate another be factored in. For example, almost every analyst understands that 4 Calories of coal are approximately equivalent to a Calorie of electricity, and a comparison of work using coal and that using electricty must not be made without multiplying by 4.

The goals of society were arrived at by selection for those that succeed in maximizing power. The items that humans come to value are those with large embodied energies (i.e., those with many successive stages of work required).

The natural area referred to by the referee involves very large work of nature, which is what energy analysis evaluates on the same basis that it evaluates human work using embodied solar equivalents.

Referee: The goal of economic analysis is not to obtain the most production, except in a global sense. The goal is efficiency of resource use. A more correct goal would be one of obtaining the most value, where value is understood to be the composite of all goods and services contributing to society's maintenance and pleasure.

Response: Maintenance of society requires maximizing power that is the rate of processing of energy transformations that contribute to survival. Society's pleasure does not long deviate from what maximizes the system's power and its competitive position. Individuals try everything and by their free will society can see what works in its public policy decisions.

Because maximizing power necessarily uses resources less than at maximum efficiency (Odum and Pinkerton 1955) for thermodynamic reasons, the objective of maximizing efficiency is incorrect analysis. This is why good economies have low efficiency.

APPENDIX B
(Continued)

COMPARISON OF ENERGY ANALYSIS AND ECONOMIC COST-BENEFIT PROCEDURES

3. CASE STUDY: LASALLE COUNTY NUCLEAR POWER PLANT

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Energy analysis and economic benefit-cost analysis were compared for the LaSalle County Station (LSCS) nuclear power plant. Major issues at the LSCS site have been the land conversion problem and the alternatives of cooling systems. These were considered with economic analysis methods when the plant was planned and authorized. Energy analysis results in Tables 4–7 may now be compared.

DATA BASE

Data for energy and dollar flows into and out of the LSCS station and alternative cooling systems are primarily based on the reports from NRC (1978), CEC (1977), AEC (1973), and Battelle Columbus Laboratories (1972). In these reports, studies were performed by classifying benefits and costs into four categories: economic benefits and costs, and environmental benefits and costs.

Economic benefits are mainly derived from the generation and use of electricity, and jobs provided. Economic costs associated with LSCS are divided into the annual fuel, operation and maintenance, and decommissioning costs. Environmental benefits are projected from the use of the cooling lake as a recreation facility. Environmental costs are assessed by environmental impacts on land, water, and air. Main plant construction costs were the same for all alternatives.

Impacts on land use include a diversion of 3885 acres of productive land (see Table 4, footnote 2.a) to industrial use at the site and a relocation of about 130 residents (AEC 1973).

Impacts on water uses attribute to an average water consumption of 44.2×10^6 m^3/yr (NRC 1978); a thermal plume of 4.1 acres by the 3°F excess isotherm and a total heat discharge of 745×10^6 Btu/hr to the Illinois River (NRC 1978); a blowdown water of 30,000 gpm (AEC 1973) containing dissolved and suspended solids from the cooling lake to the river (NRC 1978); a release of radionuclides to the river; and an entrainment of aquatic organisms and fish population.

Impacts on air are mainly due to a formation of ice and fog, resulting in hazardous road conditions and inconvenience to ground transportation, and gaseous radwaste effluents to the atmosphere.

Table B2 summarizes the essential data on economic and environmental costs and benefits that are used in energy analysis and economic analysis.

In Table B2, the data from different sources are not measured in the same units, so they are not directly additive, and no single ratio depicting the benefits and costs in dollars can be developed until a common denominator such as money or energy is used.

CRITERIA CONSIDERED SEPARATELY

Emanating from the 1972 amendments to the FWPCA, public concerns with nuclear power plants have stressted the impacts on surrounding land, the effects of thermal effluent on nearby water bodies, and the possibility of using cooling towers as a means of mitigating losses to natural systems. In response to these concerns, we have considered energy analysis results for each of three objectives separately. These are to minimize the diversion of environmental process; to minimize the unnecessary diversion of economic resources; and to minimize the environmental impact on the system. Each objective can be used separately as a goal in ranking alternatives.

Changes in environmental production and storages are ΔB and ΔS in Tables 4–6. Environmental losses are greatest by far with cooling reservoir.

Reversion of fuels, goods and services, and electricity are ΔC_2 and ΔF_2 in Table 4–6. These are greatest with the cooling tower.

Environmental impact is ΔW in Tables 4–6. Impacts are greatest with once-through cooling. However, when the embodied energies were added the once-through cooling had the largest contribution to power and the cooling reservoir the least (Table 7).

ENERGY ANALYSIS AND ECONOMIC COST-BENEFIT COMPARISON OF RECOMMENDATIONS

Economic cost-benefit analysis was applied to the proposed LaSalle County Station and several alternatives by the applicant and the licensing agency (AEC 1973). The five alternatives considered by the applicant were: (1) nuclear power station with lake managed for recreation; (2) nuclear power station with lake but no recreation; (3) nuclear power station with mechanical-draft cooling towers; (4) nuclear power station with natural-draft cooling towers; and (5) fossil fuel plant with cooling lake (no recreation). The applicant also considered seven alternative sites. The licensing agency also analyzed in detail the economic costs of four alternative cooling methods: (1) cooling reservoir; (2) spray canal; (3) mechanical-draft cooling towers; and (4) natural-draft cooling towers.

The applicant and licensing agency analyses that resulted in the choice of the present plant location are not germane to this discussion, as alternative sites are not considered here. This

Table B2. Data of Economic and Environmental Costs and Benefits Associated with LSCS Station (Adapted from NRC 1978; CEC 1977; AEC 1973; Battelle Columbus Laboratories 1972; and this study).

Classification	Magnitude and Unit of Measure	Reference
Economic Benefits		
Power generated	11,300 x 10^6 KWh/yr	NRC 1978, p.10-3
Power capacity	2,156 x 10^3 KW	NRC 1978, p.10-3
Employee payroll	2.5 x 10^6 $/yr	AEC 1973, p.XI-6
Economic Costs		
Nuclear fuel	61 x 10^6 $/yr (1980 $)	NRC 1978, p.10-3
Operation and maintenance	34 x 10^6 $/yr (1980 $)	NRC 1978, p.10-3
Decommissioning	2.18 x 10^6 $/yr (1980 $)	NRC 1978, p.10-3
Environmental Benefits		
Recreational use of cooling lake	0.2 x 10^6 $/yr	AEC 1973, p.XI-16
Environmental Costs		
Impact on Land		
Land use for site	3,885 acres	This study
Loss of 130 residents	0.72 x 10^6 $/yr	AEC 1973, p.XI-16
Impact on Water		
Water consumption	44.2 x 10^6 m^3/yr	NRC 1978, p.10-3
Area of thermal plume	4.1 acres	NRC 1978, p. 5-5
Heat discharge to river	7.45 x 10^6 Btu/hr	NRC 1978, p.10-3

Table B2. (continued)

Classification	Magnitude and Unit of Measure	Reference
Environmental Costs (continued)		
Chemical discharge to river		
Blowdown water	30,000 gpm	AEC 1973, p.XI–16
Total dissolved solids	1,100 mg/L	NRC 1978, p. 3–9
Total suspended solids	220 mg/L	NRC 1978, p. 3–9
Radionuclide contamination		
Tritium	15×10^{6} μCi/yr	NRC 1978, p.10–3
Others	1.9×10^{5} μCi/yr	NRC 1978, p.10–3
Entrainment and Impingment		
Plankton organisms	*	NRC 1978, p.10–3
Fish population	*	NRC 1978, p.10–3
Impact on Air		
Effect of fogging and icing on ground transportation	10 day/yr	NRC 1978, p.10–4
Gaseous radioactive effluents		
Noble gas effluents	0.05 mrem/yr	NRC 1978, p.10–4
Radioiodine and particulates	0.70 mrem/yr	NRC 1978, p.10–4

*Qualitative information indicate low quality and low diversity of zooplankton and fish population.

analysis also accepted the construction of a nuclear power facility as given, so the fossil fuel option is not considered. And, due to the decreased flow of the Illinois River during some periods, neither the applicant nor the licensing agency considered the option of once-through cooling. The options considered by all analyses were, therefore, the cooling reservoir and the mechanical-draft cooling towers.

In the applicants summary of environmental and economic impacts, primary impacts are listed by category with no attempt made to give an overall comparison. The main differences in impact between the cooling tower and the reservoir options are in the value of power produced, the amount of land required, the amount of increased fogging in the area, and the aesthetic impact (see Table B3). The cooling reservoir option would appear to be preferable in all categories except the amount of land used, where the difference is large (1780 acres). In an area of highly productive agricultural land such as this, such a large difference in land usage could give the cooling tower option a decided advantage. With the types of impact analysis illustrated in Table B3, however, there is no way to objectively summarize the diverse types of impacts.

The staff of the licensing agency made an attempt to summarize the economic costs of alternative cooling systems. Although this summary was based on a 4480-acre cooling lake, its results are appropriate to the present discussion. The results, which include land and capital investments, operation and maintenance, and capability loss, were as follows (AEC 1973):

Cooling reservoir $48,428,000
Mechanical-draft cooling towers $46,360,000.

The staff of the licensing agency concluded that "the above summary of economic costs suggests that there would be little, if any, economic advantage in selecting the 4480-acre cooling lake as the method of cooling for LaSalle 1 and 2" and that "none of the alternatives present a more favorable balance of benefits and costs" than the one selected (AEC 1973). In the view of the licensing agency, the alternatives are equally acceptable in overall impacts.

The energy analysis procedure presented in this manual indicates, in the overall summary of Table 7, that the preferable cooling option is once-through cooling, the second choice is the cooling tower, and the poorest option is the cooling reservoir. Since the economic cost-benefit analysis used the originally proposed 4480-acre lake, a direct comparison is difficult. However, the dollar equivalent of the difference between cooling towers and the cooling reservoir in Table 7 is $\$142 \times 10^6$/yr. This indicates a significant advantage for the cooling tower alternative. Even if the cooling reservoir cost in AEC (1973) were halved (from $48,428,000 to $24,214,000) this would still amount to a prorated change of only $605,350/yr over a 40-yr plant life, which is much smaller than the $\$142 \times 10^6$/yr noted above. Thus, this energy analysis procedure appears to show a definite advantage for the cooling tower alternative over the cooling reservoir, though once-through cooling had the highest value of the three.

The results of the overall energy analysis procedure, as summarized in Table 7, differ from the results of the economic cost-benefit analysis presented in AEC (1973). Our analysis shows a distinct advantage for the cooling towers option over cooling reservoir; the licensing agency's procedure shows no preferable advantage for either option.

Table B3. Differing Environmental and Economic Impacts of Cooling Reservoir and Cooling Tower Alternatives (information based on AEC [1973] and NRC [1978]).

	Nuclear Power Station with Cooling Reservoir	Nuclear Power Station with Cooling Towers
Value of power	$\$270 \times 10^6$/yr	$\$266 \times 10^6$/yr
Land used	3060 acres	1280 acres
Air quality	100–200 additional hours of fog per year	More than 300 additional hours of fog per year
Aesthetic impact	Plant with impact negligible. Lake impact positive.	Cooling towers and plume would dominate landscape. Impact adverse and moderate.

APPENDIX C

ENERGY QUALITY AND EMBODIED ENERGY*

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Flows of energy develop hierarchical webs in which inflowing energies interact and are transformed by work processes into energy forms of higher quality. These feed back amplifier actions, helping to maximize the power of the system. The small amounts of energy resulting from the conversion to the new forms carry the embodiment of larger amounts of lower quality energy used in the transformation process. Tracing embodied energy through webs enables flows and products to be quantitatively related to energy sources. Higher quality flows require more embodied energy and have greater amplifier effects when they feed back. Consequently, embodied energy is a measure of value, in one of the meanings of the word "value." There are several concepts of embodied energy, but it is possible to compare and clarify the various measures using diagrams. Study of the way energy flows support production and consumption is sometimes called <u>energy analysis</u>. This appendix considers the energy flows, embodied energy patterns of webs, and ratios for evaluating energy quality. We begin with definitions of one usage (Odum 1975, 1976, 1978, 1979) and then introduce other approaches.

Embodied Energy

As energy flows through webs of successive work transformations, energy changes in form, concentration, and ability to feed back and produce amplifier effects. Whereas the actual number of Calories flowing decreases as energy is used and dispersed, the quality of that energy can be said to increase. The flows become either very concentrated or very high in information content, in either case capable of controlling and causing work that would not otherwise be possible. The special transformations develop special quality. Energy used to develop energy of higher quality is the embodied energy. It is the required energy contribution.

Whereas energy is a measure of ability to do work when one is comparing energy flows of the same type and quality, heat equivalents are not measures of their value, cost, or ability to do work of different types. For example, one can compare heat releases of autos carrying different loads and measure their work, in this case the same kind of work. However, the heat content in flows of sunlight, water, coal, electricity, salmon, human services, and books do

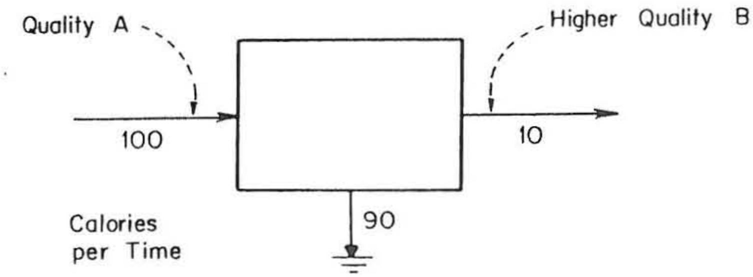
*The material in this appendix comes from chapter 14, "Energy Quality and Embodied Energy," in the book <u>Systems</u>, John Wiley and Sons, Publisher, 1982, forthcoming; included with permission of publisher.

not represent their value, cost, or ability to cause work because these flows are each of different quality.

Energy Transformation Ratio

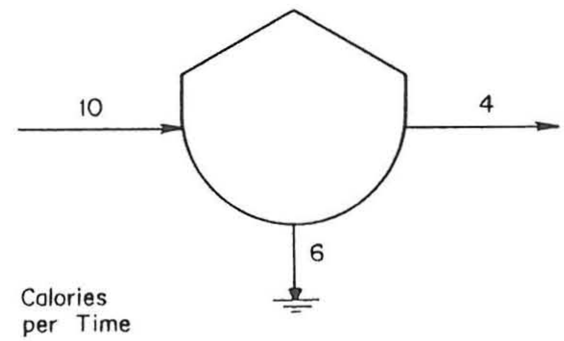
The simple idea of work using some energy to transform some other energy to higher quality is given in Fig. C1. The energy of one type required to generate a flow of another type is the embodied energy of type A required for type B. In Fig. C1, the energy embodied in outflow B is 100 Calories of type A. The ratio of input (100) to output (10) is 10.0 and is a measure of the energy required for the transformation. It is the energy transformation ratio (quality factor) relating one type of energy to another. It measures the embodied energy of one type inherent in another. The energy transformation ratio is in units of Calories per Calorie. The reciprocal is the efficiency 10/100 = 10%.

In Fig. C1b, energy is stored, some being dispersed because of the inherent depreciation of any storage. The energy emerging on the right is of higher quality, having been transformed by storage from a more variable flow to a steadier one, capable of doing more in control actions. Examples of energy transformation ratio arranged in order of embodied energy are given in Table 1.



$$\text{Energy Transformation Ratio} = \frac{100}{10} = 10 \text{ Calories / Calorie}$$

(a)



$$\text{Energy Transformation Ratio} = \frac{10}{4} = 2.5 \text{ Calories / Calorie}$$

(b)

Figure C1. Energy transformation ratio, the energy used for transformation to another form of energy. (a) Definition; (b) energy transformation through the process of storing energy.

Types of High-Quality Energy

High-quality energy may take many forms. Some are concentrations of actual energy, such as high temperatures of a furnace or the cold of a refrigerator. Some are structures of large size like a pyramid or a skyscraper. Others are tiny information-containing objects like genes, computer programs, and political symbols. What these various items have in common is the large energy used in their generation and the large amplification effects they may have.

Embodied Energy as a Measure of Value

An energy theory of value is based on embodied energy. If items and flows have value because of the effects they can exert on a system and if their abilities to act are in proportion to the energy used to develop them (after selective elimination of those which do not), then value is proportional to the embodied energy in systems emerging from the selection process. The energy transformation ratio, by giving the embodied energy per unit of actual energy, provides an intensity factor for value in the way that temperature is an intensity factor for heat. Ultimately, embodied energy may measure value because it measures the potential for contributing effects to maximize power and insure survival. Those who survive regard that as valuable.

Thermodynamic Limits for Energy Transformation Ratios

Theory suggests that there is a rate that maximizes the transfer of power and that this rate is the one that evolves under competitive conditions of real systems. The most efficient energy transformation that is possible with maximum power is the one that is both competitive and most transmissive of energy. The energy transformation ratio of the most competitive system at maximum power is at the inherent thermodynamic limit for conversion. The energy transformation ratio under these conditions measures the inherent requirement of one energy to generate another. The theory suggests that any other ratio will either be less efficient or too slow to compete.

It is not hard to observe and measure energy transformation ratios, but whether the observed ones are close to the inherent thermodynamic maximum possible is not easily known. The ratios observed in ancient systems with millions of years of operation like many in the biosphere, we sometimes assume are good numbers with efficiencies (at maximum power) not likely to be exceeded. On the other hand, energy transformations of new industrial processes may well be much less efficient when their systems are first started compared to those after years of competitions with trial and error in efforts to improve efficiency of the processes. Often, technological advance is the hidden application of additional high-quality energy and is not really an improvement in efficiency.

Examples of energy transformation ratios are given in Table 1, including some that may be near the thermodynamic maximum and others that are derived from single observations and may be superceded when more efficient ones (at maximum power) are found. An observed energy transformation ratio is a useful descriptive index of a system; an energy transformation ratio suspected as being near the thermodynamic limit helps to describe inherent relationships of kinds of energy.

Degraded Heat Equivalents and Embodied Energy Equivalents in Webs

Working with energy quality requires keeping clearly straight and separate the two kinds of energy units: (a) actual energy in degraded heat equivalents (Calories), which is the usual measure of energy and (b) embodied energy equivalents, which are the energies required of a reference type (such as sunlight) to generate the type of concern. To keep these straight, three diagrams are suggested in Fig. C2. First, place numbers for flux of the heat Calorie equivalents on the pathways. According to the first law, these should sum at each junction and at each storage where the inflows equal storages plus outflows. At steady state, inflows equal outflows. Often steady state diagrams are used for energy estimations. These are "first law" diagrams if all the values on the pathways are given in actual Calories.

In Fig. C2a an example of an energy chain is given with heat equivalents shown. They decrease as energy is used so that the last feedback has the least actual energy heat equiv-

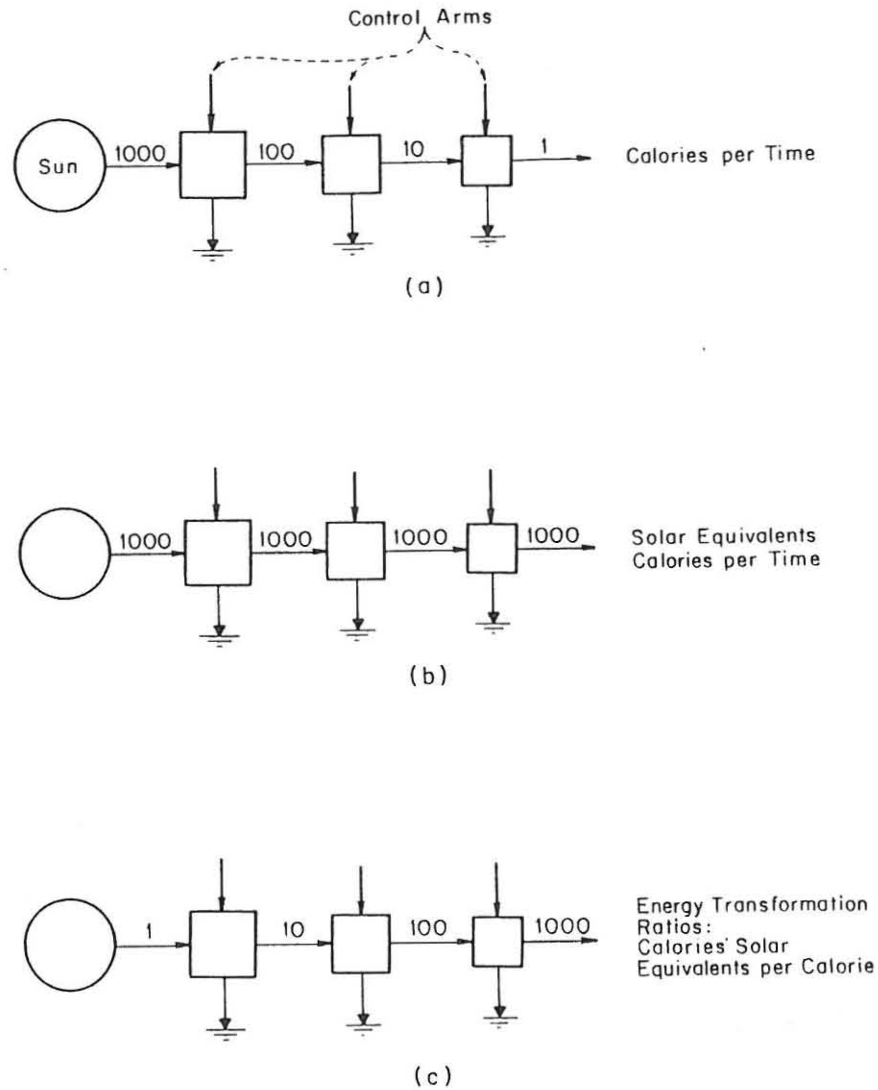


Figure C2. Concept of embodied energy and quality factors in a chain. Cost of control arm is omitted, which is correct procedure if it is a by-product of the flow.

alents that would be regarded as negligible energy flow in some usages.

The second diagram (Fig. C2b) has the solar equivalents required to generate the flow of each pathway. If the system is operating at maximum power and minimum possible waste, then each pathway is essential to the system and costs directly or indirectly 1000 Calories per unit time to generate.

Given in Fig. C2c is the ratio between the solar equivalents required (the inflowing amount at the source) and the heat equivalents of the remaining flow. These numbers are energy transformation ratios and are a measure of the quality of the flow. Notice that they increase as energy is converged and transformed. If the control arms were generated as a nondiverting by-product they need not be evaluated as to their extra energy contributions.

Space Equivalence of Time in Concentrating Energy to Higher Quality

Energy may be concentrated spatially by using some of it in the process of concentration. Or, energy may be concentrated by adding to some storage in the same place over time. In 10 units of time, one may develop the same concentration as converging with a 10-fold geometrical process. If adding is to be equivalent to converging, time used in one concentrating process is equal to geometrical concentration factor in the other. There is a space-time equivalence.

One Source Supporting an Equal Value Loop

An important reference case is the closed loop design in Fig. C3 in which producers support a consumer whose sole output is a feedback, aiding the production process. The energies embodied in all pathways are the same, all traceable to the same source. Since the embodied energies are the same within the flows of the loop, it is called an equal value loop.

Evaluating Embodied Energy and Transformation Ratios from a More Complex Energy Web

Given in Fig. C4 is an energy diagram of a web running on one source. In Fig. C4a the energy flows through transformation processes in which energy is used to generate flows of higher quality downstream. These feed back to the left, interacting to make the processes go. From left to right the flow rates decrease, but the quality increases. This is a first law diagram, and all inflows balance outflows at any point.

Next, we ask how many Calories of the type of the source such as sunlight are required for each pathway. Since each pathway is required for every other pathway, and each pathway is a by-product of every other pathway, the energy required in units of Calories of the type entering from the source is the same for each pathway. Fig. C4b is an embodied energy diagram where all numbers are embodied Calorie equivalents of the same quality.

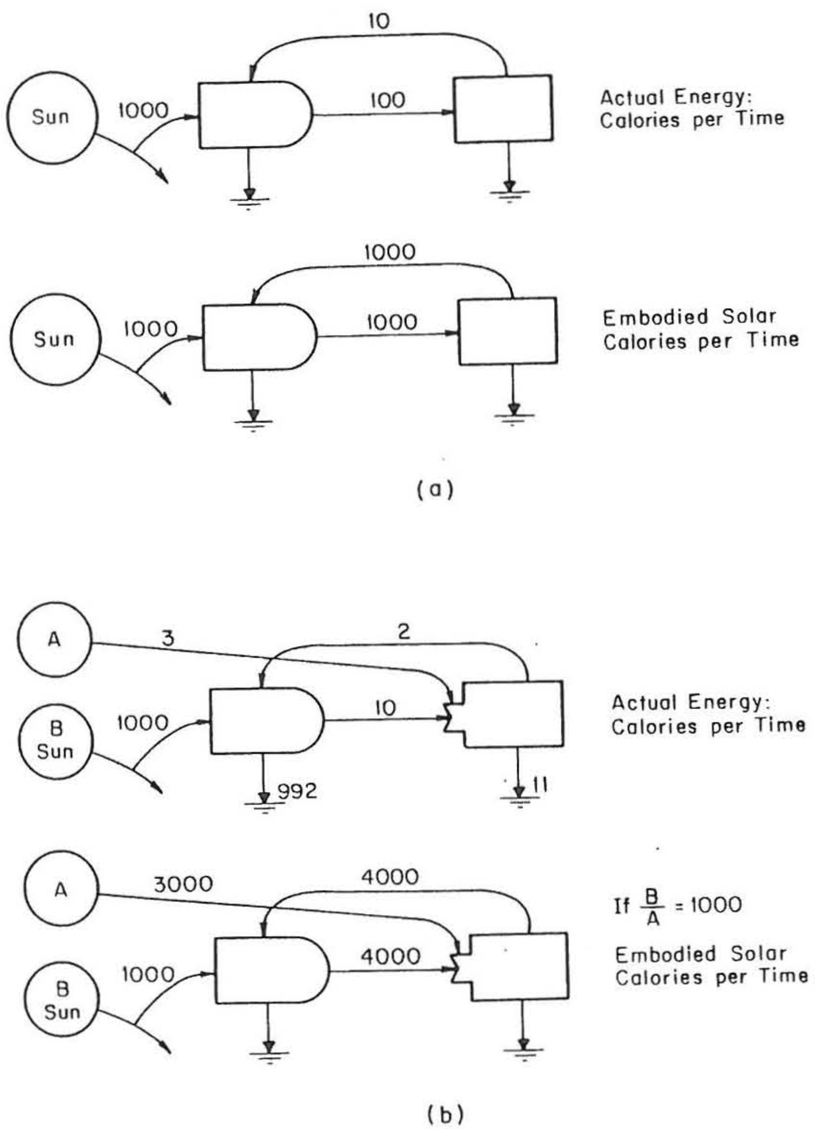


Figure C3. Evaluating embodied energy equivalents in closed loops. (a) One source; (b) two sources. Source A has an energy transformation ratio of 1000 Calories of B equivalent to one of A.

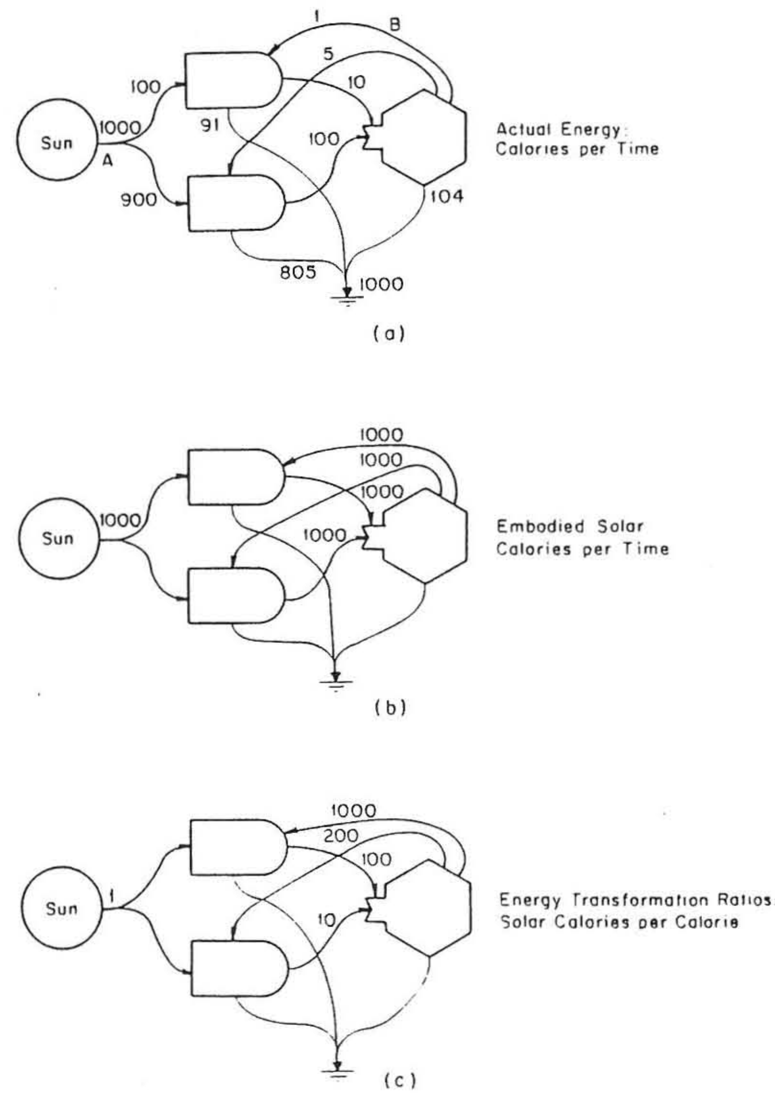


Figure C4. Energy and embodied energy relations in a web with one source. (a) Typical web of actual energy flow; (b) embodied energy in solar equivalents; (c) energy transformation ratios calculated by dividing values in (b) by those in (a).

In Fig. C4c the quotients obtained by dividing embodied energy equivalents from Fig. C4b by the heat Calories flowing from Fig. C4a are plotted. These ratios are, therefore, the energy transformation ratios. They indicate the energy at the start required to develop the energy flow of the quality flowing. The procedure is simple and clear when there is only one primary source, as in this case, or in the general flows of energy through the renewable resources of the biosphere, where most of the energy is from the single solar source.

Embodied Energy in a Process with Two Independent Energy Sources

When two input arms of a process come from two different energy sources instead of being by-products ultimately from the same source, then the embodied energy contribution to the transformation is the combination of the two. So long as both are of different quality, they cannot be added, since their interaction involves one amplifying the other.

However, if both are expressed in embodied energy equivalents of the same type of energy, such as in Calories of solar equivalents, then they can be added for the purpose of ascertaining the ultimate solar energy requirement for the process (see example in Fig. C5). The mechanics of making the calculation consists of 1. writing the actual energies on the diagram; 2. using energy transformation ratios from previous tabulations to multiply both types of inputs to convert to embodied energy equivalents of one type; and 3. then adding the inputs.

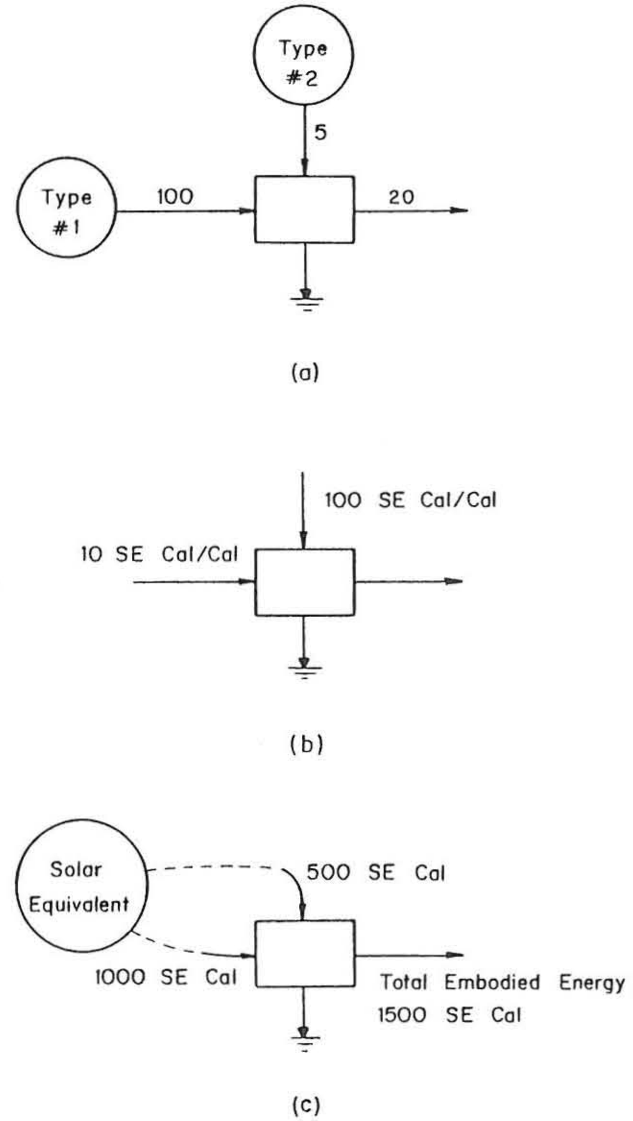


Figure C5. Evaluating embodied energy of a process with two sources each of a different quality. (a) Actual energy in heat equivalent Calories per unit time; (b) energy transformation ratios for these two kinds of energy derived independently; (c) embodied energy in solar equivalent Calories obtained by multiplying number in (a) times those in (b). Output is sum of inputs, both expressed in Calories of the same quality.

If one has a very local view of a process, one does not know if an input arm is a feedback (or feed forward) by-product of the same source or an input involving a different source entirely. Energy analysis calculations are difficult without an overview diagram of the whole system.

Evaluating Energy Transformation Ratios of a Local Process

Whereas energy transformation ratios may be estimated best from the world web as already described, ratios may also be observed for local processes without knowledge of the whole web. Consider a process in Fig. C6. C is an input of high-quality control energy. If arm C is believed to be wholly a by-product, then it may be ignored in the calculation of energy transformation ratio as in Fig. C6a.

However, if arm C is from a separate source, it is evaluated first in actual energy units (Fig. C6a). Then energy transformation ratios determined elsewhere are used to convert actual energy flow to embodied energy equivalents of either type A or type B. Then flow of input C is added to A (Fig. C6b) to get the total embodied energy of type A for generating type B.

An alternate way is shown in Fig. C6c, where the energy equivalent for input arm C is subtracted from the embodied energy output of quality B. The energy transformation ratios in (b) and (c) are larger than in (a) because more energy (that

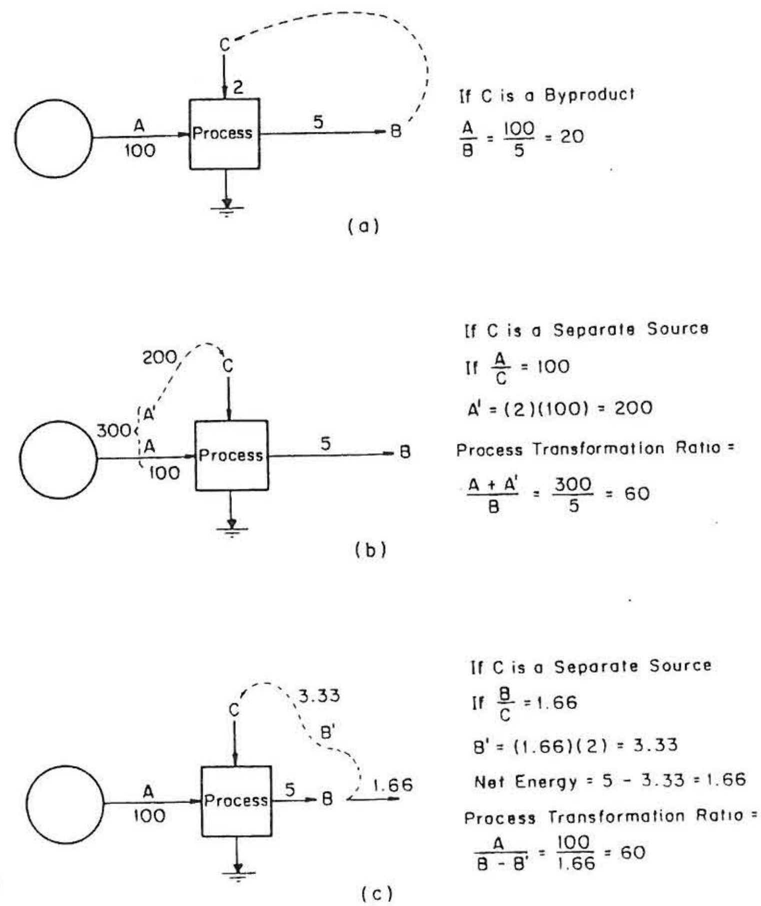


Figure C6. Estimating energy transformation ratios for locally observed processes. (a) Transformation process in which ultimate source of C is not known; (b) C is evaluated in Calories of type A and added to input to get A; (c) C is evaluated in Calories of type B and subtracted from output to get B.

of two sources) is required than in (a) where part of the work is done as with by-products.

Closed Loop Supported by Two Sources

When there is a closed loop supported by two sources of differing quality the flows around the loop have the embodied energy of both input arms, since both are necessary (see Fig. C3b for an example). The first law diagram is given first, followed by a diagram of embodied energy of solar quality, which was calculated by multiplying the energy type A by its energy transformation ratio from solar energy (B).

Energy Amplifier Ratio

The effect that a flow of energy has is not an inherent property but depends on the energy flows with which it interacts. However, it may be reasoned that surviving systems develop designs that get as much energy amplifier action as possible. The energy amplifier ratio is defined in Fig. C7a as the ratio of output (B) to control flow (C), both expressed in actual energy (heat equivalent Calories). The ratio is 10 (Fig. C7b).

In Fig. C5a is given an interaction between energy flows of different quality in which the high-quality one (type 2) is amplifying the lower quality one (type 1). A measure of this energy effect is the ratio of output of actual energy (20 Cal.) in equivalent heat Calories to

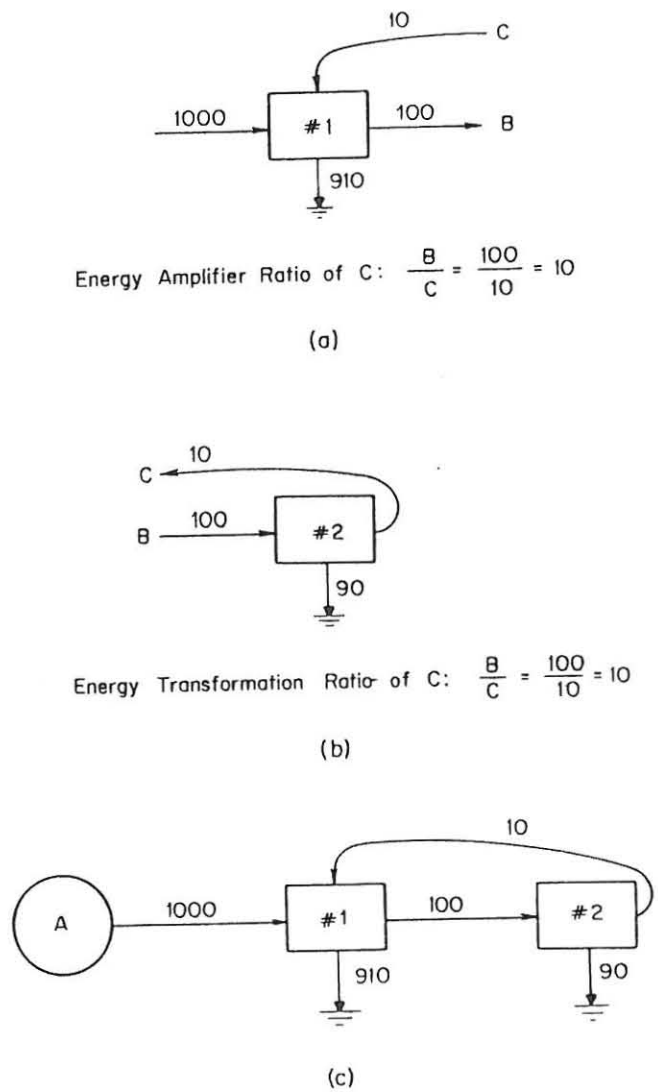


Figure C7. Energy amplifier ratio and energy transformation ratio. (a) Definition of energy amplifier ratio for flow C; (b) energy transformation ratio for generating C from B; (c) special case of closed loop where energy amplifier effect of C on B equals energy transformation ratio of C from B. Energy flows are actual Calories (heat equivalents).

actual input energy flow also in equivalent heat Calories. In Fig. C5 this is 20.

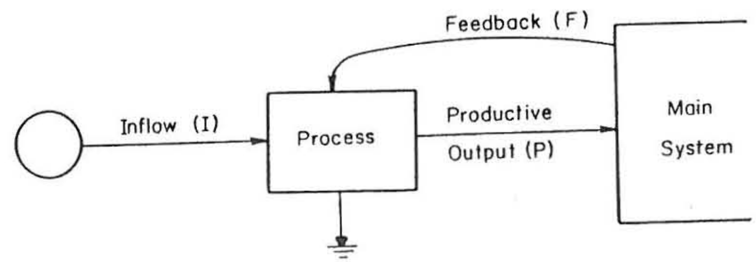
A property of the simple closed loop with one energy source is the equality of energy transformation ratio through the consumer and the energy amplifier ratio of the feedback's effect (see Fig. C7c). The energy used to develop feedback is reinforced by the feedback.

Theory suggests that in surviving systems, the amplifier effects are proportional to embodied energy. A full empirical test of this theory remains for the future. Such evidence will help confirm whether embodied energy is a measure of value. These ratios are not independent of low-quality inflows, which are also controlled by the feedback.

Ratios of Embodied Energy Flow of the Same Quality in Processing an Energy Source

A very common element of energy webs given in Fig. C8 is a three-arm transformation process involving processing of an external energy source under control of a feedback flow. The three energy flows are the resource inflow, feedback, and output flow. There are three useful ratios often calculated from the three-armed diagram as defined in Fig. C8. After the actual energy flows are converted to embodied energies of the same type, these flows may be compared using ratios.

Net energy yield ratio is the ratio of the process production rate to the feedback energy



Net Energy = P − F

Net Energy Yield Ratio = $\frac{P}{F}$

Energy Investment Ratio = $\frac{F}{I}$

Energy Added Factor = $\frac{P}{I}$

Figure C8. Definitions of energy ratios concerned with processing sources. The above quantities are calculated after all flows are expressed as energy flows of the same quality by multiplying actual energy flows by energy transformation ratios.

flowing from the main system. It is a measure of the strength with which a source may contribute energy to an economy. For example, in Fig. C3 there is no net energy, but in Fig. C6c, net energy is 1.66. Whereas the energy amplifier ratio uses actual Calories, the net energy yield ratio uses embodied energy of the same type.

Energy investment ratio is the ratio of the feedback energy flow to the resource inflow that it helps process; for example, 3.33/100 in Fig. C6c.

Energy added factor is the ratio of production generated per unit of low-quality resource processed; for example, 1500/1000 in Fig. C5c. It is a measure of the effectiveness of the resource in attracting high-quality matching energy.

Traditional Ecological Terminology for Gross Production, Net Production, Net Energy

An energy transformation unit is shown in Fig. C9 and used to identify customary ecological terminology. The output of an interaction process is gross production (G) and is measured by the flow of the carrying state variable (such as carbon), by the heat Calories in the upgraded energy, or by embodied energy of the production flow.

Some of the gross production goes into storage (Q), and some of this depreciates (D), and some is fed back as part of the interaction (C). Some of the production is fed further downstream

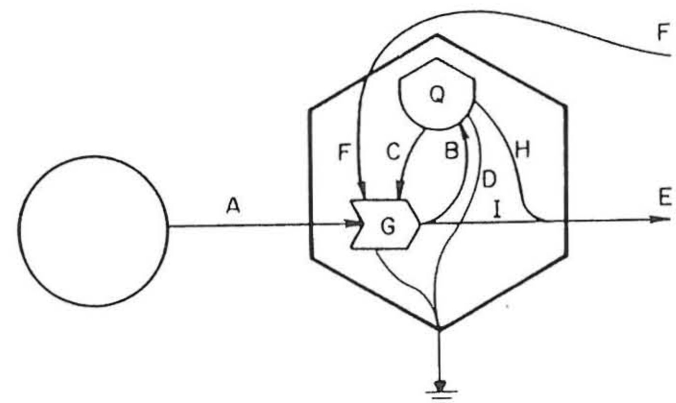


Figure C9. Ecological definitions of production and net energy usually calculated in actual energy units.

Gross production, G;
Overall net production in export yield, E;
Net production in gain and export, $\dot{Q}$ + E;
Overall net production including feedbacks, E - F (net energy if in units of same quality);
Net production in gain, dQ/dt = $\dot{Q}$;
Net production before storage, B - C - F;
Assimilation, A, F;
Export from storage, H;
Directly exported production, I.

(pathway E) to other units with their storages and feedbacks. At any stage downstream from the gross production, one may measure the remaining flow and call it net production for that point. Net production is the production remaining after some necessary processes to the production are subtracted. Because the definition depends on the place in the network and because it is also very dependent on the time interval chosen where the production is varying, net production is very ambiguous. Clarity requires an accurate energy diagram with the kind of net production that is meant being defined by designating the pathway (see Fig. C9). Traditionally in ecology, the between-unit feedbacks (F) of high quality have not been included in net production measurements, even though they are essential and require very high energy. Another kind of net production is net rate of gain in storage (net growth, Q). Some alternate kinds of net production are given in Fig. C9.

The concept of net production in ecology has usually been calculated using actual energy units, whereas the net energy concept defined in Fig. C9 is calculated using embodied energy units of the same quality. This is the one used elsewhere in this chapter. In deciding if the energy yielded at a point is greater than the feedback, since the two are of different quality, they must be converted into energy units of the same type (see E–F in Fig. C9, for example). Many efficiencies may be calculated using different ratios of pairs of flows in Fig. C9. For example, efficiency of gross production is usually calculated as G/A. The efficiency of net conversion of the yield in ecology and industry is often calculated as E/A.

Uses of Net Energy

When a source yields net energy beyond its inflow process, this energy is available to further maximize power in the system in several ways as shown in Fig. C10: 1. By causing downstream growth so that feedbacks are increased and more energy is processed from the same source, if that source will support increased pumping. The effectiveness of this alternative may be judged from the net energy of the additional increment of pumping, i.e., the marginal effect.

2. By helping process a second source, which may have a lesser net energy when considered alone. The effectiveness of this alternative is evaluated with the energy investment ratio that indicates the additional embodied energy drawn in for the amount fed back to the processing.

3. By exchanging net energy in trade for commodities of higher or lower quality energy so that the net effect is an increase in embodied energy, increased amplifier effect, or increased efficiency. The effectiveness of the exchange alternatives are evaluated with embodied energy ratio of the exchange where both are expressed in units of the same quality.

4. By supporting new structures with special characteristics that increase efficiency and conservation of energy use. Examples are storages, diversity, and control systems.

Net energy may be regarded as temporary because it is unfedback energy and is wasted until it generates more feedback. Surviving systems

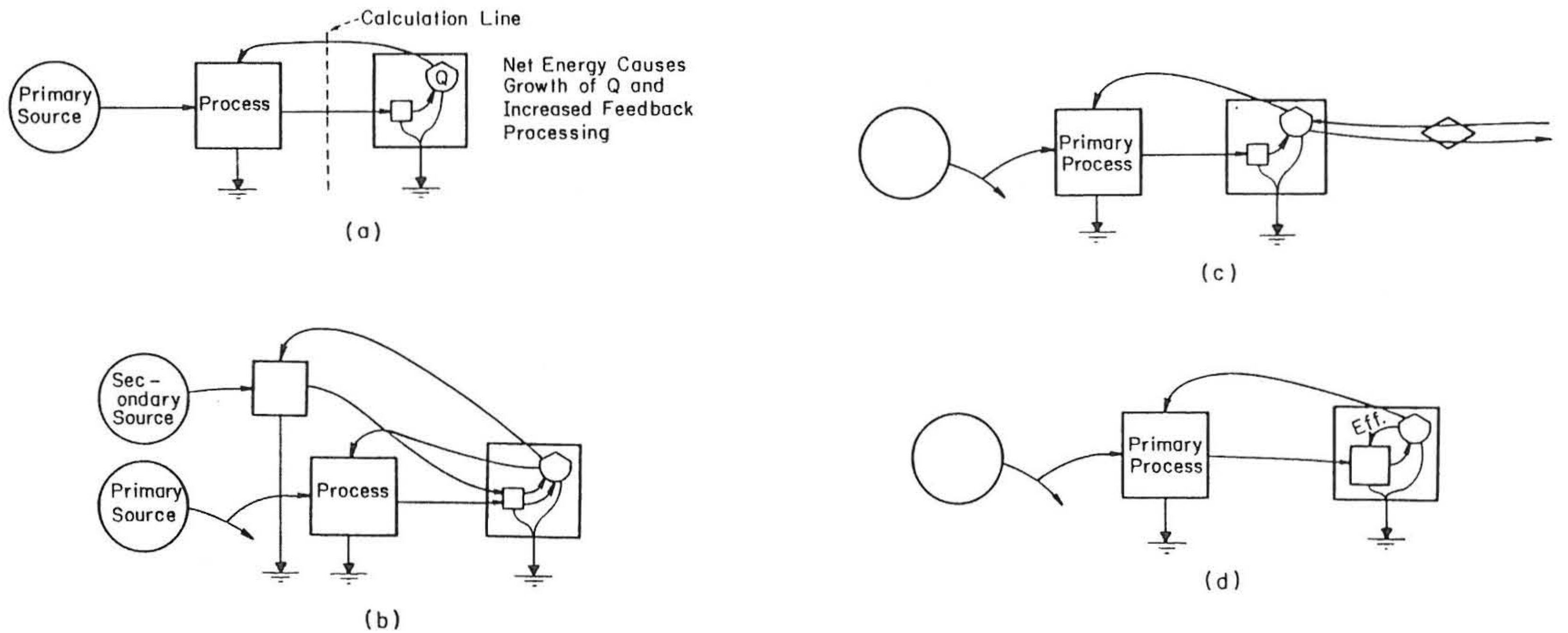


Figure C10. Alternative uses of net energy. (a) For growth that facilitates more processing from the source; (b) for subsidy to processing from a secondary source with less net energy; (c) exchange for more energy; (d) for mechanisms of conservation and efficiency when other sources are not available.

develop structure and uses for their net energies after which there is no net energy in the system considered overall. In a complex web, net energy in one part of the web subsidizes other processes elsewhere in the web.

Flexibility of High-Quality Energy

Energy is transformed successively in chains and webs to higher qualities with special amplifier abilities. One of the properties of higher quality energies (to the right in our diagrams) is its flexibility. Whereas lower quality products tend to be special, requiring special uses, the higher quality part of a web toward which the web often converges is of a form that can be fed back as an amplifier to many kinds of units throughout the web.

Because of the varying flexibility of energy with position in the energy chain, the divergence of production products in the lower part of an energy web (on the left in the diagram) tends to be like the left column in Fig. C11. Each diverging by-product carries the same embodied energy. In systems that maximize power all by-products are fed back in order to have similar amplifying effects.

In the terminal, flexible part of the web, the energy flows produced are general and when diverged represent a dividing of the embodied energy. This important principle allows use of money to evaluate embodied energy of high-quality feedbacks such as human labor.

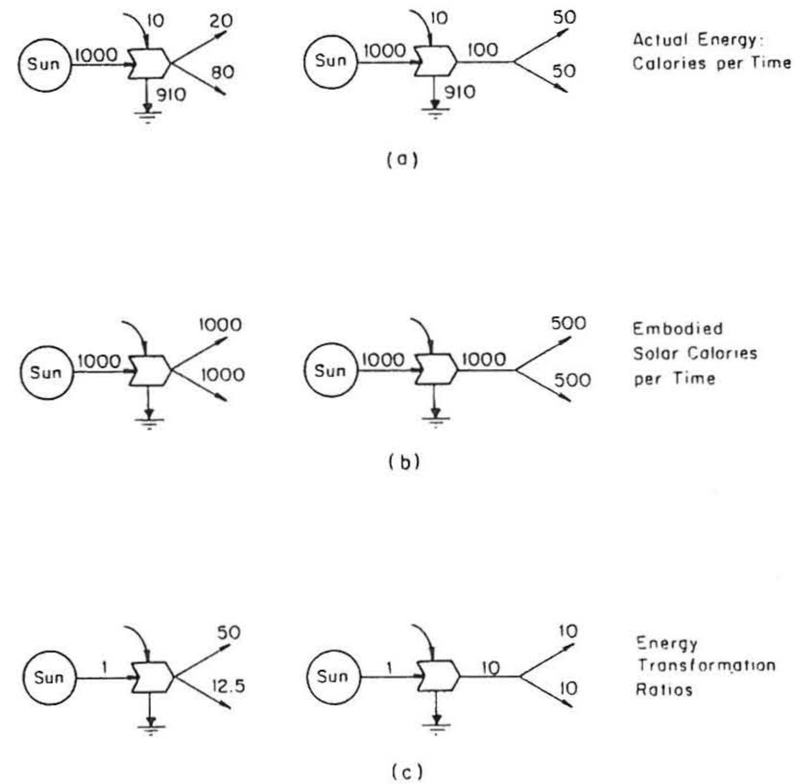


Figure C11. Comparison of diverging flows of unequal quality (on the left) with a diverging flow of equal quality (on the right). (a) Actual energy flow; (b) embodied energy flow in solar equivalents; (c) energy transformation ratio; values in (b) divided by those in (a). Diverging flows that carry the same embodied energy should never have their values added since their sources of embodiment are the same.

Energy Matching and Investment Ratio

High-quality energy has its best effect when used as an amplifier on lower quality energy. If high-quality energy is used alone it has nothing to amplify (see Fig. C12b). It gets used for low-quality purposes. Thus, surviving designs are likely to have a matching of high-quality energy with larger amounts of low-quality energy. Low-quality energy flows, thus, have the potential for attracting high-quality energies, maximizing useful power flows. Low-quality energy can generate its own feedback as in Fig. C3 or C4, but if another source of high-quality energy is attracted it may augment the self-generated feedbacks. With larger amounts of feedback, however, lower quality energy becomes shorter in supply. When either interacting flow is limiting, resources generate less than their potential. A competitive system operates with its interacting inflows equally limiting (see derivation from Costanza (1979)).

Energy investment ratio has been defined as the ratio of high-quality feedback energy to low-quality energy flow with both expressed in embodied energy equivalents of the same quality. The investment ratio that develops may be determined by that available to competitors. A system that has a low ratio can attract energy away from a system with higher ratio since power is maximized in this way.

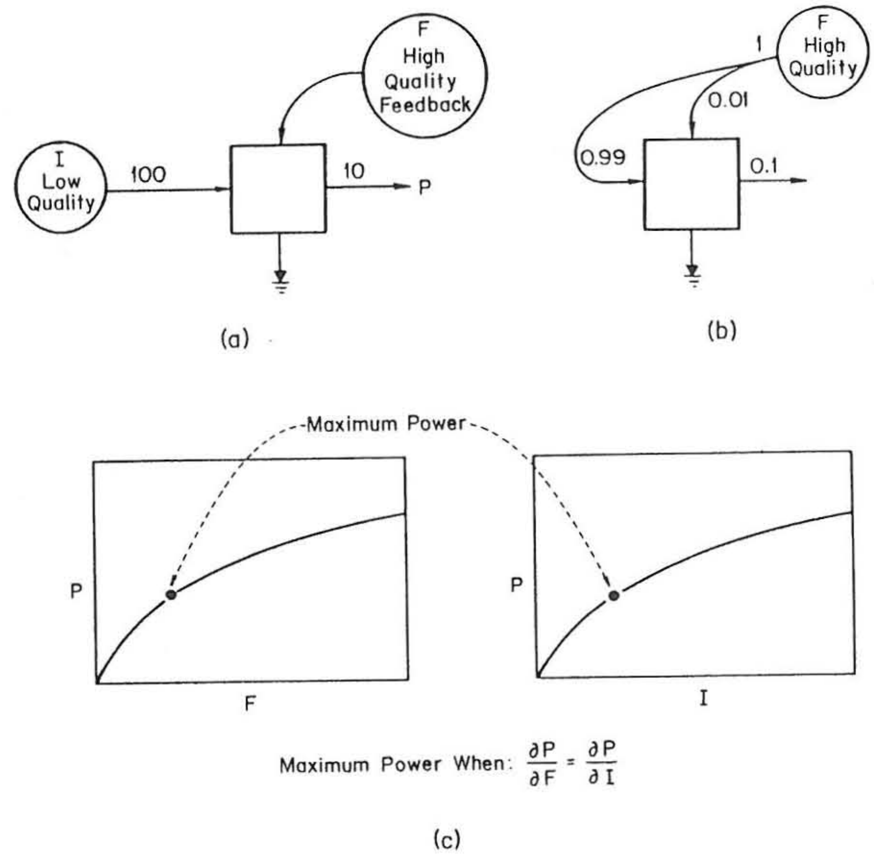


Figure C12. Feedback and matching of high-quality energy. (a) Good matching of high-quality amplifying lower quality; (b) poor use of high-quality energy for low-quality purpose; (c) maximum power of the larger systems facilitated by good energy matching with neither high- nor low-quality energy in relative excess. Derivation from Costanza (1979).

Unbalanced Arms Input to Production

Where there are two sources of different quality such as fossil fuel and sunlight, the high-quality one may be in excess of what is required for best matching by low-quality energy flow. Since the sunlight can generate its own matching high-quality energy, adding additional high-quality energy preempts the control, increases the production some, but with less efficiency, because of diminishing returns. See Fig. C13 for the relationship of increasing high-quality relative to matching lower quality energy. The upper graph shows increasing production (P) with increasing investment feedback, but at a declining rate. The left section has the feedbacks developed from its own net energy. Beyond an investment ratio of one, an outside energy source is required to increase F. When F is very large it has no low-quality energy to match it and uses itself for low-quality purposes.

The lower graph shows the amplifier effect. Below F/I equal one, the production (P) has a high amplifier action and is net energy yielding (left model). With more high-quality energy, production increases but more slowly and with less potential than if the high-quality energy was better matched. At very high excesses, the high energy can add further by being used for low-quality energy, but this gives a very small efficiency.

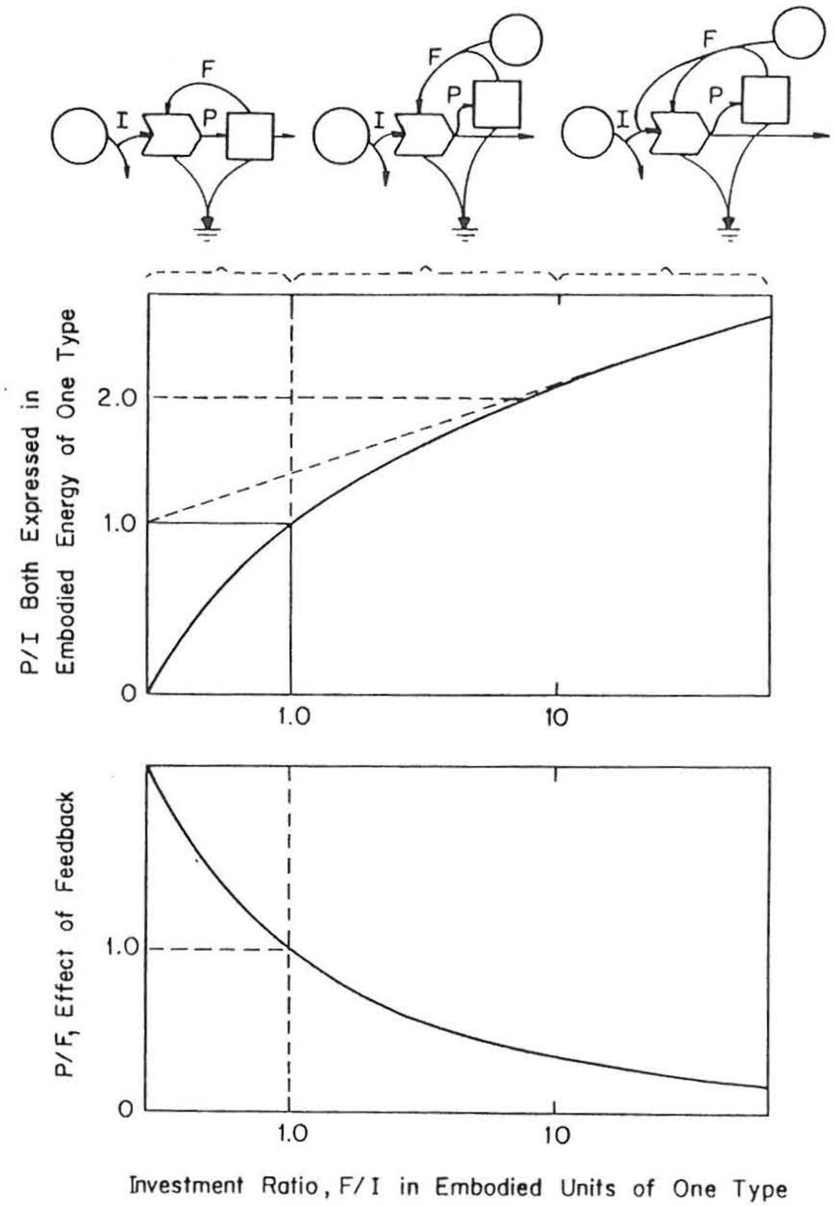


Figure C13. Effect of feedback energy on production and efficiency.

Multiple Sources; Energy Signature in Embodied Energy Units of One Type

The set of incoming energy sources can be described as an energy signature with sources arranged on diagrams in order of energy quality. In some fields these are called boundary conditions. The actions caused by source pathways crossing the boundaries are also called forcing functions. Theory was given that the more embodied energy, the more ability to control a system. By expressing the flows of the sources first in heat equivalents per time and then multiplying by energy transformation ratios relative to one type of energy, the energy sources are then expressed in embodied energy flowing of the same type. For example, Kemp (1976) calculated the energy signature for a region on the west coast of Florida peninsula (Fig. C14a). In Fig. C14b, actual energy was multiplied by energy transformation ratios expressing the energy signature in embodied energy in coal equivalents. The graph shows more similarity among sources when expressed in embodied energy, possibly suggesting self-organization of the system towards energy matching. Where high-quality and low-quality energies are flowing with similar embodied energy, the high-quality energies may be well matched to low-quality energies. How typical this is remains to be seen.

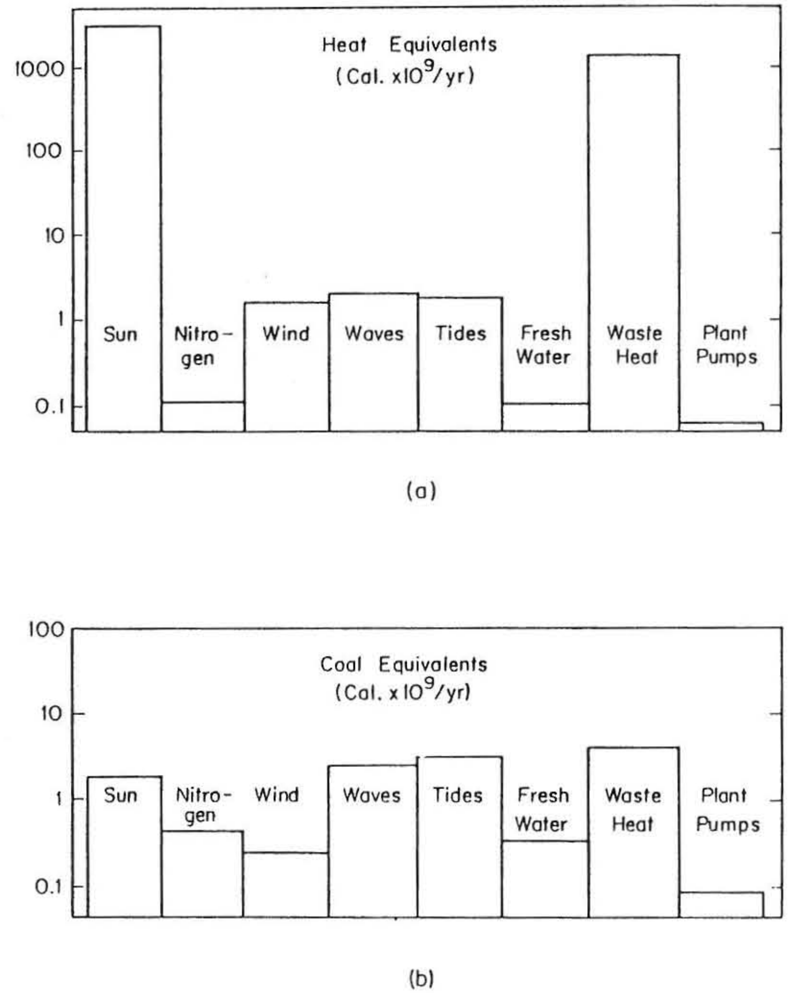


Figure C14. Signature of energy source flows for a region defined by a power plant. (a) Expressed in actual energy, heat Calories per time; (b) expressed in embodied energy, coal equivalents per time (Kemp 1977). Area is that served by Florida Power Corporation.

Energy Self-Organization and Maximum Power

Recognition of the different qualities of energy and the matching amplifier actions that maximize power helps account for the webs observed in self-organizing systems of nature and the human economy. By feeding back net energies to amplify inflow to an interconnected web, a signature of energy sources can flexibly and automatically generate a distribution of growth and efficiency, augmenting energy uses and thus draw more total power with all net energies used further to maximize power. For different energy signatures there are different resulting webs, but it may be speculated that all have the characteristics of hierarchy of converging energy quality transformation feedback amplifiers and energy matching.

If the self-organization process utilizes all by-production in useful feedbacks, then the emerging system gets more energy transformation by making many products and using them than by simple energy processing of one product at a time. The reductionist tendency in humans to solve energy problems item by item runs counter to the maximum power principle, requiring whole-system plans so that by-products are fed back into the system. No flow is wasted in a well-organized system. The embodied energy in a so-called "waste product" is as great as the end products.

Self-Organization Derived from Second Law or Vice Versa

The idea of energy quality control helps explain why systems build order and storage to survive. With higher quality energy to feed back, the inflow can be pumped better than if the energy were left to flow by simple diffusion driven by its own gradient. Thus, to use energy faster and degrade it faster, the system must build order, providing the energy levels are higher than the minimum necessary to keep up with the depreciation of the storages. This reasoning ties the second law and the maintenance of structure together as the same principle and explains why there are characteristic autocatalytic loops and other feedback arcs where energies are above some minimum levels.

Estimating Maximum Power from Energy Signature

If one knows the energy sources (signature) to a system, how can one calculate the maximum power that a well-adapted, self-organizing system can generate from the sources? Estimating the power flow is tantamount to evaluating the economic potential in the special case of human systems.

Some approaches to the problem of estimating power of a web from its sources are suggested with the diagrams in Fig. C15. These abbreviations of the actual webs are <u>index models</u>, which retain some essence of the whole web, generating an index that may be convenient for practical purposes of estimating energy-economic potentials. Which of these or other indices will be most useful remains to be decided by empirical testing.

The following are ways of estimating potential production given the energy signature as illustrated in Figs. C15 and C16.

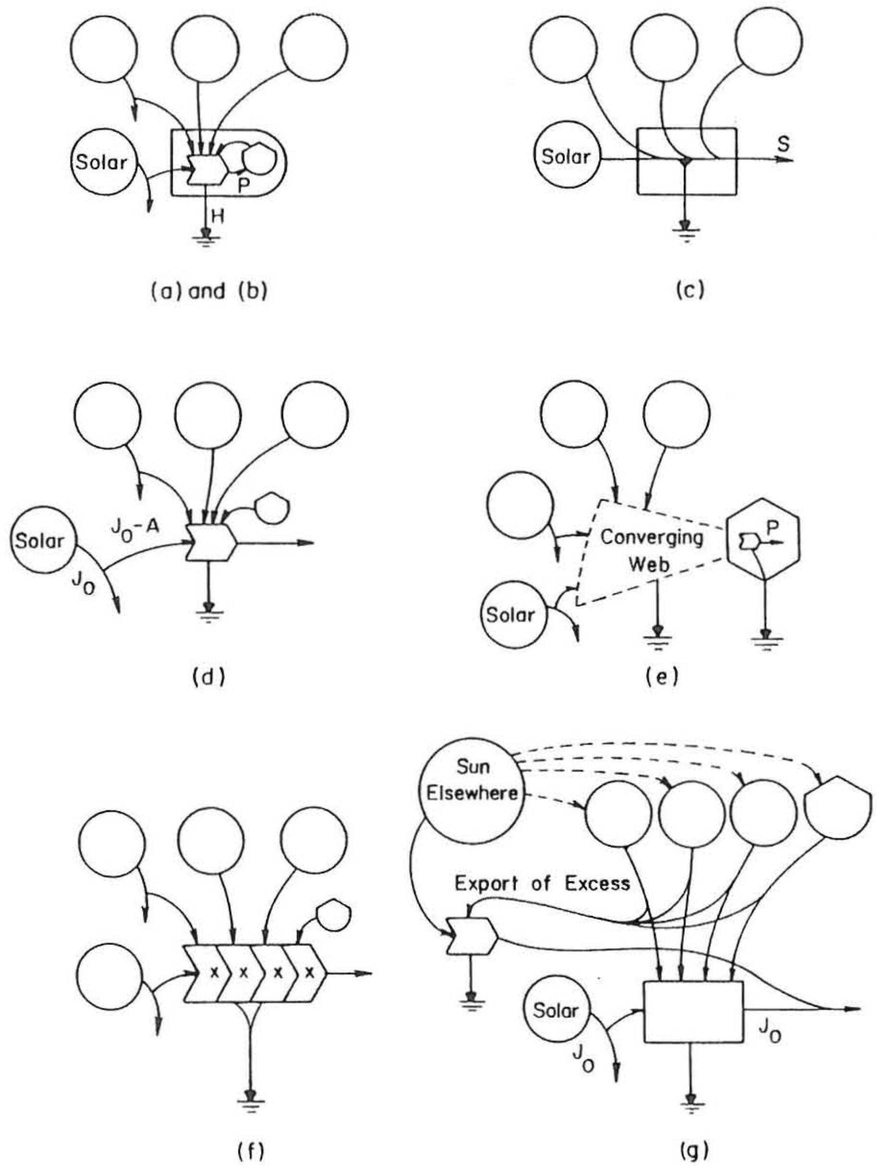


Figure C15. Diagrams of ways of calculating the power generating potential of a combination of input energies of different quality and quantity. (a) Measure observed production (P); (b) sum energy dispersal (H); (c) calculate sum (S) in units of embodied energy and divide by number of inflows; (d) measure unused low-quality flow (A) and subtract from J_o as a measure of effectiveness of P; (e) measure production of top consumer and multiply by quality factor; (f) multiply driving forces; (g) evaluate flows in solar equivalents and add that excess greater than J_o.

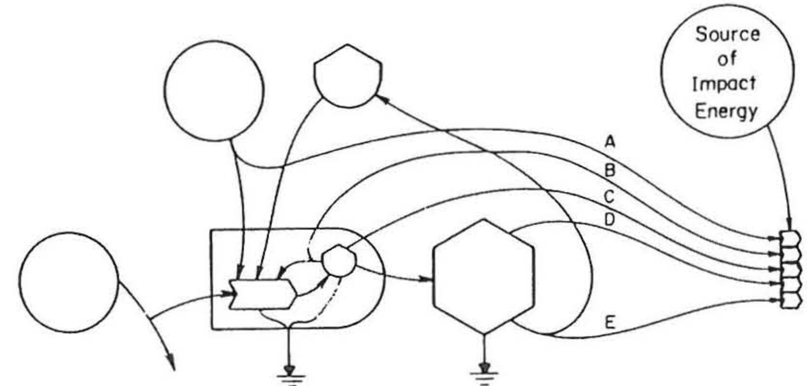


Figure C16. Production change estimated as the change in embodied energy of the maximum impact factor. Largest embodied energy among A, B, C, D, E, etc. is taken as estimate of total impact on production.

Fig. C15: (a) Measurement of the Dominant Productive Process

Because webs involve loopbacks and interactions of each unit in other units, a central dominant productive process feeds back and receives flows interacting from most other units. Thus, measuring the energy flow of the dominant production process and multiplying by its quality factor provides an integrated measurement of production potential. Adding in alternative productions that are secondary, whether upstream or downstream, would involve double counting. This system of counting would not work where the webs are not well organized.

(b) Sum of Heat Dispersed

When the web develops more interactions, amplifications, and energy capture, the total flow of energy increases in high- and low-quality flows alike, so that the total heat flow from the web in the combined heat sink also increases. This includes the energies attracted in by exchange and investments.

(c) Sum of Energy Flows, Each Expressed As Embodied Energy of One Type

Each flow is multiplied by its quality factor to convert all flows into solar equivalents (or other common type of energy). These are added. Since the inflows are all by-products of the same solar processes of the biosphere, adding converging components that diverged earlier is multiple counting of the potential of the same original solar energy. Hence, we divide the sum by the number of pathways added to obtain a mean solar embodied energy. This procedure gives greater weight to flows locally greater than the average in the biosphere. Geological flows are also expressed in solar equivalents (Odum 1978).

(d) Measuring Total Low-Quality Energy Used

The more higher quality energy is well used, the more low-quality energy becomes incorporated as matching energy, and the less unused low-quality energy (such as sunlight) passes unused. Measuring the albedo is a way to measure the effectiveness of the production process.

(e) Measuring Production of Consumers High in Energy Chain

If webs are organized so that the top consumers represent a converging of embodied energy of all sources in useful production, evaluating flow through top consumers can represent the total energy system. For example, conservationists often use large dominant species as indicators of the ecosystem in which they live. This index measures energy flow through terminal units of the web. The GNP is a measure of flows through the final demand sectors of the economy.

(f) Multiplying Driving Forces

Where two flows of different quality intersect, output is often proportional to the product of the driving or population force of each. Webs of interactions of many flows involve a series of interactions of this type, although usually interdispersed with storages and other units in the web. The Cobb-Douglas production function developed empirically from correlations in data is a product function, with exponents.

(g) Evaluating Solar Embodied Energy of Each Flow, Adding Excess of Each Over Actual Solar Energy to the Solar Energy Flow

Evaluate low-quality energy and add the embodied energy of the higher quality flows that is in excess of the low-quality flow. As shown in Fig. C2, these additions represent the energies that the high-quality excess could generate if exported in trade, so as to have full matching solar energy elsewhere, the productive products being returned in trade.

Fig. 16: Using Investment Ratio between High-Quality Energy and Lowest Quality Energy to Evaluate Production

After evaluating all flows in embodied energy of one type, calculate ratio of sum of high-quality flows to the low-quality flow and estimate production from Fig. C13.

Evaluating a Change in Production Due to Change in External Sources

Changes can be evaluated by sensitivity analysis of a simulation model. Energy analysis calculations can also evaluate change in embodied energy and the effect it has on the total power as visualized through one of the concepts given in Fig. C15.

Lavine and Butler (1978), considering impact of development on the interdependent web of the environment, use the largest impact as an index of the total energy change, since the impact site affects most other parts of the system through feedbacks. The idea is that lesser impacts will be less of a limiting factor than the largest impact and to add impacts would be to double count the impact on the productive energy flow (see Fig. C16).

Comparison of Concepts of Embodied Energy

In Figs. C3 and C4, each pathway was given the embodied energy equal to the total flow, because each was necessary to the others. With this concept of embodied energy, the energy is not portioned among pathways, and feedbacks are not additive at their amplifier intersections. Compare this concept with others in Fig. C17.

A part of this procedure does partition energy on diverging, flexible, high-quality energies that feed back (see Fig. C11).

Where energy transformation ratios are available from independent studies, they may be multiplied by actual energy flows of a web to get embodied energies. These may differ from those in the web if it is more or less organized for maximum power.

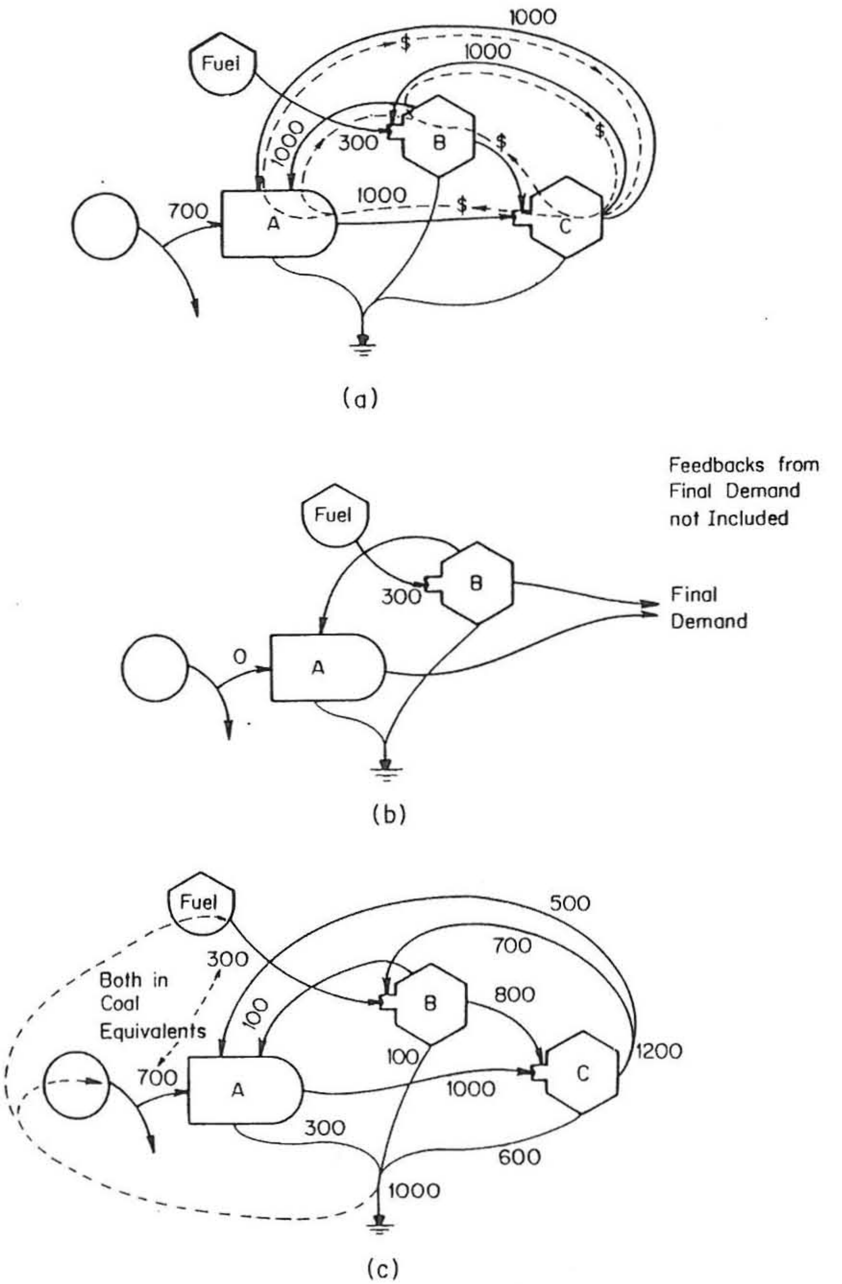


Figure C17. Comparison of alternative concepts of embodied energy. (a) Embodied energy assigned to all pathways as the sum of all necessary energy required; (b) embodied energy asigned in proportion to dollars but omitting feedbacks; (c) embodied energy assigned in proportion to dollars including feedbacks and environmental energies (Costanza 1979).

Embodied Energy Assigned by Matrix of Dollar Flows

Another definition of embodied energy uses the input-output matrix of dollar flows of the economy to assign the inflow energies to pathways (Herendeen and Hannon 1974; Krenz 1967). The inflowing energies considered are usually only the fuels (not the renewable energies of environment), which are assigned in proportion to the dollar flow, using a set of energy per dollar coefficients. The dollars that produce a contribution to final demand are multiplied by energy to dollar ratios to get the energy contributions to final demand. Inverse matrix coefficients are used. The calculation usually leaves off the feedback from the final demand. (See Fig. C17b, which shows the way the web is abbreviated as compared with Fig. C17a). Thus, energy that flows from fuel to B to C and then A in Fig. C14a is omitted from the calculations of energy reaching A in the procedure shown in Fig. C14b.

Another definition of embodied energy illustrated in Fig. C17c was used by Costanza (1979, 1980). The whole web is used, and environmental energies are included. In order to make a symmetrical matrix, degraded energies are connected to sources to make a closed loop evaluation. Numbers are obtained by the matrix inversion method.

In this use of embodied energy the totals are partitioned and are additive, whereas the first concept does not partition energy. The second and third concepts in Fig. C17 may underestimate the energy actually required for the flows.

Expression of mechanical work in terms of heat energy was demonstrated as the mechanical equivalent of heat (established by Joule). The concept of work as an energy transformation was given by Maxwell (1877). The application of energy to measure the total process has spread into different scientific fields; for example, quantification of potential energy as ability to drive processes in chemistry (Gibbs 1901). Energy transformations at infinitely slow rates were calculated to relate energy transformations necessary to changes of states (Carnot 1824; Gibbs 1901). That energy could be a common denominator to measure all useful works was proposed widely with statements by the following, to mention a few: Boltzman (1905); Ostwald (1907); Soddy (1935).

Lotka (1922) provided the maximum power principle as an extension of natural selection. DeGroot (1952), Prigogine (1955) and Onsager (1931) formulated descriptions of linear open system energy transformations. Energy analysis describing observed embodied energy in transformations was attempted in various ecological systems by Juday (1940) and Lindeman (1942).

Recent books on energy analysis by Pimentel (1979) and Steinhart and Steinhart (1974) do not distinguish energy quality clearly. Slesser (1978) and Fluck and Baird (1980) discuss alternative concepts.

Other Energy Quality Concepts

The Carnot Ratio is often regarded as a measure of the energy quality of heat gradients, measuring their ability to be converted into useful work of mechanical quality. The Carnot Ratio estimates the efficiency at reversible condition (stalled). The efficiency of conversion of heat gradient source to mechanical energy at maximum power is half the Carnot Ratio.

High- and low-quality information content is not distinguished by calculations of bits of information. Embodied energy per actual Calorie goes up with the bits per actual Calorie. The latter a measure of the quality of information.

Essergy, Exergy

Another concept offered as a measure of energy quality is essergy (Gibbs 1901; Evans 1969). Essergy is a concept defined to evaluate the ability of energy sources to do mechanical work. It is the sum of the energies, each multiplied by the fraction of each energy, that can be converted into mechanical work. For those energy types of lower quality than mechanical energy, it is a measure of theoretical efficiency. It does not consider efficiencies at maximum power. Energy flows of higher quality than mechanical work are not given greater value per Calorie. Exergy is used for some of the components of the potential energy included in essergy. Energy analysis done in units of solar equivalents, coal equivalents, or other types of energy may also be expressed in mechanical work equivalents by multiplying by the appropriate energy transformation ratio. Sussman (1981) provides an exergy manual.

Historical Note

The concept of energy as a measurement of process related to heat was adapted to scientific usage from ancient vernacular usage about 1842 by Robert Julius Mayer, Herman Helmholtz, and Prescott Joule (see Thirring (1968) and Cook (1976)). Marx used human labor as a metric for measure of useful works in 1840 before energy concepts were well established.

Summary

In this chapter, useful work was defined as those transformations of energy that contribute to maximum power and survival of the system because of the system designs. Energy transformations, by means previously selected under competition for the best possible efficiency commensurate with maximum power, define the inherent thermodynamic energy of one type necessary to generate another type. Ratios of energy of one type to generate another under these conditions are energy transformation ratios. To compare the relative contribution of energies of different types to potential value, energies are converted to embodied energy equivalents of the same type using transformation ratios.

Embodied energy was defined as a way to measure cumulative action of energies in chains and webs. Embodied energy constitutes an alternative theory of value useful for tracing sources, estimating net energy, determining relative importance of components, and comparing free items that are not covered by money. The study of relative importance of sources, feedbacks, and alternative designs is facilitated by energy diagraming followed by energy evaluations using quality factors and embodied energy. Such energy analysis has been applied to human problems and the energy crisis, but is more generally applicable to all systems.

Embodied energy, energy quality, and the various ratios used to evaluate system configurations provide techniques of energy analysis and independent approaches to understanding value. Whereas real, self-designing systems develop complex webs to combine the signature of available energy sources, each of different quality, apparently maximizing combined power, it is not yet clear which of a number of simplified models best predicts the combined production potential. Recognition of a scale of energy quality provides new principles of energy use such as matching high and low quality, requiring that control of hierarchies be cascaded, and requiring that net energy be utilized as a feedback. At present there is no concensus on embodied energy measures and their appropriate use.

APPENDIX D

DISCUSSION OF CONCEPTS AND ASSUMPTIONS

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Part 1: Utility of Energy Analysis

The ability to consider values in both natural-environmental and human systems all on a common basis is often recognized as the most important attribute of energy analysis. Energy analysis uses a common denominator (energy flow) to assess the generation or loss of value in both environmental and human systems, thereby supplementing the traditional valuation techniques in which environmental flows and resources are often considered externalities. Because the common denominator is governed by the laws of nature, energy analysis may offer a more responsive as well as a more holistic approach to planning and policy making. Being grounded in the universal laws of nature, the analysis technique is able to treat the system of concern as the "combined economy of man and nature," rather than as two separate systems with recognized but poorly understood linkages. In energy analysis, the use of energy and time (i.e., energy flow) to generate work is seen as the linking mechanism between the natural-environment system and the human system, thereby setting the stage for unified, more complete analyses of the combined system.

Conceptually, all elements can be evaluated in energy flow terms. In practice, uncertainties remain with various energy flow evaluations. Those uncertainties are discussed in the comments throughout this manual. Overall, the manual does demonstrate that energy analysis has reached a level of refinement commensurate with benefit-cost and other traditional analysis forms. Therefore, the manual is offered as a supplement to the traditional tools for analyzing the combined systems of man and nature.

Part 2: Issues Involved in Using Power as an Indicator of Value

The basic premise, that "systems with the most energy resources can use them to meet all other contingencies so as to survive competition and maximize vitality of the combined economies of man and nature," has been viewed as an energy theory of value. The theory is based on the assumption that it is inevitable that any surviving system of man and nature tends toward operation at maximum power loading. Consequently, it is assumed that maximizing work accomplished in the combined economy of man and nature is desirable and is the appropriate goal of the manual's analysis procedure. In the past, these assumptions have been controversial, although few of the issues of the controversy have been presented in the literature.

One issue is the disputed validity of the maximum power theory, which states that systems that maximize their flows of energy (i.e., work) survive in competition. Although there is evidence to support this theory, it is not yet proved. Its validity is probably comparable to that of the more common theory that maximizing economic production enables a system to meet contingencies so as to survive competition and maximize vitality. If maximizing useful work for the combined economy of man and nature is the goal of the analysis procedure, then the analysis conclusions are dependent on the validity of the maximum power theory.

Even if the maximum power theory were proved, some may question whether its application is the appropriate goal of the manual's whole analysis procedure. Essentially the debatable component is whether survival alone is an appropriate goal. History has provided examples of human systems in which survival is valued less than other goals, such as achieving honor, a high quality of life, happiness, etc. However, it may be argued that in such historical examples only a subsystem does not survive. For example, although an individual may die to preserve his honor, the larger social system based on the honor value is thereby preserved. With this view, it is evident that the boundaries within which the maximum power theory is applied are very important. That is, the issue may be one of determining for which system should power be maximized in order to promote survival.

To be generally accepted, the analysis model's boundaries must match the boundaries of the value system of concern. It is always possible that maximizing power for a given subsystem might have the effect of decreasing power for the system, or vice versa. Subsystems are, of course, systems themselves. For this manual, is the appropriate boundary of application the developed region of the human economy? That region plus all the natural environment? or That region plus only the part of the natural environment, which we can prove is directly important to the human economy? Similarly, is the appropriate boundary of application the local area? The regional or state area? The nation? The whole world?

According to this manual, power will tend to be maximized (and thus calculations for survival should be made) for a globally bounded system so that full life-cycle effects of a change of any energy flow will be considered, regardless of where they occur. This is consistent with a concern for valuing environmental externalities, which of course are not constrained by political boundaries. It should be noted, however, that the value system of concern, and its boundaries, are not always well defined in the decision-making process. Such lack of definition often makes it impossible to avoid controversy in choosing model boundaries. For example, conflicts between boundaries of governmental and environmental concern (e.g., air pollution from one political entity causing costs to another) often lack resolution and consequently leave the choice of appropriate analysis boundaries open to considerable controversy.

Like many models, including those in economics analyses, the energy analysis model is very sensitive to changes of boundaries. That has been demonstrated in past work where a similar energy analysis model was applied to environmental impact assessments of transportation actions, using local, regional, and national boundaries. It has also been demonstrated in net energy analyses, which have shown considerable variations depending on boundaries.

Part 3: Accuracy of Energy Transformation Ratios

The concept of embodied energy as an indicator of the amount of energy used in a system to generate any specific energy flow is generally accepted in all schools of energy analysis. The concept that, for an energy-effective system (i.e., one with the best possible efficiency consistent with maximum power loading), embodied energy is also an indicator of value in the system is somewhat more controversial. Actually, this concept is homologous to the economic concept that for an economical system (i.e., one in which costs are balanced by utility), the cost of labor and capital embodied in the system is an indicator of the value of that system. Consequently, the controversiality of the theoretical bases of value indicators in both energy analysis and economics may be very comparable.

Embodied energy analysis, however, is a relatively new discipline; and thus some of the required energy data have been only broadly estimated. Therefore, some have questioned whether energy transformation ratios, which are at the heart of embodied energy evaluation, can be calculated with sufficient accuracy for purposes of power plant siting analyses. Several of the issues relevant to this question are discussed below.

One issue concerning the accuracy of energy transformation ratio calculations involves the appropriateness of the choice of systems to be evaluated. Many of the energy transformation ratio calculations are based on evaluations of the steady state global natural system. That is, that system is used as a model of a system operating "under competitive conditions in which there is the best possible efficiency consistent with maximum power loadings." While there is considerable reason to believe that the steady state global natural system meets those conditions, some reviewers in the past have taken issue with that assumption. The basis of the argument that the steady state natural global system is appropriate is that it has developed over long periods of evolutionary competition and has achieved an energy budget of near steady state conditions over the long term. In addition, according to the maximum power theory, surviving systems (e.g., evolved steady state systems) operate under conditions of maximum power loading. Therefore, it appears unlikely that the steady state global natural system could be far from an appropriate model for energy transformation ratio calculations.

However, some of the energy transformation ratio calculations (e.g., for urban structure and commodities of human exchange) are based on evaluations of some human-industrial systems as models of systems operating "under competitive conditions in which there is the best possible efficiency consistent with maximum power loadings." Whether the human-industrial systems evaluated do indeed meet those conditions has also been questioned. In theory, a free-market economy should guarantee the competitive conditions and the maximum power incentive, and the choice of mature human-industrial processes in such an economy should assure the best possible efficiency consistent with maximum power loadings. In practice, however, the economy, with its non-free-market components, does not always guarantee competitive conditions in every market, and whether a given human-industrial process has indeed matured (i.e., operating with the best possible efficiency) is never certain. Thus, some uncertainty remains about the appropriateness of human-industrial systems as models for calculating energy transformation ratios.

The analysis findings will vary in proportion to changes of the energy transformation ratios used. Consequently, analysis findings may lack accuracy to the extent that the energy transformation ratio calculations are led astray by evaluations of inappropriate system models. It should also be noted that, the question of just what is accurate enough for purposes of the plant-siting analysis is also relevant to assessing the model's sensitivity. That question can be answered only by comparison with the accuracy of alternative analysis tools and with the risks of the consequences of being inaccurate.

Even if the systems evaluated in the calculation of energy transformation ratios do meet the specifications of operating "under competitive conditions in which there is the best possible efficiency consistent with maximum power loadings," there remains some question of the quality of data available to evaluate the energy flows of those systems. The global system's use of sunlight to power all of the world's natural processes has been evaluated by a number of methods and researchers and appears to be well-accepted data. However, determination of the natural-system global energy flux of particular classes of energy transformations in natural processes often requires data that have not been well established. For example, the base data on the natural global flux (of resource cycles and associated energy changes) of wind, carbon, acid substances, vapor, rocks, and dissolved solids, have been only broadly estimated. As is the case with many data used in all forms of environmental and economic analyses, levels of confidence have not yet been determined.

The data problem may be more severe when evaluating embodied energy flows of human-industrial systems used as models for energy transformation ratio calculations. Although data on the energy flux of the particular transformation of concern may be well established, the data needed to evaluate the whole human/industrial system's energy flux used in generating that transformation are often not well established. Often there is controversy concerning what energies contribute to the transformation of concern. For example, there is considerable controversy about whether the energy required to support the labor force should be considered as the energy contribution to the transformation (i.e., production process) achieved by that labor force. In addition, often the needed data are dependent on private-industrial or public sector statistics, which are often broad approximations. That is especially relevant in the case of urban structure or land use calculations. Of course such data concerns are common in many other forms of environmental and economic analyses.

Another issue concerning the accuracy of energy transformation ratio calculations involves the validity of the assumption that the <u>total</u> annual amount of sunlight absorbed in the global system is used (either directly or indirectly) to generate the annual energy transformation of each individual natural process. This assumption is inherent in most of the energy transformation ratio calculations that use the steady state global natural system as a model for evaluation. For example, in calculating the solar energy used by the global system to generate the chemical energy of all primary production, not only the sunlight used directly in photosynthesis is counted, but also all other sunlight absorbed by the global system. This much larger amount is counted because it is assumed that the sun is the only significant energy source for all processes of the global natural system and that this system is such a highly interdependent web of processes that all processes are at least indirectly interdependent. Therefore, the sunlight used to drive the hydrologic, atmospheric, and all other global processes at their particular rates of production is used indirectly to drive photosynthetic production at its global rate. In other words, even an annual loss of the sunlight that would have been absorbed by the middle of the ocean or by the highest clouds would cause a change in the global steady state flux of primary production. That is, the total amount of sunlight absorbed by the global system is needed to drive the global photosynthetic production at the global steady state rate.

The unproved parts of this reasoning, and consequently the parts that may be at issue, are the assumptions that the sun is the only nonnegligible energy source for the global natural system and that this system is such a highly interdependent web of processes that all processes are at least indirectly interdependent. The question is unsettled with regard to the global importance of tidal energy and the ultimate energy source of some geologic work. The first assumption, that the sun is the only nonnegligible energy source, is commonplace in the literature of many fields, although there probably is no way to verify it. The second assumption, that all of the world's natural processes are at least indirectly interdependent, is somewhat less common and is more likely to be a point of contention in the use of energy analysis. Probably there is no way to verify the second assumption either, although it should be noted that no disproof has yet been shown. Continued use of this assumption relies on the considerable evidence in its support. Calculated energy transformation ratios may be inaccurate if these assumptions are incorrect.

The accuracy of some energy transformation ratio calculations depends on knowledge of the particular energy transformation ratio between sunlight and coal (or other fuel) or between sunlight and electricity. Such knowledge is needed in order to express industrial energy flows (usually expressed in fuel or electricity equivalents) as solar equivalents, so that both natural-system and human/industrial-system flows may be compared. For example, in calculating energy transformation ratios for commodities of human exchange (e.g., cement, glass, steel, etc.) or for human assets (e.g., urban structure), the energies used directly in the industrial production processes are usually reported as fuel or electricity equivalents, which must then be translated into solar equivalents so that all energy contributions can be accounted for on a comparable basis.

Precise knowledge of the energy transformation ratio between sunlight and coal (or other fuels or electricity) is not known. Estimates have been made based on a combination of natural and industrial processes. The steady state global natural system is used as a model to calculate the amount of sunlight required to generate each Calorie of wood; a wood-fueled electricity-producing system is used as a model to calculate the number of Calories of wood (and the number of Calories of fossil fuels used indirectly in harvesting, power plant construction, etc.) required to generate each Calorie of electricity; and the inferred number of solar Calories required to produce each Calorie of electricity is compared with the number of Calories of coal required (directly and indirectly) to produce a Calorie of electricity (calculated based on a coal-fired power plant model). Approximate findings are outlined below.

Global natural system: 1000 Cal Solar = 1 Cal wood
Wood-fired power plant: 2.8 Cal Wood + 2.6 Cal Coal (indirect) = 1 Cal Electricity
Coal-fired power plant: 4 Cal Coal (direct and indirect) = 1 Cal Electricity
Combining equations: 2 Cal Wood = 1 Cal Coal; 2000 Cal Solar = 1 Cal Coal

Although this procedure provides ball-park estimates, it has some soft spots. It assumes that both the wood-fired and coal-fired power plant systems evaluated are operating "under competitive conditions in which there is the best possible efficiency consistent with maximum power loadings." As discussed above, that assumption may be questioned. In addition, the set of data used to evaluate the indirect energy contributions to the power plant systems (e.g., energies used to mine the coal or harvest the trees and to build, operate and maintain the power plants) may be contested, as indicated above in the discussion regarding questions of what should be counted as energy contributions and how accurate are the available data. Because of these soft spots, all energy transformation ratios expressing industrial energy flows as solar equivalents must be considered first-cut estimates pending more exhaustive tabulations of transformations from sunlight to coal (or other fuels).

One other issue concerning energy transformation ratios is discussed in the energy analysis literature. Even if the maximum power theory were proved, a question remains concerning the need for assuming maximum power loading as a criterion in the determination of energy transformation ratios. In practice, however, the question of loading is often not a problem since observed transformations are used without assumptions about loading. When loading assumptions are used, they are based on observations that surviving systems tend toward operation at maximum power loading. In general, these observations have been of natural rather than human-industrial systems. Whether such a condition is appropriate for human-industrial systems, especially whole economies, may be debated. Probably, definition of time boundaries is important in this concern because it would appear that operation far from maximum power loading can exist, but not persist for very long periods of time. Thus, with long-time boundaries, it may well be appropriate to assume maximum power loadings in the determination of energy transformation ratios. Deviations from maximum power behavior are regarded as part of the necessary variation for creative fitting of the system to maximum power in the long run. Hence, some deviation is regarded as a necessary useful energy diversion. (It should be noted that a similar, although less likely, issue could arise concerning the appropriateness of assuming "competitive conditions" as a criterion in the determination of energy transformation ratios. That is, our economy provides many examples where, at least in the micro-view, processes can proceed without competition due to imperfect knowledge, government regulation, etc. However, this issue too may become negligible if time boundaries of concern are set far in the future.)

The issue of assuming operation at maximum power as a necessary criterion in the determination of energy transformation ratios is an issue at the heart of the analysis procedure. Energy transformation efficiencies vary according to power loading of energy transformation processes, and the analysis model is extremely sensitive to changes in the energy transformation ratios. Analysis findings will change in direct proportion to changes in the ratios used. The focus of concern here is whether the maximum power requirement sets a stricter, or a less strict, limitation on energy transformation efficiencies than is found in the operation of the particular (human) system, which is supposed to be protected by the whole power plant siting analysis. In other words, if the human system of concern can achieve energy transformations at a higher efficiency than is observed (and reflected in the energy transformation ratios), then the analysis model overestimates the human system's energy flows needed for achieving the energy transformations, and therefore for achieving the required work. Similarly, if the human system of concern can achieve only less than the level of efficiency assumed in the energy transformation ratio calculations, then the analysis model underestimates the human system's energy flows.

Part 4: What Should Be Counted as Energy Contributions

The embodied energy accompanying each pathway in the diagram (Fig. 1 in the manual) is intended to be a comprehensive indication of all energies contributing to each pathway. There has been some controversy among energy analysts as to just what should be counted as energy contributions. Those energy analysts working within the framework of economic analysis have often excluded some renewable energy flows, some nonrenewable energy flows embodied in nonfuel minerals, and some energy flows used in the life support of (and therefore embodied in) human labor. In this manual, all such energies are intended to be included in the embodied energy evaluation of any pathway. The following discussion expands this issue.

Energy analyses have been applied to a variety of undertakings requiring a consideration of various sets of energy flows and storages. Natural-ecosystem analyses often require consideration of only the natural environment's energy flows and storages. These include sunlight and its many transformations and subsequent storages in land, air, water, and biotic cycles. However, human-system analyses or analyses of the combined system of man and nature (as intended in this manual) involve several categories of energy flow or storage that are not significant in natural ecosystem analyses. For example, fossil fuels, although technically a storage of energy from natural ecosystems, play a dominant role in human-system energy flows even though they appear to contribute only little of their embodied energy flow to natural-ecosystem functions. Similarly, it might be argued that many other minerals—such as iron, copper, and aluminum—may contribute much more of their embodied energies to human-system production than to the natural ecosystems from which they were generated. Although not normally considered as energy contributors, each mineral used in the human system process carries embodied energy that is released according to the specific mineral's uses in those processes. Consequently, when evaluating energy use in man-nature systems, the important categories of energy flow and storages include: natural ecosystems (including major flows and storages in land, air, water, and biotic cycles); fossil fuels; and other minerals.

All of these categories contribute embodied energy to production processes in the economy of man and nature. However, when evaluating energy contributions to any particular economic production process, many analysts exclude from consideration any use of these embodied energies that are chanelled to that process via human laborers. That is, any energy used as life support for labor (i.e., the energy embodied in the goods and services consumed by labor) is excluded. The argument for this exclusion is that, "since the objective of the economy is to furnish people with their needs, to count the energy for life support of labor is to double count" (Slesser, M. 1974. Letters. Science 196:259–61). The validity of this exclusion has been a major issue in the field of energy analysis. In addition, because solar radiation is often considered a free good, some analysts exclude from consideration sunlight or any of the energy flows of its transformation products in the natural environment.

The energy analysis methodology presented in this manual does not exclude the counting of energies used in the life support of labor or the energies from sunlight in the natural environment. Indeed, one of the major premises of the whole methodology is that energy analysis provides an empirically based means of valuing the effects of resource allocations that are external to other means of analysis (particularly economic analysis). Because there are energy requirements, and subsequent effects, for all resource uses—including environmental, labor, and fuel, mineral and other capital resources—a complete accounting of the energy cost of any process requires that no resource contributions to that process be excluded from consideration. In sum, because even the so-called "free" resources (e.g., sunlight) and the end-use feedbacks (e.g., labor) are required contributions (up to the amount that would be embodied under competitive and maximum power-loaded conditions, i.e., the least energy cost requirements of those resources and feedback flows), they are assumed to add value to the economy.

Should solar-derived energy flows and storages of the natural environment be excluded from consideration, analysis findings would not reflect any of the value changes associated with environmental impacts. Should the energy cost of labor be excluded from consideration, analysis findings would not reflect the extent to which changes in system-wide labor requirements associated with plant siting proposals and alternatives might affect value in the economy. It should be noted that these conclusions assume the validity of the overall concept that value and the embodied energy cost of achieving that value are consistently related. Whether that concept is indeed valid, could be determined with definitive findings of either the maximum power theory (discussed above in Part 2) or the theory that there is a consistent proportional relationship between economic production and embodied energy flow (discussed below in Part 8). As indicated in Parts 2 and 8, considerable, although not definitive, evidence exists in support of both theories, and further research would be useful.

Part 5: Space and Time Boundaries of Concern

In evaluating the change of overall flow of value in the web, it is important to define the space and time boundaries of the web which is of concern. The space boundary issue is discussed above in Part 2, noting that in this manual, evaluations are made of a globally bounded system. That is, power is to be maximized for the largest possible system of concern. In addition, the time boundary of concern in this manual is large enough to include full life-cycle effects of any change, even those changes occurring in the very slow-moving cycles of nature. For example, the destruction of a high-quality agricultural soil today is valued as a loss not only during the life of a power plant, but rather for all the time (and associated energy flow) it will take the most effective processes to replace that soil. The use of such a long life-cycle time boundary for maximizing the overall flow of value in the web may often differ considerably from the time boundary assumed in many economic analyses, where value is determined according to market decisions in which often there is very limited reward for considering full life-cycle effects.

Part 6: Double Counting Possibilities in Embodied Energy Evaluations

Aggregating effects according to the algebraic summation of the changes in embodied energy flows requires considerable care to avoid double counting. Because embodied energy values are indicators of system-wide energy requirements for generating a given flow, two different flows that may be cogenerated by a single system may carry at least some of the same embodied energy. In such situations, adding embodied energy values may constitute double counting to the extent that embodied energy evaluations are based on same-system energy flows that are generated (a) from the same source or sources, and (b) during overlapping periods of time.

For example, it would be double counting to sum the embodied energy values of photosynthetic production of vegetation and evaporation of any water that is inherently transpired within the system's web of processes that contribute to the photosynthesis. In such a case, the photosynthesis and evaporation would be merely different manifestations of the same sunlight. However, there is some uncertainty regarding possible double counting of embodied energy values when the two flows being considered take place on vastly different time scales (e.g., photosynthetic production processes and fossil fuel generation processes). Similarly, there is some uncertainty when the two flows being considered are generated by two systems with unknown degrees of interdependencies (e.g., photosynthetic production in the natural environmental system and economic production in the human system, when we know that the two systems are at least partly interdependent, i.e., driven by common energy sources). Although some care has been taken in the development of this manual to avoid such double counting, any user who may expand the parameters considered in the manual should be aware that to the extent that any two energy transformations (and resulting flows) are dependent on a common energy source, their embodied energy values may double count against each other. It should be noted that the manual's procedure emphasizes the importance of the detailed energy diagram in making clear what relationships are believed to exist. Often the diagram clarifies uncertainties and helps prevent double counting or misunderstandings about what has been assumed.

Part 7: Consistency of Governing Mechanisms in Energy and Economic Systems

The fundamental concept in energy analysis, that there exists a single economy of man and nature with a single set of rules governing all flows among all parts, differs significantly from the economics concept of an economy. In economic analysis, some flows are governed by market dynamics and other flows, governed only by the laws of nature, are not amenable to economic quantification. This fundamental difference in the models used to evaluate resource flows explains why energy analysis is proposed as a tool that inherently enables evaluations (of nonmarket flows) that are not amenable to evaluations with traditional economics models.

Part 8: Comparison of Monetary and Embodied Energy Indicators

When using the ratio of total energy to GNP, there are assumptions and potential pitfalls to be aware of. The major assumption is that there is a consistent proportional relationship between economic production, as measured by GNP, and the embodied energy flow of the man/nature system generating that production. Although testing of that assumption has been very supportive, it is not yet broadly accepted. Most testing has compared money with only fuel energy, not all the energies of the environment.

Even if the hypothesized consistent proportional energy/GNP relationship is accepted, there are some important constraints to its appropriate use. The energy/GNP ratio is a measure of energy flow as it is first absorbed by the economy to money flow at final demand. As indicated in Fig. D1, most energy is first absorbed by primary processes of the economy and then is used in a series of transformations, each with attendant conversion losses before it is actually embodied in a good or service consumed at final demand. Therefore, the ratio of actual

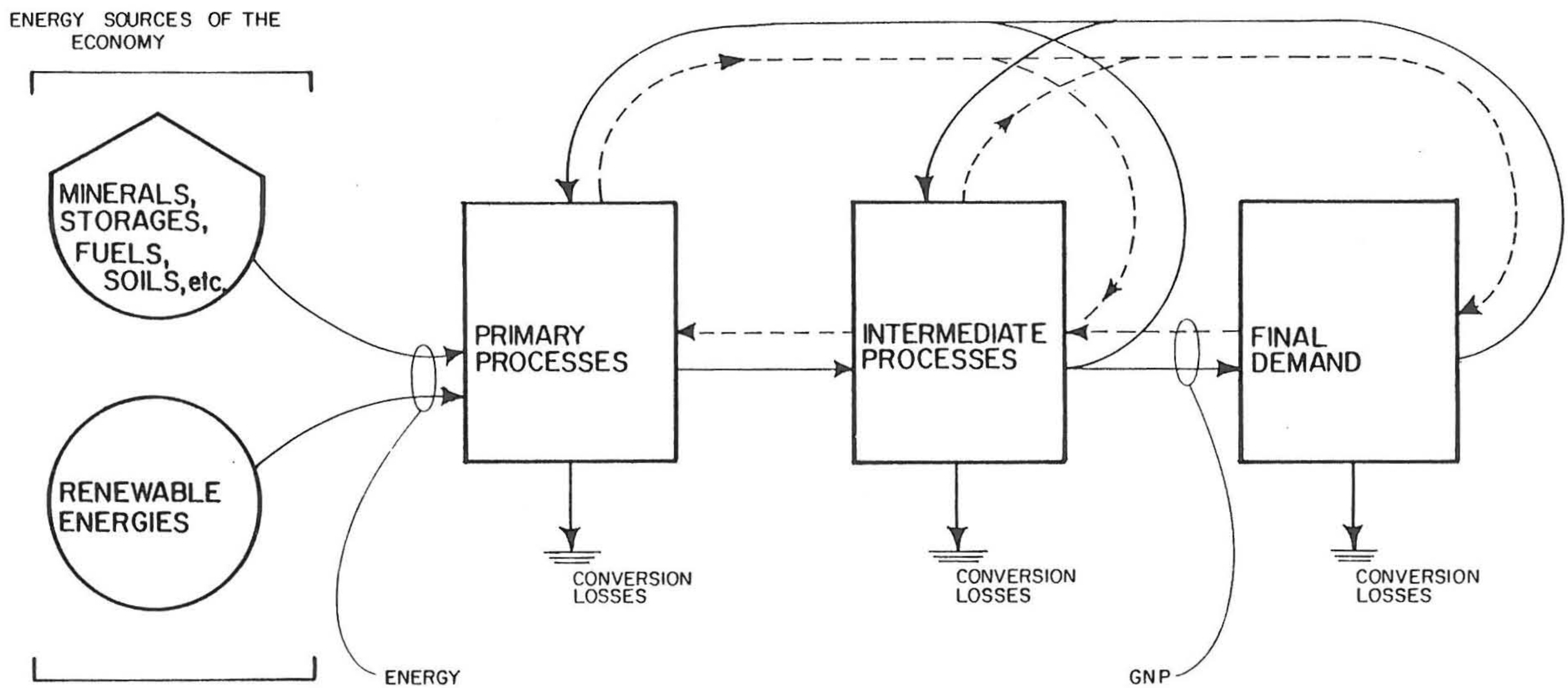

Figure D1. Energy flow (solid lines) and money flow (broken lines) in an economy. Most energy is absorbed by the economy in primary sectors. The energy is then transformed, with attendant conversion losses, in the process of producing goods and services for final demand. GNP is a measure of money flow at final demand. Total money flow in the economy is larger than GNP.

energy flowing at final demand to GNP dollars (which are measured at final demand) is much lower than the total embodied energy/GNP ratio. That is, actual energy flowing at final demand has a larger effect on GNP than would be indicated by the total energy/GNP ratio. Consequently, the total energy/GNP ratio would underestimate the effect on GNP due to any energy that is first absorbed by the economy by interacting directly with intermediate or final-demand processes. For example, a calorie of tree production in the landscaping of a residential front lawn (interacting directly with a final demand sector) has a larger effect on GNP dollar value than a calorie of tree production in a lumber industry's forest. (The latter first interacts with a primary economic process before becoming embodied in a final demand economic process.) Thus, the total energy/GNP ratio may be accurate for calculating GNP value from energy flow only when the energy being considered first interacts with the economy in primary processes and then is used in a typical series of transformations before reaching final demand. Because most energy absorbed by the economy meets that criterion, this constraint on the use of the energy/GNP ratio should not be a significant barrier to use of the ratio in the manual.

A second constraint must also be considered. Because GNP is a measure of money flow only at final demand, when using the ratio to calculate the amount of energy absorbed by the economy in support of any given money flow, that money flow should be a measure at final demand, not at primary or intermediate transactions. Application of the ratio to money flows at primary or intermediate transactions would underestimate the energy absorbed by the economy. This is because the ratio assumes more conversion losses than have actually occurred between the energy's first interaction with the economy and the transaction where money is flowing. Therefore, the total energy/GNP ratio may be accurate for calculating total (embodied) energy flow only when the money flow being considered is at final demand. Because many flows of money associated with construction and operation of a power plant do not meet that criterion, the user of this manual should not rely on indiscriminate use of the energy/GNP ratio as an accurate indicator of embodied energy associated with economic goods and services that are inputs to the power plant system.

Part 9: Sensitivity of Energy and Economic Models to Environmental Changes

Another way of understanding some of the basic differences between energy analysis and economic analysis is to compare the models they use for predicting utility, i.e., how much value can be generated with the use of a given resource in the economy. Energy analysis makes evaluations of future effects using a model based on the physical laws of nature that set limits on the efficiencies of energy transformation processes. Economic analysis uses a model based on human perceptions and projections of the future utility of resources; the model is often referred to as market pricing, or "Adam's invisible hand." Although ultimately both models may provide the same findings, the energy analysis model may enable man to be more rapidly responsive to certain near-term and long-term resource changes in the combined system of man and nature, before

"Adam's hand" recognizes markets for those resources.

Part 10: Assumptions Concerning Discounting in Energy Analysis

Although energy evaluations may be independent of the shifting value of money due to inflation, they may not be independent of shifting value due to real discount, which is another component of apparent change of value with time. Real discount is an estimate of the rate at which a resource changes value with time beyond the effect of inflation. In the energy analysis procedure for comparing various values, it appears as if energy values need not be discounted with time. That, of course, would appear to contradict traditional economic theory. Several different arguments on this issue have been posited, and none yet has received general acceptance.

Some energy analysts argue that energy analysis accomplishes the same thing as discounting because evaluations are made of what could have been done in the future with the same energy. Accordingly, the only difference from traditional discounting is that the rate is not made explicit. This argument appears to include the assumption that energy use in the future will be accomplished at maximum efficiency for a system "under competitive conditions with processes of transformation loaded for maximum power." In other words, that efficiency is assumed for the evaluation of what could have been done in the future with the same energy. Because all future uses of that energy assume that efficiency, it is not clear how this argument leads to different values of the same energy if used at different times in the future (as would occur with discounting in traditional economic valuation). Although calculated dollar values would change, due to changing energy-dollar ratios of the economy, it appears as if embodied energy values would remain constant. It should be noted that some energy analysts have suggested that it is inappropriate to discount energy, or even that energy should have a negative discount rate, because of the apparently increasing real value of energy in the world today. It has also been argued that the value of energy in the economy of man and nature changes according to the rate at which that economy uses energy. This argument is based on the observation that energy transformation efficiencies decrease as energy is used more rapidly. Accordingly, in times of increasing growth rates, energy use becomes less and less efficient as time progresses. Therefore, the same energy is capable of generating less and less value in the economy. This argument suggests that projection of recent discount rates far into the future would be appropriate only if growth rates continue to change as they have in the past. With no general acceptance yet of any one of these arguments, there appears to be need for further research and discussion of this issue.

It is commonly understood that economic benefit-cost analyses are extremely sensitive to changes of discounting assumptions. To the extent that energy analysis is used to estimate social values, there remains considerable uncertainty regarding the effects of the discounting issue.

APPENDIX E*

ENERGY ANALYSIS OF ENVIRONMENTAL VALUES§

A Manual for Estimating Environmental and Societal Values According to Embodied Energies

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*Part of A Manual for Using Energy Analysis for Plant Siting.
§Modified from Report to Nuclear Regulatory Commission, Contract NRC-04-77-123, 1980.

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ABSTRACT

This is a manual for estimating the energy embodied in environmental values and in human interactions with the landscape. The energy flows of nature develop storages and patterns of organized flow in the form of ecosystem, earth systems, and interfacing systems of human activity. By estimating energy flows and expressing them in solar equivalents, numerical values are found for the environment on a natural, universal scale, one that can be related to economic potential according to the prevailing ratio of dollar circulation to energy use.

First, main environmental flows and storages of energy are identified and ranked according to the solar equivalent energy with the help of a general model diagram for most landscapes, which serves as a checklist. Then, values of energy flow are determined, first in actual energy values, i.e., their heat equivalents, if they were converted into heat. Next, all external energy flows are converted into embodied solar equivalent Calories, thus making dilute and concentrated energies comparable so far as their original source. Energy flows multiplied by the time for storage provides embodied energy values for the structures, storages, and accumulations, also in solar equivalents.

Estimates of energy flows or storages of the environment expressed as solar equivalent Calories may be expressed as dollar equivalents by multiplying by the ratio of dollar flow to solar equivalents used in the economy for that year. This is an estimate of the proportionate contribution of that environmental resource directly and indirectly to the economy.

When evaluations are made for a particular area, the embodied energy within that area includes not only environmental energy resources initiated from the area, but matching energy attracted from fuels and environmental sources outside the region. For the United States the ratio of attracted energies to original environmental resources is about 3:1.

INTRODUCTION

The economy of nature and of humanity is based on the transformation and utilization of energy, most of it ultimately derived from the sun. Solar based energy flows and resulting storages are the externalities of the environment upon which humanity and its economy is based. As Fig. E1 shows, the economy depends on the web of external energy sources (and the accompanying flows of materials, information, and structures). Removing externalities (such as fuels, land, or other environmental flows) reduces the true work done and the real dollar value. For a general explanation of these concepts and premises see recent book (Odum and Odum 1976, 1981).

Ways of evaluating the external energy basis of the economies of both nature and man are needed so that observed or anticipated changes in externalities can be related quantitatively and the ultimate effect on future economies estimated. This is a manual for evaluating resource and environmental values according to the solar equivalent Calories in energy storages and flows.

Energy and Embodied Energy

All energies may be converted 100% into heat, and this property is actually the working definition of energy. The calories (or joules) of heat are a common denominator by which energies of different types are compared.

However, as they flow, energies are transformed into flows and storages of commodities of higher quality (goods, services, materials, information, etc.). These are energy flows of higher quality because they have a greater ability to feed back and amplify other flows. Since more solar energy was used to make them, the higher quality energies have greater embodied solar energy. Embodied energy is the energy of one type required to develop another type of energy that is lesser in quantity.

Chains and webs of energy flow like those in Fig. 1 have large quantities of low-quality energy at the start and small quantities of high-quality energy after successive transformations. Thus, there is the confusing property that the less actual energy in a commodity, the greater the embodied energy and energy quality. Human labor, information, culture, complex life, and expensive technological devices have relatively small energy flows, but very high embodied energies are required for their formation and maintenance.

The evaluation of the resources and the environment requires that the flows and storage be evaluated in embodied energy of one type so that they may be compared. The embodied solar energy in a flow or storage is solar energy required to replace that flow or storage.

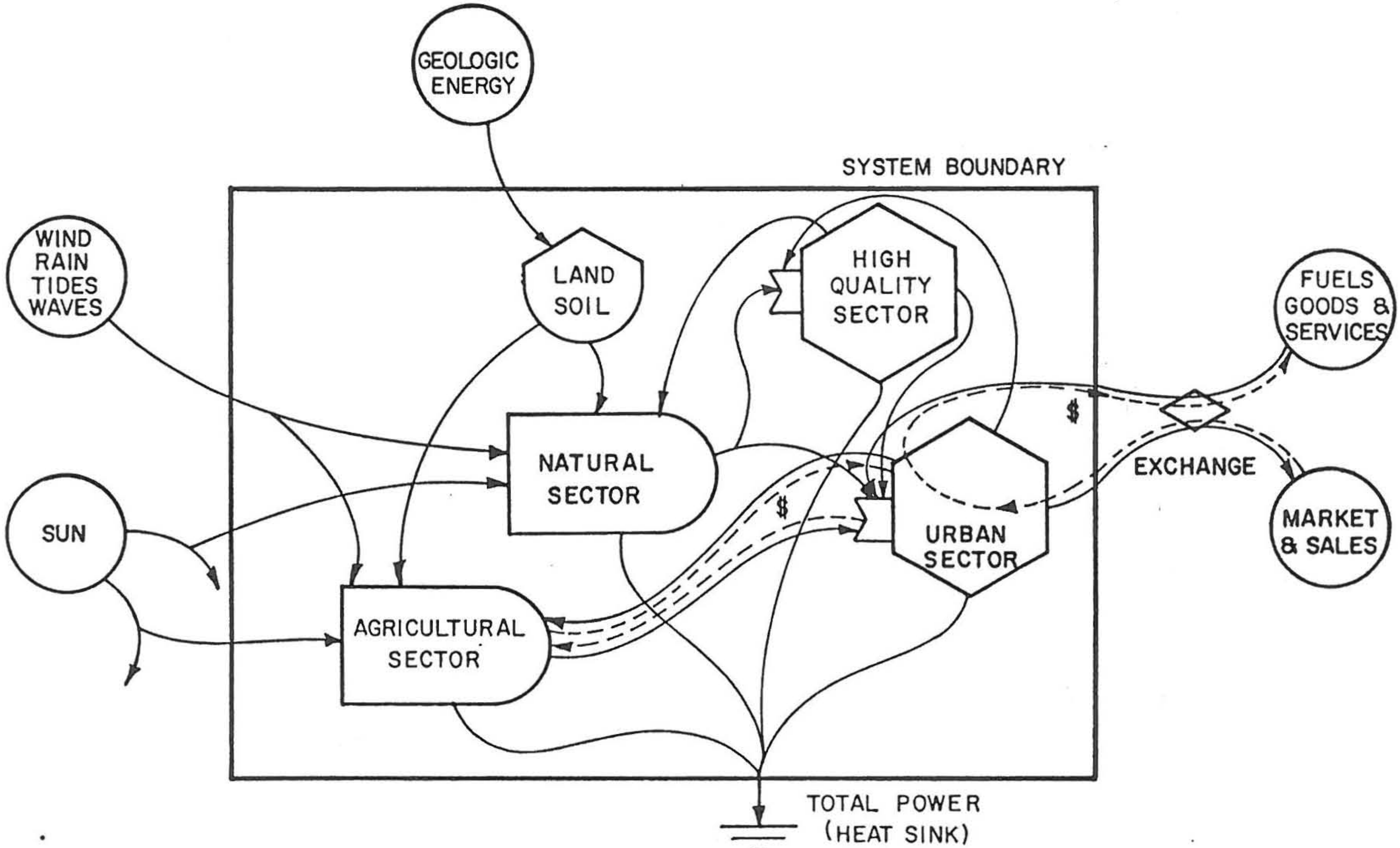

Figure E1. Relation of energy signature and important storages of the environment to flows of the monied economy (pathways accompanied by dashed lines for $). Some of the high-quality energies are in human urban sector and some are in aspects of environmental quality and human culture not closely connected to the dollar flow.

Embodied Energy Theory of Long-Range Value

In one sense the procedures given here implement a theory of value. Although immediate economic value of a commodity depends on the immediate effect it can produce on the flows of energy and money (marginal utility value), the long-range value depends on the energy embodied in the commodity. The energy required to develop a commodity determines the use that should be made of it. Items with high embodied energies like human labor require more important amplifier effects to justify the energy expenditures in the development. The long-range value is not the momentary effect on an existing system, but the effect that the system should be getting and toward which it will reorganize so as to maximize the overall good use of energy.

Prices give us indications of the short-term effect a commodity has on economic pathways. Similarly, the slopes of the curves of limiting factors give indications of the short-term effect in noneconomic pathways. The ultimate values, however, may be estimated from the embodied solar energy, because systems evolve so as to use high embodied energy only for interaction with high amplifier effect. A system for evaluating the environment with embodied energies provides a way to estimate values before systems of economic use have been developed. Embodied energies measure the work of the environment that supports the economy.

Energy Transformation Ratio

The embodied solar Calories required to generate a Calorie of energy of higher quality is the energy transformation ratio (sometimes called quality factor). These ratios are multiplied by actual energy flows to obtain embodied solar equivalents. Energy transformation ratios are given in Tables E1a and E1b.

Methodology of Energy Analysis of Value

If embodied energy predicts effects in nonmonied systems of nature, as well as economic effects after uses develop, environments may be evaluated by tabulating the important energy flows and storages of an area in embodied solar equivalents. Evaluations include those of land, soils, marine resources, climate, catastrophic events, and the high-quality storages of information and human works. Because energy flows interact, one amplifying the other, understanding of the energy basis is best visualized by an aggregated overview model on which energy flows and storages can be written (see Fig. E1). Embodied solar energy values may then be written on the diagram and calculations documented with tables.

Table E1a. Energy transformation ratios of environmental sources in global solar Calories per Calorie.

Pathway or Storage (Number or Letter in Fig. E2)	Name of Item	Transformation Ratio, Solar Cal/Cal	Basis in Footnotes
FLOWS:			
1	Sun	1.0	1
2	Wind	56.7	2
	Heat		
3	Vertical exchange	12.9	3
4	Horizontal advection	5.3	4
	Vapor		
5	Vertical exchange	55.9	5
6	Horizontal advection	55.9	6
	Rain		
7	Kinetic potential	2.38×10^{5}	7
8	Gravitational potential over land, 875 m	4.00×10^{3}	8
9	Chemical potential of rain over land	6.90×10^{3}	9
10a	Chemical potential of nitrogen over land	2.91×10^{9}	10a
10b	Chemical potential of phosphorus over land	2.61×10^{10}	10b
11	Chemical potential of acid rain over land	1.09×10^{9}	11
	Tide		
12	Physical potential of tidal inflow	11.56×10^{3}	12
13	Chemical potential of tidal inflow	6.9×10^{3}	13
14	Chemical potential of tidal outflow	6.9×10^{3}	14
15	Wave	1.16×10^{4}	15
	Sand		
16a	Chemical potential in sand flux	4.6×10^{5}	16a
16b	Elevated potential in sedimentation	1.77×10^{14}	16b
	Streams		
17	Physical energy in stream flow	1.06×10^{4}	17
18	Chemical potential of water in stream	3.57×10^{4}	18
19	Chemical potential energy in sediments in streams	0.88×10^{6}	19
20	Physical potential energy in materials in stream flow	2.33×10^{7}	20
	Catastrophic		
21a	Earthquake	3.98×10^{6}	21a
21b	Tornado	2.61×10^{10}	21b
21c	Hurricane	1.11×10^{3}	21c
21d	Flood	4.00×10^{5}	21d
22	Species		
	Algae	7×10^{29}	22
	Microinvertebrates	7×10^{26}	22
	Vascular plant seeds	9×10^{27}	22
	Insects	7×10^{24}	22
	Vertebrates	4.6×10^{21}	22
23	Human exchange	4.5×10^{3} to 5.1×10^{5}	23
24	Money flow	---	24
25	Potential energy in land uplift	1.5×10^{12}	25
26	Chemical potential energy in land uplift.		26
	Granite	10.19×10^{7}	

Table E1a. (continued).

Pathway or Storage (Number or Letter in Fig. E2)	Name of Item	Transformation Ratio, Solar Cal/Cal	Basis in Footnotes
	Basalt	2.08×10^7	26
	Shale	5.22×10^7	26
	Limestone	0.77×10^6	26
	Sandstone	2.83×10^7	26
STORAGES:			
A	Wood biomass	2.89×10^3	27
B	Soil	11.9×10^4	28
C	Species	4.6×10^{21} to 7.0×10^{29}	29
D	Human assets	30.3×10^3 to 171×10^3	30
E	Uplifted land	1.50×10^{12}	31
F	Chemical potential energy in rock	0.77×10^6 to 10.19×10^7	32
G	Physical potential energy in land form	1.50×10^{12}	33
	Corn crop	6.32×10^3	34

[1]Global solar energy: one by definition. Coal equivalents of direct sunlight were found to be about 2000 terrestrial solar Cal/Cal coal by calculating energy for growing wood, for collecting wood, and converting wood to electricity. Four coal Calories can generate a Calorie of electricity. For each Calorie of terrestrial sunlight about 3.4 Calories of total global sunlight generates rain, wind, etc. used on land. Thus there are two energy transformation ratios from sun to coal: 2000 direct solar Calories/Calorie coal; 6800 global solar Calories/Calorie coal.

[2]Wind kinetic energy: Rate of production of atmospheric kinetic energy P_m for the entire atmosphere (Monin 1972) $P_m = 2 \times 10^{12}$ kw $= 1.51 \times 10^{19}$ Cal/yr. Solar energy S = solar insolation - albedo (Sellers 1965) = (4600 Cal/$m^2 \cdot$day)(5.1×10^{14} m^2 area of earth)(365 day/yr) = 8.56×10^{20} Cal/yr. Energy transformation ratio for wind is: $Q_w = S/P_m$ = (8.56×10^{20} Cal/yr)/(1.51×10^{19} Cal/yr) = 56.7 Solar Cal/Cal.

[3]Heat vertical exchange: Global average turbulent sensible heat transfer J_h (Trewartha 1968; Budyko 1974) J_h = (1.3×10^5 Cal/$m^2 \cdot$yr)(5.1×10^{14} m^2) = 6.63×10^{19} Cal/yr. Energy transformation ratio of turbulent heat transfer equals: $Q_h = S/J_h$ = (8.56×10^{20} Cal/yr)/(6.63×10^{19} Cal/yr) = 12.9 Solar Cal/Cal.

[4]Heat horizontal advection: Average meridianal advection of heat from the equator to 40°N (Budyko 1974) equals 11.12×10^{16} Cal/day; from 40°N latitude to the pole, the flux is of the same magnitude, but opposite sign. Thus the heat flux for the northern hemisphere F_n equals: F_n = (11.12×10^{16} Cal/day) - (-11.12×10^{16} Cal/day) = 22.24×10^{16} Cal/day. For a global rate, we double this number. Thus, global heat advection F_y equals: F_y = (44.48×10^{16} Cal/day)(365 day/yr) = 1.62×10^{20} Cal/yr. Energy transformation ratio for heat advection equals: $Q_y = S/F_y$ = (8.56×10^{20} Cal/yr)/(1.62×10^{20} Cal/yr) = 5.3 Solar Cal/Cal.

[5]Vapor vertical exchange: Total mass of water in atmosphere = 1.24×10^{19} g; turnover time for water in the atmosphere T = 11.23 days (Monin 1972); average flux of vapor = 1.24×10^{19} g/11.23 days = 1.104×10^{18} g/day. Gibbs free energy per gram of vapor diffusing ΔF = [(1.99×10^{-3} Cal/mole$\cdot$deg)/(18 g/mole)](275°K)(2.3 $\log_{10}$ 7 mb/2 mb) = 0.038 Cal/g.

Equation for flow of Gibbs free energy due to vapor pressure flux: $F_g = (1.104 \times 10^{18}$ g/day)(365 day/yr)(0.038 Cal/g) $= 1.53 \times 10^{19}$ Cal/yr. Energy transformation ratio of vapor vertical exchange is: $Q_g = S/F_g = (8.56 \times 10^{20}$ Cal/yr)/(1.53×10^{19} Cal/yr) = 55.9 Solar Cal/Cal.

[6]Vapor horizontal advection: Energy transformation ratio for air advection is assumed to be the same as the transformation ratio for vapor vertical exchange. See footnote 5.

[7]Rain kinetic potential energy: Total world rain (Ryabchikov 1975) P = 520,000 km^3/yr = 5.2×10^{20} cm^3/yr. Assuming the world raindrop is 4 mm in size, then read the kinetic energy of rain per unit volume from Table E12, we obtain $\Delta K = 6.91 \times 10^{-6}$ Cal/cm^3) = 3.59×10^{15} Cal/yr. Energy transformation ratio of rain kinetic energy is: $Q_k = S/K_e$ = (8.56×10^{20} Cal/yr)/(3.59×10^{15} Cal/yr = 2.38×10^5 Solar Cal/Cal.

[8]Rain gravitational potential energy: The total continental rain is 105,000 km^3/yr, and the world average elevation is 875 meters (Ryabchikov 1975), this gives the potential energy of rain: $G_e = P\rho gh$ = (1.05×10^{20} cm^3/yr)(1 g/cm^3)(980 cm/s^2)(8.75×10^4 cm)(2.38×10^{-11} Cal/erg) = 2.14×10^{17} Cal/yr. Q = (8.56×10^{20} solar Cal/yr)/(2.14×10^{17} Cal/yr) = 4×10^3 solar Cal/Cal.

[9]Rain chemical potential energy: An average concentration of salts of 10 ppm in rainwater and 35,000 ppm in seawater is assumed. The free energy per gram of water given by: $\Delta F = nRT\ln(C_2/C_1)$ = (1.99×10^{-3} Cal/°K·mole)/(18 g/mole) (300°K)ln(999,990/965,000) = 1.18×10^{-3} Cal/g water. The total continental rain is 105,000 km^3/yr (Ryabchikov 1975), and the chemical potential energy of rain is: $F_r = PC_2\Delta F$ = (1.05×10^{14} m^3/yr)(999,990 g/m^3)(1.18×10^{-3} Cal/g) = 1.24×10^{17} Cal/yr. Energy transformation ratio of rain chemical energy is: $Q_f = S/F_r$ = (8.56×10^{20} Cal/yr)/(1.24×10^{17} Cal/yr) = 6.9×10^3 Solar Cal/Cal.

[10a]Rain chemical potential of nitrogen over land: Average nitrogen concentration as NO_3^- and NH_4^+ in rainwater (Chapin and Uttormark 1973), C_2 = 0.2 ppm. Average nitrogen concentration in seawater (Considine 1976), C_1 = 0.51 g/metric ton = 0.51 g/10^6 g = 0.51 ppm. The chemical potential of nitrogen per gram of rainwater is computed as: ΔF_n = $(nRT)\ln(C_2/C_1)$ = [(1.99×10^{-3} Cal/°K·mole)/(40 g/mole)](300°K)ln(0.2/0.51) = 0.014 Cal/g. Total global rain P = 105,000 km^3/yr = 1.05×10^{20} cm^3/yr and the chemical potential of nitrogen as NO_3^- and NH_4^+ in rainwater equals $F_n = PC_2\Delta F$ = (1.05×10^{20} cm^3/yr)(0.2×10^{-6} g/cm^3)(0.014 Cal/g) = 2.94×10^{11} Cal/yr. Energy transformation ratio of rain chemical potential of nitrogen as NO_3^- and NH_4^+ is: $Q_n = S/F_n$ = (8.56×10^{20} Cal/yr)/(2.94×10^{11} Cal/yr) = 2.91×10^9 Solar Cal/Cal.

[10b]Rain chemical potential of phosphorus over land: Average phosphorus concentration as PO_4 in rainwater (Chapin and Uttormark 1973) C_3 = 0.11 ppm. Average phosphorus concentration in seawater: C_1 = 0.07 ppm. The chemical potential of phosphate per gram of rainwater is estimated as: $\Delta F_p = (nRT)\ln(C_3/C_1)$ = [(1.99×10^{-3} Cal/°K·mole)/(95 g/mole)] (300°K)ln(0.11/0.07) = 2.84×10^{-3} Cal/g. The chemical potential of phosphate in rainwater equals: $\Delta F_p = PC_3\Delta F_p$ = (1.05×10^{20} cm^3/yr)(0.11×10^{-6} g/cm^3)(2.84×10^{-3} Cal/g) = 3.28×10^{10} Cal/yr. Energy transformation ratio of rain chemical potential of phosphorus as phosphate is: $Q_p = S/F_p$ = (8.56×10^{20} Cal/yr)/(3.28×10^{10} Cal/yr) = 2.61×10^{10} solar Cal/Cal.

[11]Rain chemical potential of acid rain over land: Average number of H^+ in rainwater = 0.0025 mg H^+/l = 2.5×10^{-6} moles H^+/l (at normal pH of 5.6 at equilibrium with atmospheric CO_2). Average pH of seawater = 8.2. X_{H^+} = (2.5×10^{-9} g acid/g water). The average surface temperature (Visher 1965) = 283°K, and the drop in temperature due to 6000 m

elevation rise = 33°K, thus the average temperature at cloud height of 6000 m equals T = 283°K - 33°K = 250°K. The chemical potential energy of acid substances in rain relative to seawater is computed as: $F_a = P(nRT)(X_{H^+})\ell n X_{H^+}$ = (1.05 x 10^{20} cm^3/yr)(2.5 x 10^{-9} g acid/g water)(1 g acid/mole acid)(1.99 x 10^{-3} Cal/°K·mole)(250°K)(2.3)(8.2 - 5.6) = 7.81 x 10^{11} Cal/yr. Energy transformation ratio of rain chemical potential of acid is: $Q_a = S/F_a$ = (8.56 x 10^{20} Cal/yr)/(7.81 x 10^{11} Cal/yr) = 1.09 x 10^9 Solar Cal/Cal.

[12]Tide physical energy: The average tide energy is 0.0058 watts/m^2 (Hubbard 1971) = (5.8 x 10^{-6} Kw/m^2)(860 Cal/Kwh)(24 hr/day) = 0.119 Cal/m^2·day. Unlike other flows, tide is not from sunlight. Thus, the energy transformation ratio is based on the energy analysis of tidal electric plant at LaRance, France (Odum et al. 1977), (1.7 coal equivalent Cal/Cal tide)(6800 solar Cal/Cal coal) = 11,560 solar Cal/Cal.

[13]Chemical potential of tidal inflow: Same as for 9.

[14]Chemical potential of tidal outflow: Same as for 9.

[15]Wave energy: The average wave energy that comes ashore in 1 yr throughout the world (Kinsman 1965) is about: 1.68 x 10^8 Cal/m^2·yr; multiplied by 4.39 x 10^8 m of facing shoreline = 7.38 x 10^{16} Cal/yr. Energy transformation ratio for waves equals: $Q_w = S/E_w$ = (8.56 x 10^{20} Cal/yr)/(7.38 x 10^{16} Cal/yr) = 1.16 x 10^4 Solar Cal/Cal.

[16a]Chemical potential energy in sand flux: Assume 1.46 x 10^5 miles of coastline (Wenk 1972) with sand flux. Assume average littoral drift along coastline Q = 100,000 m^3/yr (Table E21). Assume sand moves 1000 m/yr. Assume 1% organic matter content of sediments O, and the free energy of organic matter K = 5.4 Cal/g. We obtain the total chemical potential in sand flux: $F_s = LOQ\rho K$ = (2.35 x 10^8 m.)(.01)(10^5 m^3/yr·1000 m)(1.47 x 10^6 g/m^3)(5.4 Cal/g) = 1.87 x 10^{15} Cal/yr. Energy transformation ratio for chemical potential in sand flux equals: $Q_s = S/F_s$ = (8.56 x 10^{20} Cal/yr) /(1.87 x 10^{15} Cal/yr) = 4.6 x 10^5 Solar Cal/Cal.

[16b]Elevated potential energy in sedimentation: Assume 1.46 x 10^5 miles of coastline (Wenk 1972) = 2.35 x 10^8 m and the width of coast affected by sedimentation = 3000 m. Assume average sedimentation rate h = 2 mm/yr (Table E24). We obtain the heat equivalent of elevated potential from sedimentation: $G_s = A\rho ghd$ = (2.35 x 10^8 m)(3000 m)(1.47 g/cm^3)(980 cm/s^2)(0.2 cm/yr)0.5(0.2 cm)(100^2 cm^2/m^2)(2.38 x 10^{-11} Cal/erg) = 4.83 x 10^6 Cal/yr. Energy transformation ratio of elevated potential in sedimentation is: Q_s = (8.56 x 10^{20} Cal/yr)/(4.83 x 10^6 Cal/yr) = 1.77 x 10^{14} Solar Cal/Cal.

[17]Physical energy in stream flow: The global annual runoff q = 39.6 x 10^3 km^3/yr (Todd 1970) and the world average elevation is 875 m (Ryabchikov 1975). The physical energy in stream flow is then: $G_q = q\rho gh$ = (3.96 x 10^{19} cm^3/yr)(1 g/cm^3)(980 cm/s^2)(8.75 x 10^4 cm)(2.38 x 10^{-11} Cal/erg) = 8.08 x 10^{16} Cal/yr. Energy transformation ratio for physical energy in stream flow equals: $Q_q = S/G_q$ = (8.56 x 10^{20} Cal/yr)/(8.08 x 10^{16} Cal/yr) = 1.06 x 10^4 Solar Cal/Cal.

[18]Chemical potential of water in stream: The global annual runoff q = 39.6 x 10^3 km^3/yr (Todd 1970), and the average total dissolved solids concentration C_1 is assumed to be 150 ppm. We obtain the global free energy of water in streams by: $\Delta F_d = qC_1(nRT)\ell n(C_1/C_0)$ = (3.96 x 10^{19} cm^3/yr)(0.999850 g/cm^3)[(1.99 x 10^{-3} Cal/°K·mole)/(35 g/mole)](300°K)ℓn(999,850/965,000) = 2.40 x 10^{16} Cal/yr. ETR = (8.56 x 10^{20} Cal/yr)/(2.40 x 10^{16} Cal/yr) = 3.57 x 10^4 Solar Cal/Cal.

[19]Chemical potential energy in sediments in streams: Total global sediment discharge to oceans (Goldberg 1972) is 1.8 x 10^{16} g/yr. Assume 1% organic matter content of sediments, and the free energy of organic matter K = 5.4 Cal/g. The

global chemical potential in sediment flux is estimated as: $F_o = OJK = .01(1.8 \times 10^{16}$ g/yr)(5.4 Cal/g) = 9.72×10^{14} Cal/yr. Energy transformation ratio of chemical potential energy in sediments in streams is: $Q_o = S/F_o$ = (8.56×10^{20} Cal/yr)/(9.72×10^{14} Cal/yr) = 0.88×10^6 Solar Cal/Cal.

[20]Physical potential energy in materials in stream flow: Total global sediment discharge to oceans (Goldberg 1972) is 1.8×10^{16} g/yr. The world average elevation is 875 meters (Ryabchikov 1975). This gives the potential energy of materials in stream flow against gravity as: $G_m = J\rho gh$ = (1.8×10^{16} g/yr)(980 cm/s^2)(8.75×10^4 cm)(2.38×10^{-11} Cal/erg) = 3.67×10^{13} Cal/yr. Energy transformation ratio for physical potential in materials in stream flow equals: $Q_m = S/G_m$ = (8.56×10^{20} Cal/yr)/(3.67×10^{13} Cal/yr) = 2.33×10^7 Solar Cal/Cal.

[21a]Catastrophic energy in earthquakes: Global earthquake energy $E_e = 2.15 \times 10^{14}$ Cal/yr (Richter 1958). This gives the energy transformation ratio for earthquakes as: $Q_e = S/E_e$ = (8.56×10^{20} Cal/yr)/(2.15×10^{14} Cal/yr) = 3.98×10^6 Solar Cal/Cal.

[21b]Catastrophic energy in tornadoes: Global average number of tornadoes per year = 888 (Fujita 1973) and the average tornado energy = 3.7×10^7 Cal in heat equivalents (Sellers 1965). This yields a global tornado energy of E_t = (3.7×10^7 Cal/tornado)(888 tornadoes/yr) = 3.28×10^{10} Cal/yr. Energy transformation ratio of tornadoes is given as: $Q_t = S/E_t$ = (8.56×10^{20} Cal/yr)/(3.28×10^{10} Cal/yr) = 2.61×10^{10} Solar Cal/Cal.

[21c]Catastrophic energy in hurricanes: The global average hurricane frequency equals nine per year (Dunn and Miller 1964) and the hurricane energy averages about 9.5×10^{15} Cal/day. With a duration of nine days per hurricane, this produces the global hurricane energy of: E_h = (9.5×10^{15} Cal/day)(9 day/hurricane)(9 hurricane/yr) = 7.69×10^{17} Cal/yr. Energy transformation ratio for hurricanes equals: $Q_h = S/E_h$ = (8.56×10^{20} Cal/yr)/(7.69×10^{17} Cal/yr) = 1.11×10^3 Solar Cal/Cal.

[21d]Catastrophic energy in floods: The total continental rain is 105,000 km^3/yr (Ryabchikov 1975). Assuming 1% of continental rain and average elevation of 875 m are involved in flood events, the total energy consumed by floods is: $E_f = P\rho gh$ = .01(1.05×10^{20} cm^3/yr)(1 g/cm^3)(980 cm/s^2)(8.75×10^4 cm)(2.38×10^{-11} Cal/erg) = 2.14×10^{15} Cal/yr. Energy transformation ratio of floods is: $Q_f = S/E_f$ = (8.56×10^{20} Cal/yr)/(2.14×10^{15} Cal/yr) = 4.00×10^5 Solar Cal/Cal.

[22]Embodied energy of species: The energy transformation ratio of a species is calculated on the basis of the energy cost to evolve it. The total solar energy flux received since the earth was formed 4×10^9 years ago is about: S_t = (8.56×10^{20} Cal/yr)(4×10^9 yr) = 3.42×10^{30} Cal. The total number of species that have existed since the earth was formed is about 1.5×10^9 (Ager 1965). This gives an estimate of average solar calories per species: S = (3.42×10^{30} Solar Cal)/(1.5×10^9 species) = 2.28×10^{21} Solar Cal/species. From Table E26 of Calories of DNA per species propagule, we obtain the energy transformation of species as follows: Algae, (2.28×10^{21} Solar Cal/species)/(3.25×10^{-9} DNA Cal/species) = 7×10^{29} Solar Cal/DNA Cal; Microinvertebrates, 7×10^{26} Solar Cal/DNA Cal; Vascular plant seeds, 9×10^{27} Solar Cal/DNA Cal; Insects, 7×10^{24} Solar Cal/DNA Cal; Vertebrates, 4.6×10^{21} Solar Cal/DNA Cal. Larger ones have more redundancy. Embodied energy lost with extinction of a species is the energy to evolve it from nearest living relative.

[23]Human exchange: Table E28 lists the potential energy in representative commodities. The following table shows the embodied energy and energy transformation ratios for a representative mix. The transformation ratio ranges from 1300 to 150,000 Solar Cal/Cal. Energy transformation ratios for representative commodities:

Commodity	Potential Energy[a], Cal/lb	Embodied Energy[b], 10^6 Solar Cal/lb	Energy Transformation Ratio, Solar Cal/Cal
Cement	20	10.2	510,000
Glass	1900	30.6	16,105
Steel	700	81.6	116,571
Organic			
Food	1500	163.2	108,800
Fiber	1500	47.6	31,733
Paper	1900	27.2	14,316
Wood	1500	13.6	9,067
Plastic	3000	13.6	4,533

[a]See Table E28.

[b]Adapted from Steinhart and Steinhart (1974:242). This figure includes fossil fuel and natural embodied energies multiplied by 3.4 to convert to global solar Calories.

24 Money flow: Not applicable. See Table E4 for solar energy to dollar ratios.

25 Potential energy in land uplift: An average uplift rate of .036 m/1000 yr is assumed (Judson 1968), and an average density of rock ρ = 2.5 g/cm^3 is used. The area of continents is A = 1.5 x 10^{14} m^2, and the flux of potential energy against gravity is estimated as: $E_\mu = A\rho ghd = (1.5 \times 10^{18}\ cm^2)(2.5\ g/cm^3)(980\ cm/s^2)(3.6\ cm/1000\ yr)(0.5)(3.6\ cm)(2.38 \times 10^{-11}\ Cal/erg) = 5.67 \times 10^8\ Cal/yr$. Energy transformation ratio for potential energy in land uplift equals: $Q_\mu = S/E_\mu = (8.56 \times 10^{20}\ Cal/yr)/(5.67 \times 10^8\ Cal/yr) = 1.50 \times 10^{12}$ Solar Cal/Cal.

26 Chemical potential energy in land uplift: Table E31 lists the Gibbs free energy for each rock type. The following table shows the global average erosion rate (Gilliland et al. 1978) and the embodied energy and energy transformation ratios for each rock type. The transformation ratio ranges from 0.76 x 10^6 to 10.20 x 10^7 Solar Cal/Cal. Energy transformation ratios for rocks:

Rock Type	Gibb's Free Energy, Cal/g	Erosion Rate, 10^{14} g/yr	Chemical Potential Energy, 10^{14} Cal/yr	Energy Transformation Ratio, Solar Cal/Cal*
Granite	0.012	6.98	0.084	10.19 x 10^7
Basalt	0.041	10.06	0.412	2.08 x 10^7
Shale	0.024	6.83	0.164	5.22 x 10^7
Limestone	0.146	76.46	11.163	0.77 x 10^6
Sandstone	0.012	25.25	0.303	2.83 x 10^7

*Energy transformation ratio is obtained by dividing the chemical potential energy into the average global solar insolation value of 8.56 x 10^{20} Cal/yr.

[27]Energy stored in dominant biomass: Net primary productivity and energy fixation estimates for the world around 1950 were obtained from Lieth and Box (1972). The following table shows the heat calories per gram of biomass, and the embodied energy of total biomass, which is about 2.96 x 10^{17} Cal/yr. Embodied energy in dominant biomass:

Forest Type	Area, 10^6 km^2	Mean Net Primary Productivity, $g/m^2 \cdot yr$	Combustion Value, Cal/g	Rate of Energy Storage in Biomass 10^{17} Cal/yr
Tropical rain forest	17.0	2000	4.1	1.39
Raingreen	7.5	1500	4.2	0.47
Summergreen	7.0	1000	4.6	0.32
Chaparral	1.5	800	4.9	0.06
Warm temperature mixed	5.0	1000	4.7	0.24
Boreal forest	12.0	500	4.8	0.29
Woodland	7.0	600	4.6	0.19
				2.96

The energy transformation ratio for the energy stored in dominant biomass is derived as: $Q_b = S/E_b = (8.56 \times 10^{20}$ Cal/yr)/(2.96 x 10^{17} Cal/yr) = 2.89 x 10^3 Solar Cal/Cal.

[28]Energy stored in soil: Estimate for the embodied energy of U.S. soils was obtained by Leibowitz (1979). In the study, it is assumed that the rate of soil formation is equal to the natural rate of soil erosion. A value of 16 cm/1000 yr is used. The following table summarizes the values used to calculate the embodied solar energy and heat content of soils for the eastern two-thirds of the U.S. The energy transformation ratio for the six soils averages about 11.9 x 10^4 Solar Cal/Cal. Embodied energy heat content of six U.S. soils:

Soil Type[c]	Direct Solar Radiation, Sr, 10^6 $Cal/m^2 \cdot yr$	Soil Depth, D, m	Soil Area, A, 10^{12} m^2	Embodied Global Solar Energy[a], S, 10^{21} Solar Cal	Heat Content[b], H, 10^{16} Cal	Transformation Ratio, S/H, 10^4 Solar Cal/Cal
RY	0.75	1.07	1.13	19.28	5.46	35.3
GBP	0.60	0.76	1.21	11.73	9.36	12.5
PRP	0.65	0.91	0.66	8.30	11.97	6.93
CCL	0.65	0.91	0.56	7.04	10.85	6.49
CRC	0.65	0.91	0.69	8.67	8.92	9.72
BRB	0.65	0.91	0.51	6.43	4.94	13.02
Total	---		2.93	61.45	51.50	11.93

[a]Embodied solar energy S = (SrDA/rate of soil formation)(3.40 global solar Cal/direct solar Cal).

[b]Heat content H = (5.4 Cal/g)(20)(Nitrogen)(Soil area, A)[c].

[c]See Table E33.

[29]Energy stored in species: See footnote 22.

[30]Energy stored in human assets: Estimate for the embodied energy in urban structure by land use type was based on studies in central and south Florida by Brown and Genova (1973). Power density of land use type is multipled by the number of years thought necessary to obtain a "mature" system. The following table shows the embodied energy, chemical potential, and the energy transformation ratio of human assets. CE = coal equivalents with 6800 global solar equivalents/coal equivalent. Embodied energy and chemical potential of urban structure:

Land Use Type	Power Density, 10^8 CE Cal/acre·yr	Cumulative Embodied Energy, 10^9 CE Cal/acre	Chemical Potential, 10^9 Cal/acre[c]	Transformation Ratio, 10^3 Solar Cal/Cal
Single Family Residential[a]				
Low density	2.67	5.3	0.63	57.1
Medium density	4.88	9.8	1.0	66.6
Multifamily Residential[b]				
Low rise	22.3	11.1	2.2	34.3
High rise	24.2	12.1	1.4	58.8
Commercial[b]	25.8	12.9	1.5	58.5
Industrial[b]	12.4	6.2	1.4	30.3
Central Business District	100.6	50.3	2.0	171.0

[a]Time necessary to reach full maturity estimated to be 20 yr.

[b]Time necessary to reach full maturity estimated to be 5 yr.

[c]Using Tables E27, E28, and E36.

[31]Energy stored in uplifted land (see footnote 25).

[32]Energy stored in base rock (see footnote 26).

[33]Energy stored in land form: Energy stored in land form is in depressions and elevations of the land surface. The energy transformation ratio for energy stored in land form is taken as the same as the transformation ratio calculated in footnote 25.

[34]A corn crop is produced combining 1. energy of sun for the year times 3.4 to convert to global solar Calories; 2. embodied energy in 7 g phosphorus fertilizer/m^2; and 3. embodied energy in goods and services \$0.0668/m^2·yr. Solar input: (1 x 10^6 direct solar Cal/m^2·yr)(3.4 global/direct Cal) = 3.4 x 10^6 global solar Cal/m^2·yr. Fertilizer input: 2.25 x 10^5 direct solar Calories/g phosphorus (Odum and Odum 1980); (7 g P/m^2·yr)(2.25 x 10^5 direct solar Cal/g P)(3.4) = 5.35 x 10^6 global solar Cal/m^2·yr. Goods and Services input: (\$0.0668/m^2·yr in 1973)(120 x 10^6 Cal/\$ global solar) = 8.0 x 10^6 global solar Cal/m^2·yr. Sum of embodied energy inputs: (3.4 + 5.35 + 8.0) x 10^6 = 16.75 x 10^6 global solar Cal/m^2·yr. Corn yield per m^2 per year: 2.65 x 10^3 actual Cal in corn; 7.7 x 10^3 actual Cal in whole biomass of corn plant. Energy transformation ratios: Corn (16.75 x 10^6 global Cal/m^2·yr)/(2.65 x 10^3 actual Cal/m^2·yr) = 6320 global solar Cal/Cal. Corn plants: 16.75 x 10^6/7.7 x 10^3 = 2175 global solar Cal/Cal.

Table E1b. Other Energy Transformation Ratios.

Name of Item	Global Solar Cal/Cal	Footnote
Fissionable uranium fuel	306	1
Typical aquatic gross primary production	200	2
Typical terrestrial gross primary production	340	3
Coal	6,800	4
Gasoline	11,492	5
Electric power	27,200	6
Average human service in U.S.	887,000	7
Fertilizer (with phosphate)	1,990,000	8

[1] Calculations of steady state nuclear fission power plant operations by Kylstra and Ki Han (1975) quoted by Odum et al. (1977). About 109×10^{13} Cal fissionable uranium (coal equivalent) generates 4.9×10^{13} Cal coal equivalents of electrical net energy = 22.2 Cal uranium/Cal coal. (6800 solar Cal/Cal coal)/(22.2 Cal uranium/Cal coal) = 306 solar Cal/Cal uranium.

[2] Typical aquatic gross primary production converts 0.5% of direct sunlight and does not use the global solar energy. ETR = 200 Cal sunlight direct/Cal gross production.

[3] Typical terrestrial plant gross production has efficiency about 1% of direct sunlight but utilizes subsidies from global sunlight such as rain and wind. ETR = (100 Cal direct sun/Cal gross prod.)(3.4 global solar Cal/Cal direct) = 340 global solar Cal/Cal.

[4] Calculations were made of direct solar energy required to generate wood, its collection, and its use in a power plant to make coal equivalent Calories of electricity (Odum et al. 1977). Direct solar Calories (2000 Cal direct sun/Cal coal) were multiplied by 3.4, the ratio of land to water on the globe, to obtain global solar equivalents of coal. ETR = (2000 direct solar Cal/Cal coal)(3.4 earth area to land) = 6800 global solar Cal/Cal coal.

[5] One process for converting coal to gasoline has an efficiency of 59% (Odum et al. 1977) including all embodied energy inputs. ETR = (1.69 Cal coal/Cal gasoline)(6800 global solar Cal/Cal coal) = 11,492 solar Cal/Cal gasoline.

[6] 4 Cal coal required per Cal electricity including goods and services (many sources) ETR = (4 Cal coal/Cal electricity)(6800 global solar Cal/Cal coal) = 27,200 global solar Cal/Cal electricity.

[7] Average embodied energy in U.S. dollars prorates per person [(2.48×10^{12} \$/yr GNP of U.S.)(75×10^{6} global solar Cal/\$)]/(230×10^{6} people) = 809×10^{9} global solar Cal/person·yr. Average basal metabolism is 2500 Cal/person·day. ETR = (809×10^{9} global solar Cal/person·yr)/[(2500 Cal/person·day)(365 days/yr)] = 887,000 global solar Cal/Cal.

[8] Phosphate fertilizer: direct solar energy required to develop swampwater that concentrates phosphate from limestone was calculated for north Florida (Odum and Odum 1980). 7.63×10^{5} solar Cal/g calcium phosphate and when related to Gibbs free energy of the phosphate concentration relative to environment: ETR = 1.99×10^{6} solar Cal/Cal.

Diagrammatic Checklist of Energy Quality

Figure E2 is provided as a checklist of kinds of energy flows commonly found supporting an environmental system. Energy sources are arranged by convention from solar energy on the lower left in order of increasing energy quality to the right. Storages are included that have a turnover time larger than 1 yr. This checklist diagram may be useful in preparing a list of energy flows and storages to be evaluated in any situation.

Energy Systems Diagrams

Because systems of nature and man are organized with complex webs and feedbacks (see Fig. E1), all energies interact with each other and with all by-products feeding back so as to contribute to efficiency and to help to maximize total energy transformation and utilization. Theories explaining the observed patterns in terms of the maximum power principle are given elsewhere (Odum 1971, 1981; Odum and Odum 1976, 1981).

In any evaluation situation, an energy systems diagram should be drawn so that the various interactions and feedbacks are recognized. In this way, one may determine when an energy flow is receiving contributions from several sources. The diagram helps to avoid "double counting" where one adds embodied energy from one source more than once because of unrecognized feedbacks.

Average Dollar Energy Ratio

The ratio of gross national product to total use of embodied energy in the United States was calculated in Table E2 and graphed in Fig. E4. This ratio may be used to estimate embodied energy in human goods and services that feed back from the high-quality end of the economy.

Dollar Value of Environment

The dollar energy ratio can also be used to put an approximate dollar value on environmental flow or storages by multiplying times the embodied energy content of the resource being considered.

Local Economic Potential of Embodied Energy

The Theory of Maximum Power suggests that systems competing in nature and in the economic scene develop patterns that maximize energy inflow and feedback to further maximize power flow, eliminate waste, and eliminate limiting factors other than energy. In the economy of nature and in the economy of man, power is maximized by developments that export some products in exchange for additional energy imports. Conversely, high-quality energy (assets developed through energy use) can develop more additional energy flow if they are used as amplifying

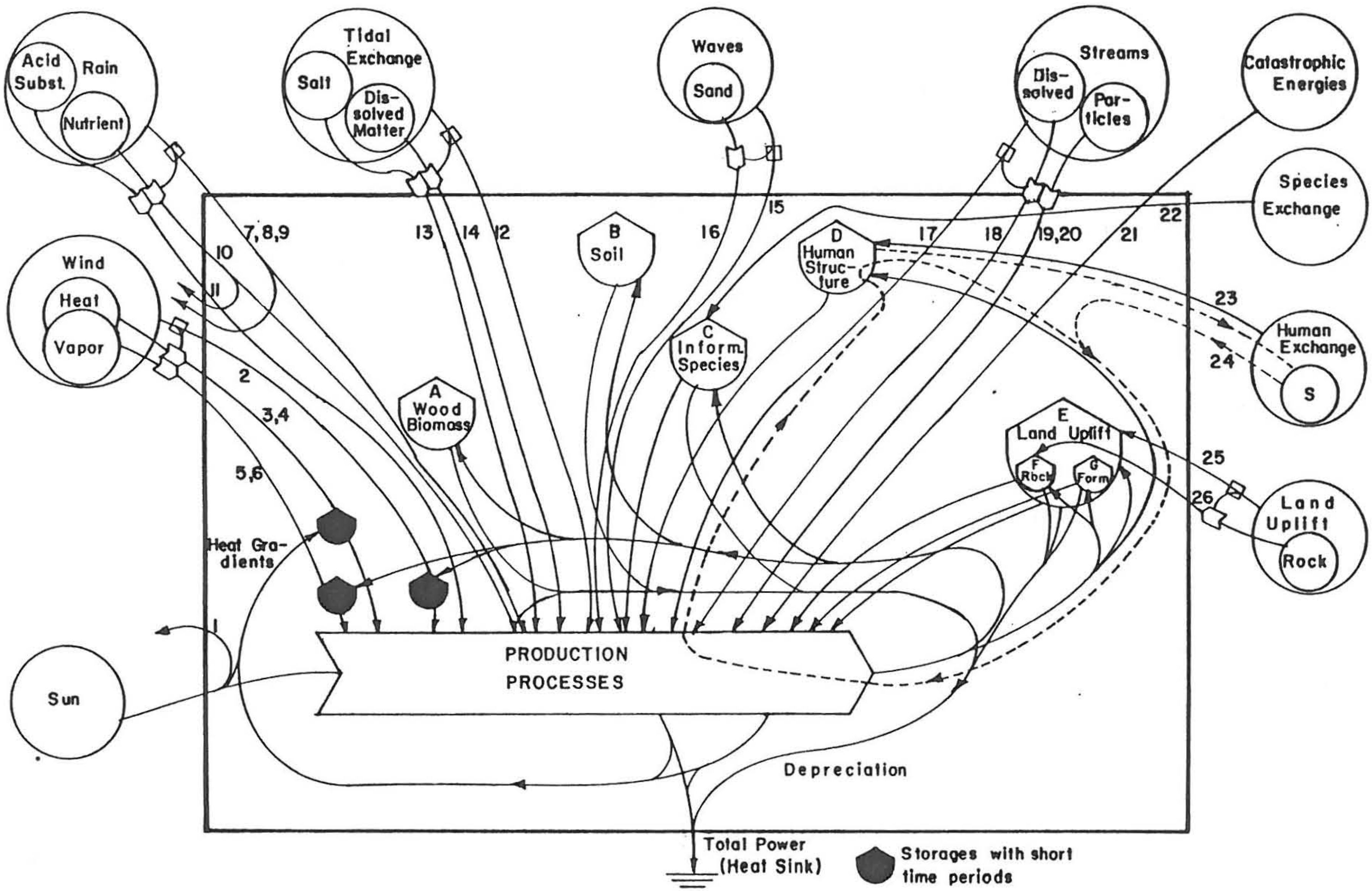

Figure E2. Categories of energy flow signature and more valuable storages of the environment. (Energy quality increases from left to right.)

Table E2. Ratio of energy flows in U.S. society to gross national product (GNP) (Kylstra 1974; USDC 1979). See Fig. E4.

Year	Fossil Fuels Cal/yr 10^{15}	Fossil Fuel Plus Natural* Cal/yr 10^{15}	GNP $ 10^9	Fossil Fuel per GNP Cal FF/$ 10^3	Fossil Fuel Plus Natural per GNP Cal FF/$ 10^3	Direct† Solar Cal per GNP Cal Sol/$ 10^6
1947	8.28	15.02	231.3	35.8	64.9	129.8
1948	8.57	15.31	257.6	33.3	59.4	118.4
1949	7.96	14.70	256.5	31.0	57.3	114.6
1950	8.60	15.34	284.8	30.2	53.9	107.8
1951	9.30	16.04	328.4	28.3	48.8	97.6
1952	9.22	15.96	345.5	26.7	46.2	92.4
1953	9.50	16.24	364.6	26.1	44.5	89.0
1954	9.16	15.90	364.8	25.1	43.6	87.2
1955	10.07	16.81	398.0	25.3	42.2	84.4
1956	10.58	17.32	419.2	25.2	41.3	82.6
1957	10.56	17.30	441.1	23.9	39.2	78.4
1958	10.46	17.20	447.3	23.4	38.4	76.8
1959	10.94	17.68	483.7	22.6	36.6	73.2
1960	11.33	18.07	503.7	22.5	35.9	71.8
1961	11.52	18.26	520.1	22.1	35.1	70.2
1962	12.06	18.80	560.3	21.5	33.6	67.2
1963	12.51	19.25	590.5	21.2	32.6	65.2
1964	12.98	19.72	632.4	20.5	31.2	62.4
1965	13.60	20.34	684.9	19.9	29.7	59.4
1966	14.40	21.14	749.9	19.2	28.2	56.4
1967	14.68	21.42	793.9	18.5	27.0	54.0
1968	15.56	22.30	864.2	18.0	25.8	51.6
1969	16.37	23.11	930.3	17.6	24.8	49.6
1970	16.94	23.68	976.4	17.3	24.3	48.6
1971	17.33	24.07	1050.4	16.5	22.9	45.8
1972	18.17	24.91	1151.8	15.8	21.6	43.2
1973	18.80	25.54	1306.6	14.4	19.6	39.2
1974	18.24	24.98	1412.9	12.9	17.7	35.4
1975	17.82	24.56	1528.8	11.7	16.1	32.2
1976	18.70	25.44	1700.1	11.0	15.0	30.0
1977	19.30	26.04	1887.2	10.2	13.8	27.6
1978	19.66	26.48	2107.6	9.3	12.5	25.0

*Solar energy contribution to the U.S. is estimated at 6.74 x 10^{15} coal equivalent Calories/yr.
†To obtain global solar Calories per Calorie direct sun on land multiply by ratio of globe to land, 3.4.

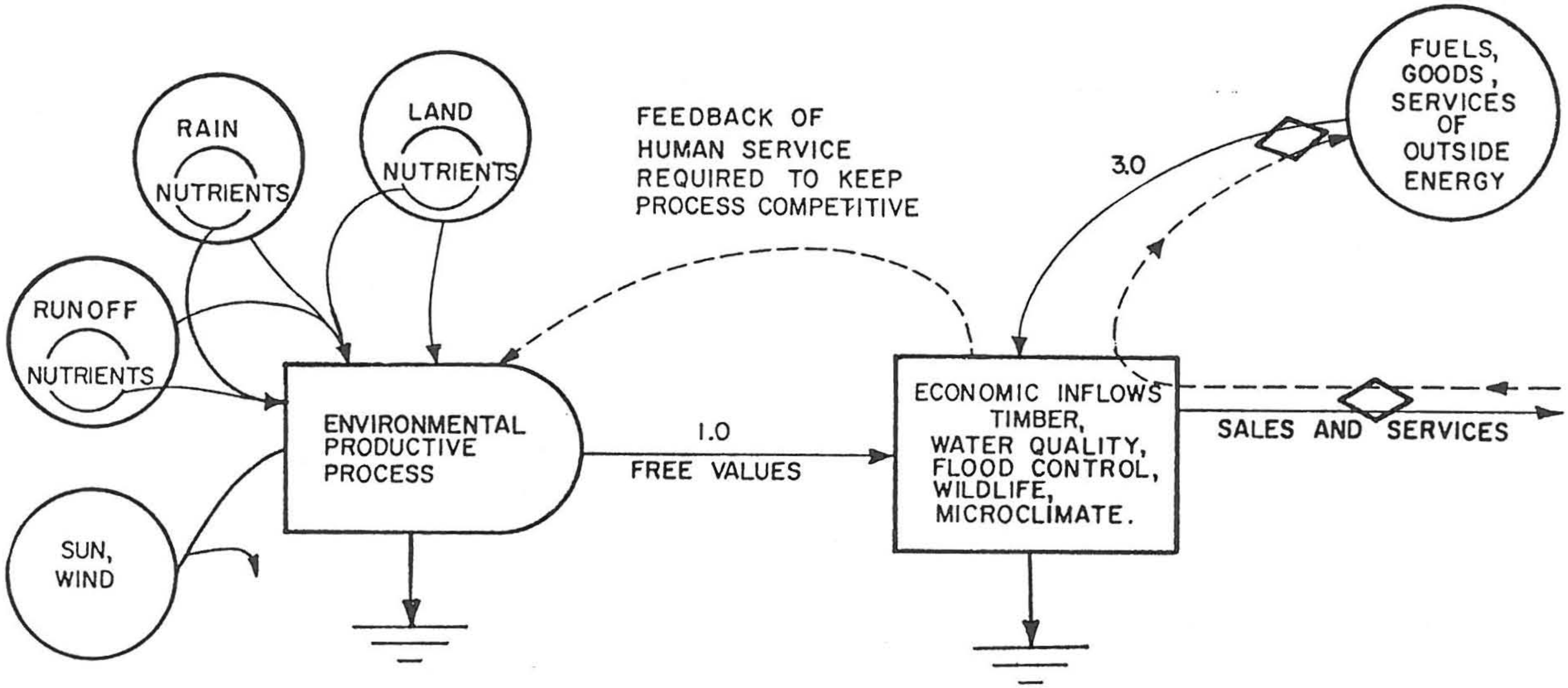

Figure E3. Diagram of the flow of purchased fuels, goods and services attracted by the resident energy flow of an environmental area, and the accompanying economic flow. (Flows of energies from the left determine energy and dollars circulating from the right.)

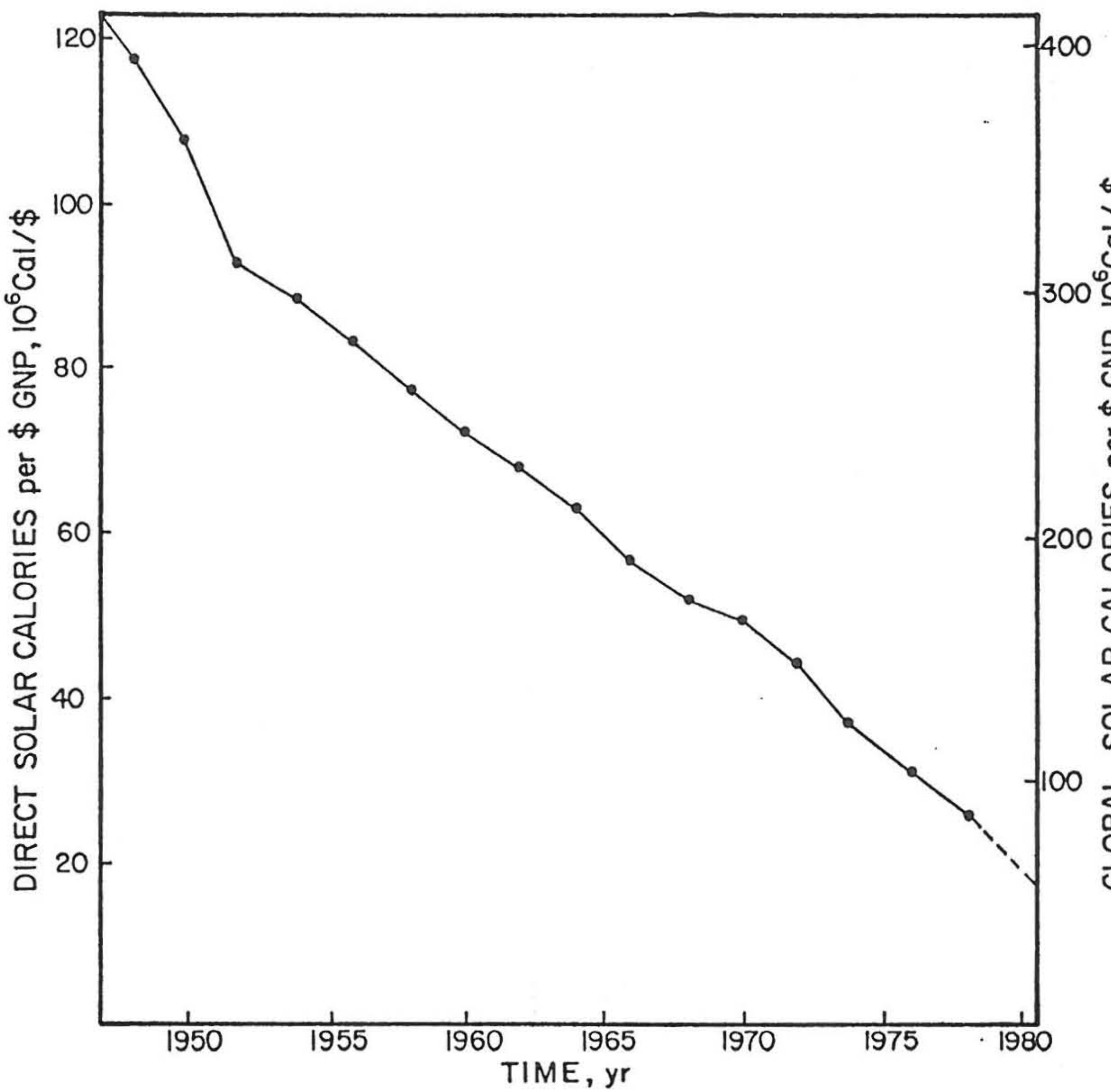

Figure E4. Ratio of embodied solar energy flow to GNP in the United States. Energy was estimated as sum of solar energy and solar equivalents of fuel use (see Table E2). Left-hand scale is Calories of direct terrestrial sunlight per dollar. Right-hand scale is Calories of global sunlight per dollar. See footnote 1 in Table E1.

interactions with a lower quality energy such as those of the environment. As shown in Fig. E3, an economy maximizes power when the ratio of its high-quality investments interacting with resident energies yields as much power as its competing neighbors. Consequently, if we are given a measure of the energy flow of an environmental area, we can estimate the high-quality energy flows that can be attracted from outside in exchange processes according to the ratio of these two that is competitive. In the United States this ratio is about three attracted for each environmental unit.

EVALUATION PROCEDURE

The procedure for evaluating environmental energy values is set forth in Table E3. The items in that list of steps have roman numerals. For each roman numeral there is a more detailed explanation given subsequently, in which appropriate references to tables are given so that calculations may be readily made. The procedure provides an evaluation of one or more of the flows and storages in Fig. E2, depending upon the purposes of the study.

Step I. Define Area and System of Concern

Based on the problem and alternatives, define the area for the evaluation, marking boundaries on maps and aerial photographs. The area should include zones to be affected by construction, wastes, or other changes. Then with the help of Fig. E2 identify main flows and storages.

Selection of the areas for evaluation may be done on two scales: (1) Identify the immediate area of a proposed project where the core of new construction and assets are developed and the environment is directly affected. For example, a power plant has its adjacent property and buffer zones where environmental energy flows and storages are affected; (2) Identify the area of the larger system of nature and man that is affected by the project's general effect on the economy. For example, a new power plant affects the economy over its powershed, which may be many counties. This larger area must be defined for the purpose of identifying any changes expected in the environmental energies of the larger system.

Step II. Identify Main Inflows and Storages

The second step in landscape evaluation is the identification of main inflows and storages prior to measurement in Calories of heat equivalents. A checklist of categories to be evaluated is shown in Fig. E2. A preliminary calculation can establish those that are most important.

Figure E2 is a checklist model containing the types of energy inflows and major storages of most landscapes. The lower quality energy inflows such as sunlight and thermal gradients

Table E3. Summary list of procedural steps for evaluating environmental resources.

Step	Procedure
I	Define area and system; get map of land and water use, or an aerial photograph to calculate areas of system to be evaluated (see page E18).
II	Identify main inflows and storages, writing specifics on an energy diagram and on tables formatted like those in Tables E4 and E5 (see page E18).
III	Evaluate inflows; evaluate each flow in heat equivalent Calories according to formulae given in numbered instructions that are keyed by number in Fig. E2. Write values on column 3 in Table E4 and on energy diagram (see page E21).
IV	Evaluate actual energy in long-term storages in Calories according to the lettered instructions. Write values in Table E5 and on energy diagram (see page E71).
V	Without double counting determine embodied energy of flows and storages. Multiply heat flows and storages by energy transformation ratios to obtain embodied solar Calories. This is completed as the last columns of Tables E4 and E5. Energy transformation ratios are given in Table E1 (see page E80).
VI	Estimate the dollar equivalents by multiplying solar equivalents by a characteristic $/energy ratio (see Fig. E4) (see page E80).
VII	Estimate changes due to projects of concern. Estimate $ equivalents changed because of storages lost and flows interrupted (see page E85).

Table E4. Example of a table for evaluating inflows to the system.

(1) Number* of Pathway and Footnote	(2) Flow	(3) Heat Equivalent Cal/yr	(4) Energy Transformation Ratio Solar Cal/Cal	(5) Solar Equivalents Solar Cal/yr
1	Sunlight	1.5×10^{11}	1	1.5×10^{11}
2	Wind	2.0×10^{9}	56.7	1.134×10^{11}
etc.				

*Number is also written on energy diagrams that may have been drawn to represent the system.

Table E5. Example of a table for evaluating long-term storages.

(1) Letter* of Storage and Footnote	(2) Storage	(3) Estimated Formation Time, yr	(4) Heat Equivalent Calories	(5) Energy Transformation Ratio Solar Cal/Cal	(6) Stored Solar Equivalents, Solar Cal
A	Soil	500	5×10^{9}	12×10^{4}	60×10^{13}
B	Wood	100	4×10^{9}	3×10^{3}	12×10^{12}
etc.					

*Letter is also written on energy diagrams that may have been drawn to represent the system.

are on the left. Higher quality inputs come in from the top. These include rain, water flows, nutrients, etc. Very high-quality inflows such as species exchanges and information are on the right. The storages within the system to be evaluated are those that take long periods to accumulate such as soil structure, landscape geomorphology, and the land itself.

After selecting from Fig. E2 the energy flows that are important, an energy diagram for the system can be drawn like that in Fig. E1 (see Odum and Odum 1981). Drawing the diagram helps understanding.

Step III. Evaluate Inflows

Evaluate each of the pathways in Fig. E2 selected as important. The paragraphs that follow provide formulae and data.

For this manual, some tables and maps of typical data on energy flows and storages in the United States are included. These can be used to determine which pathways and storages are important. More detailed and accurate local data may be assembled for the important pathways where desired.

Energy flows that are or seem to be disordering and stressful are counted as positive energy contributions, nevertheless, since they are used by those subsystems that can adapt and can use the stress to eliminate competition, maintain diversity, etc.

Equations Used in Evaluating Energy Flows and Storages

Thirty equations are used in the procedure of steps below. Calculations of actual energy flows and storage are made using standard textbook formulae for various kinds of energy. Chemical potential energies in equations 8–11, 13, 15, 18, 19, 22, 25, and 30 (Gibbs free energy) are calculated from the Neinst equation found in physical chemical texts where concentrations are estimated from field conditions. Chemical potential energy of organic substances are from text sources quoting bomb calorimeter values (equations 27 and 28).

Equations 3, 5, 13, 15, 18, and 19 are expressions evaluating advection. Advection of energy was estimated as product of flows of wind, river, tide, or land times the change in energy content due to energy use while the flow is within the boundaries of the area. Advection brings energy of chemical contents, sand, thermal content, etc.

Equations 1, 2, and 4 involve transfer of energy by eddies down into the system of interest as wind flows transport energies above an area. These equations evaluate product of vertical gradient and vertical eddy diffusion coefficients.

Equations 7, 20, 24, and 29 involve potential energy of elevated matter in streams, mountains, etc. Energies due to elevated matter against gravity are calculated according to mechanical work stored by force activity for a distance. See mechanics texts.

Equation 6 is the kinetic energy of falling raindrops with velocities of drops a function of droplet size.

Equation 12 on tide absorbed is calculated as the potential energy of elevation times the volume of water where energies are absorbed in each tide times the number of tides.

Equation 14 evaluates energy in waves at the depth they are measured using a classical expression that is one eighth the square of the height. The velocity by which waves move ashore is calculated for that same depth.

Equations 21–24 are so-called catastrophes. The long-term surges of larger systems of the earth provide exceptional energies to the ecosystems as floods, earthquakes, and hurricanes. The high-energy systems have high quality and are evaluated separately from lower energy flows of air and water and land.

Paragraph 22 on DNA of species seeding and paragraph 23 on human exchanges are for calculations of small quantities of actual energy, but are nonetheless important. When multiplied by the large energy transformation ratios of the valuable items, large embodied energy may result.

Equations 27–29 are used to calculate storages of actual energy using the same expressions used for estimating flows of those types of energy.

1. Solar Energy

Find annual flux of solar energy reaching the ground from Fig. E5 or Table E6. Estimate the unused reflection from the ground from Table E6. Subtract to obtain the solar energy used in the system or use last column in Table E6. See Sellers (1965) for more information.

2. Kinetic Energy from Wind

From Tables E7 and E8 or other sources estimate the vertical gradient of horizontal wind and the eddy exchange coefficient (K_m), and use equation 1 to obtain the rate of turbulent energy transfer down into the system.

$$P_m = Z_b \rho K_m \left(\frac{du}{dz}\right)^2 \text{ Watts/m}^2 \qquad (1)$$

$$P_m = Z_b \rho K_m \left(\frac{du}{dz}\right)^2 (7534) \qquad \text{Cal/m}^2\cdot\text{yr.}$$

where,

P_m = rate of production of turbulent kinetic energy per unit area in the planetary boundary layer;
Z_b = the average height of the atmospheric boundary layer (1000 m);
ρ = air density = 1.23 kg/m^3 (if area is at sea level);
K_m = eddy diffusion coefficient, m^2/s (see Table E7);
$\left(\frac{du}{dz}\right)$ = vertical gradient of wind, 1/s (see Table E8).

3. Potential Energy in Vertical Thermal Exchange

From Table E9, read the average potential temperature gradient in the planetary boundary

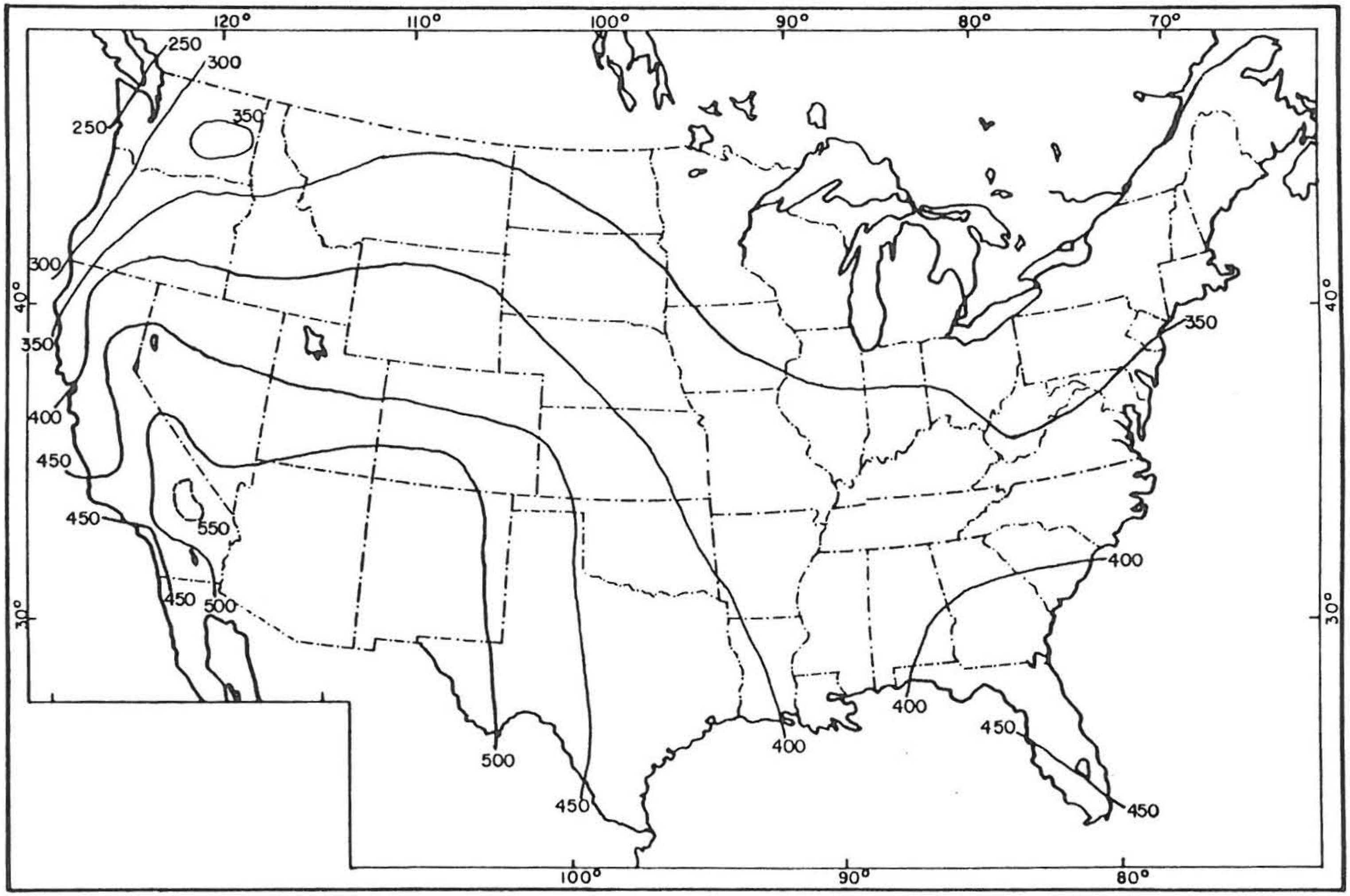

Figure E5. Annual mean daily insolation, in langleys, 1950-1964 (1 langley = 10 Cal/m^2) (Visher 1954).

Table E6. Annual mean solar radiation, albedo, and net solar radiation, albedo, and net solar radiation in the United States (from Kung et al. [1964]).

Table E6. (continued).

State	Average Annual Solar Radiation $Cal/cm^2 \cdot yr$	Average Ground Albedo	Net Absorbed Solar Radiation $Cal/cm^2 \cdot yr$
Alabama	145	0.14	124.7
Arizona	195	0.36	124.8
Arkansas	145	0.14	124.7
California	165	0.25	123.8
Colorado	160	0.36	102.4
Connecticut	130	0.14	111.8
Delaware	135	0.14	116.1
Florida	150	0.14	129.0
Georgia	145	0.14	124.7
Idaho	140	0.25	105.0
Illinois	125	0.19	101.3
Indiana	120	0.14	103.2
Iowa	125	0.19	101.3
Kansas	145	0.24	110.2
Kentucky	130	0.14	111.8
Louisiana	150	0.14	129.0
Maine	110	0.14	94.6
Maryland	135	0.14	116.1
Massachusetts	125	0.14	107.5
Michigan	115	0.14	98.9
Minnesota	120	0.19	97.2
Mississippi	150	0.14	129.0
Missouri	130	0.15	110.5
Montana	130	0.31	89.7
Nebraska	140	0.24	106.4
Nevada	165	0.24	125.4
New Hampshire	120	0.14	103.2
New Jersey	130	0.14	111.8
New Mexico	180	0.36	115.2
New York	120	0.14	103.2
North Carolina	140	0.14	120.4
North Dakota	120	0.27	87.6
Ohio	120	0.14	103.2
Oklahoma	155	0.21	122.5
Oregon	135	0.19	109.4
Pennsylvania	125	0.14	107.5
Rhode Island	125	0.14	107.5
South Carolina	140	0.14	120.4
South Dakota	130	0.29	92.3
Tennessee	135	0.14	116.1
Texas	170	0.30	119.0
Utah	170	0.36	108.8
Vermont	110	0.14	94.6
Virginia	140	0.14	120.4
Washington	120	0.23	92.4
West Virginia	130	0.14	111.8
Wisconsin	115	0.14	98.9
Wyoming	150	0.36	96.0

Table E8. Representative wind velocity gradient (from Swaney [1978]).

Station	Vertical Wind Velocity Gradient, du/dZ, $m/s \cdot m \times 10^{-3}$ January	July
Albany, New York	6.56	3.46
Albuquerque, New Mexico	6.23	2.21
Athens, Georgia	8.25	2.05
Boise, Idaho	3.7	- 0.61
Brownsville, Texas	5.1	6.64
Charleston, South Carolina	6.67	2.29
Dayton, Ohio	8.5	2.17
Denver, Colorado	6.09	- 0.51
Dodge City, Kansas	5.48	2.8
Flint, Michigan	8.07	3.76
Great Falls, Montana	4.33	1.0
Greensboro, North Carolina	7.86	1.10
Jackson, Mississippi	6.18	2.10
Little Rock, Arkansas	7.02	1.02
Medford, Oregon	3.14	- 0.18
Nashville, Tennessee	9.31	2.55
Oakland, California	4.29	1.59
Omaha, Nebraska	6.79	3.47
Peoria, Illinois	7.28	1.70
Pittsburg, Pennsylvania	8.42	2.39
Salt Lake City, Utah	6.1	0.98
Shreveport, Louisiana	6.32	
Tampa, Florida	2.26	1.51
Tucson, Arizona	0.3	- 1.06
Washington, D.C.	7.7	2.17

Table E9. Average vertical potential temperature gradient (from Swaney [1978]).

Station	Average Potential Temperature Gradient, $d\theta/dZ$ °K/m x 10^{-3} January	July
Albany, New York	8.11	17.24
Albuquerque, New Mexico	6.98	5.89
Athens, Georgia	12.03	6.10
Boise, Idaho	10.50	9.65
Brownsville, Texas	9.81	6.82
Charleston, South Carolina	10.48	6.57
Dayton, Ohio	8.14	6.68
Denver, Colorado	11.13	1.06
Dodge City, Kansas	12.78	8.50
Flint, Michigan	7.08	8.26
Great Falls, Montana	7.22	8.78
Greensboro, North Carolina	11.64	5.92
Jackson, Mississippi	9.68	8.11
Little Rock, Arkansas	10.96	8.98
Medford, Oregon	9.91	8.82
Nashville, Tennessee	9.40	7.23
Oakland, California	13.43	16.55
Omaha, Nebraska	12.36	8.22
Peoria, Illinois	9.84	7.72
Pittsburg, Pennsylvania	6.85	6.42
Salt Lake City, Utah	6.80	8.53
Shreveport, Louisiana	10.74	
Tampa, Florida	9.44	5.65
Tucson, Arizona	11.40	6.56
Washington, D.C.	11.19	8.86

layer for your location in either winter or summer. Multiply by the eddy diffusion coefficients given in Table E7, using equation 2 to obtain Calorie flux into the landscape system, or if minus, contributed out as an export.

$$J_h = C_p \rho K_h \frac{d\theta}{dz} \qquad \text{Cal/m}^2\cdot\text{s} \qquad (2)$$

where,

J_h = the vertical flux of heat due to turbulent transport, $\text{Cal/m}^2\cdot\text{s}$;
C_p = specific heat of dry air = 0.24 Cal/kg·°K;
ρ = air density = 1.23 kg/m^3;
K_h = turbulent eddy diffusion coefficient for heat, $\text{m}^2\text{/s}$ (see Table E7);
$\frac{d\theta}{dz}$ = vertical potential temperature gradient, °K/m (see Table E9).

4. Potential Energy in Thermal Advection

From the map in Fig. E6, determine the horizontal temperature gradient, dT/dx, in the direction of the local prevailing wind direction (Fig. E7). Use equation 3 to determine the maximum power available from horizontal advection.

$$F_y = C_p \rho Z_b \frac{dT}{dx} u \qquad \text{Cal/m}^2\cdot\text{s} \qquad (3)$$

where,

F_y = the rate of change of heat in the planetary boundary layer, $\text{Cal/m}^2\cdot\text{s}$;
C_p = specific heat of dry air = 0.24 Cal/kg·°K;
ρ = atmospheric density = 1.23 kg/m^3;
$\frac{dT}{dx}$ = local temperature gradient in the direction of u, °K/m;
Z_b = height of boundary layer = 1000 m;
u = local prevailing wind vector, m/s.

5. Vertical Exchange of Dry Air Potential

Calculate the Gibbs free energy difference, ΔF, per gram of water vapor, e_1, in air diffusing down across the boundary into the system and that, e_2, within the boundaries.

$$\Delta F = \frac{RT}{18} \ln \frac{e_2}{e_1} \qquad \text{Cal/g water vapor} \qquad (4)$$

where,

R = the gas constant, 1.99×10^{-3} Cal/mole·degree, and
18 = the molecular weight of water.

Then determine the rate of diffusion of water vapor out (dry air in) J_w:

$$J_w = \frac{18}{RT} K_w \frac{de}{dz} \qquad \text{g/m}^2\cdot\text{s}$$

where,

K_w = the diffusion coefficient from Table E7, and
$\frac{de}{dz}$ = the gradient of vapor with height from Table E10.

Multiplying free energy per gram times flux of grams per area per time provides the combined

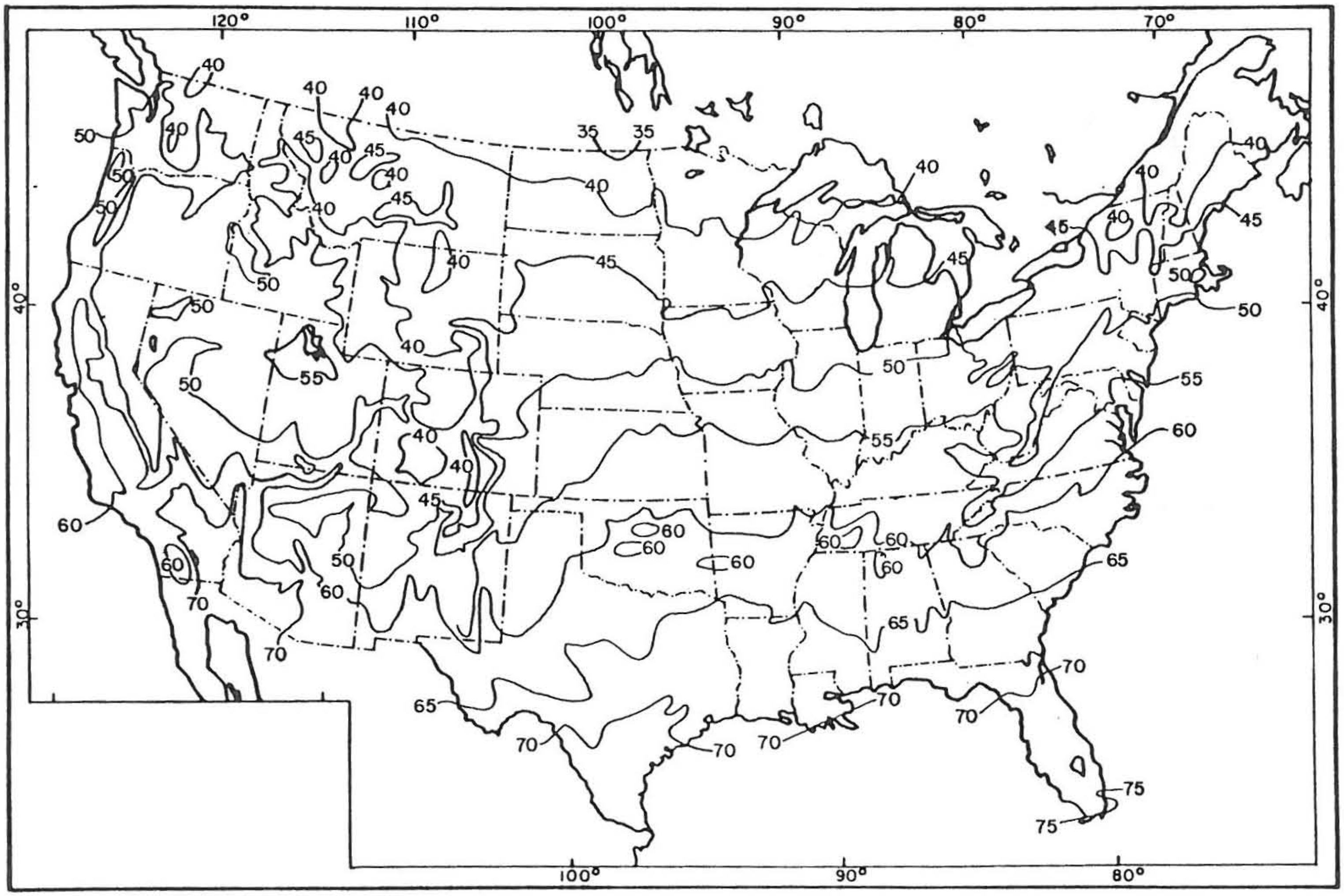

Figure E6. Map of average annual temperature (°F) 1899-1938 (NOAA 1977).

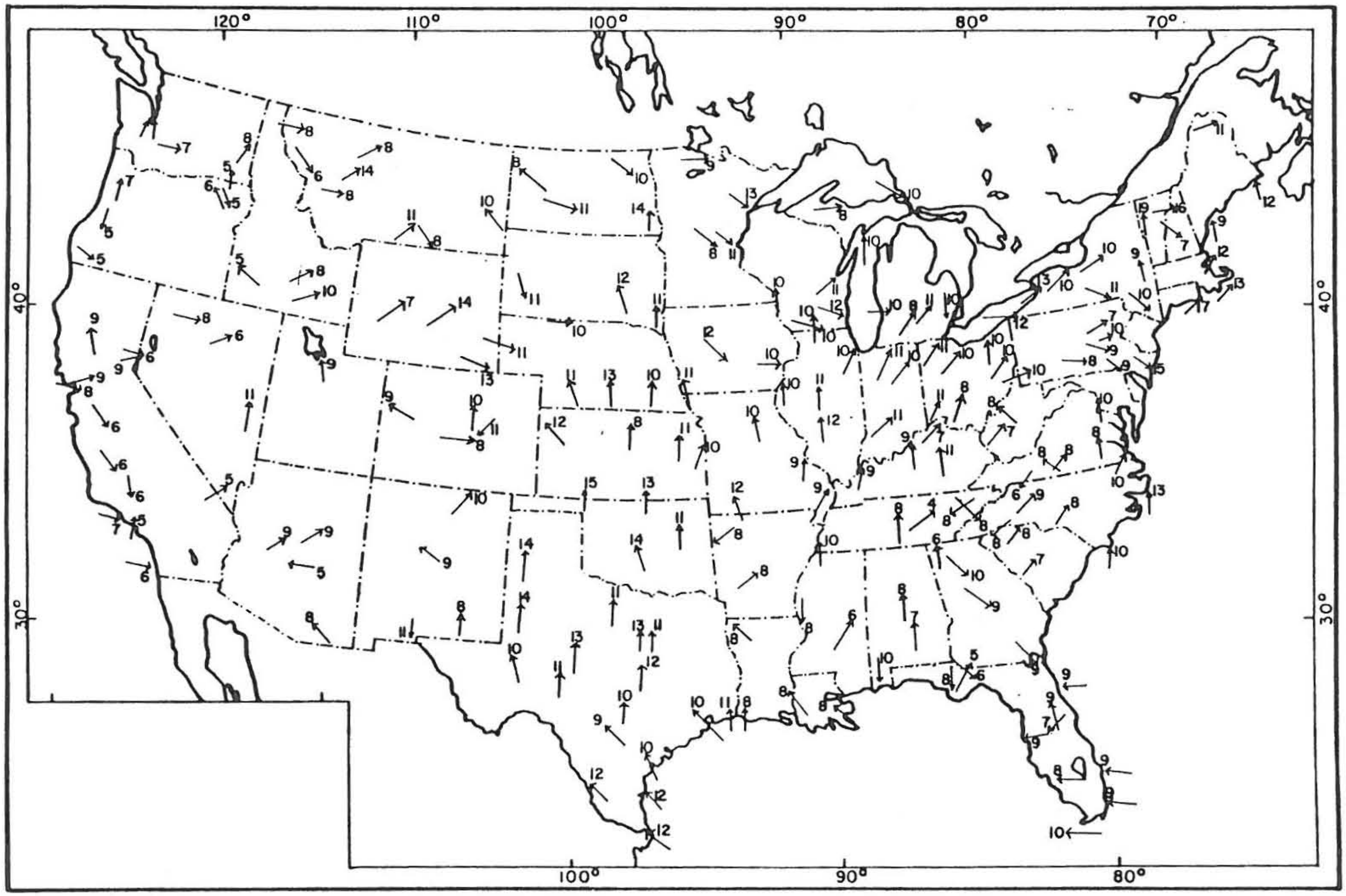

Figure E7. Prevailing wind direction and annual mean wind speed in MPH (NOAA 1977).

Table E10. Representative vapor pressure gradient (from Swaney [1978]).

Station	Average Surface Vapor Pressure, e, mb		Average Atmospheric Pressure, p, mb	Average Gradient of vapor pressure, de/dZ, mb/m x 10^{-4}	
	January	July		January	July
Albany, New York	3.76	18.0	1009	9.33	95.49
Albuquerque, New Mexico	2.84	13.1	838	9.45	38.64
Athens, Georgia	7.05	21.0	991	16.12	8.76
Boise, Idaho	3.76	11.6	920	5.3	21.83
Brownsville, Texas	12.3	23.9	1017	40.23	56.79
Charleston, South Carolina	9.39	21.5	1019	49.48	85.99
Dayton, Ohio	4.78	16.4	982	13.13	40.32
Denver, Colorado	2.74	10.4	834	9.01	34.19
Dodge City, Kansas	3.66	15.1	924	10.61	60.2
Flint, Michigan	3.89	14.64	986	4.50	46.87
Great Falls, Montana	2.78	11.58	885	5.88	47.33
Greensboro, North Carolina	5.87	20.75	987	22.03	13.43
Jackson, Mississippi	8.98	21.84	1008	10.98	85.53
Little Rock, Arkansas	6.74	20.63	1010	26.70	99.39
Medford, Oregon	5.84	11.09	976	18.0	48.16
Nashville, Tennessee	6.4	18.94	998	27.60	82.94
Oakland, California	7.81	12.53	1021	34.13	17.76
Omaha, Nebraska	3.09	15.44	967	8.07	32.77
Peoria, Illinois	3.98	15.9	993	13.99	49.91
Pittsburg, Pennsylvania	4.23	15.26	974	13.41	44.46
Salt Lake City, Utah	3.59	11.3	875	17.0	17.09
Shreveport, Louisiana			1010	32.42	
Tampa, Florida	13.79	23.1	1020	45.72	54.25
Tucson, Arizona	4.44	17.16	927	8.8	69.53
Washington, D.C.	4.47	18.29	1009	5.31	62.36

formula using decimal logarithms for convenience.

$$J_w = 2.3 \log_{10} \frac{e_2}{e_1} K_w \frac{de}{dz} \qquad Cal/m^2 \cdot s$$

If evapotranspiration rate is known and is in steady state exchange with dry air above, Calories may be calculated as in footnote 5 of Table E1. A more elaborate formula for vapor diffusion was derived by Swaney (1978) and this was used in Table E37.

6. Energy in Horizontal Advection with Vapor Pressure Gradient

From the map in Fig. E8, read average surface vapor-pressure values and calculate local gradient $(e_2 - e_1)/\Delta X$ in the direction of u (Fig. E7). Use these values in equation 5 to calculate F_g due to advection of dry air.

$$\Delta F = 2.3 \frac{RT}{18} \log_{10} e_2/e_1 \qquad Cal/gram\ vapor \quad (5)$$

$$J_g = Z_b \frac{18}{RT} e_2 - e_1/\Delta X\ u \qquad g\ vapor/m^2 \cdot s,$$

combined equation,

$$F_g = Z_b\ 2.3 \log_{10} e_2/e_1\ (e_2 - e_1/\Delta X)\ u \quad Cal/m^2 \cdot s$$

where,

F_g = flow of chemical free energy due to advection of dry air, $Cal/m^2 \cdot s$;
Z_b = average height of the planetary boundary layer = 1000 m;
$(e_2 - e_1/X)$ = local horizontal gradient of vapor pressure in the direction of u, mb/m;
u = local prevailing wind vector, m/s;
R = gas constant, 1.99×10^{-3} Cal/deg·mole;
T = Kelvin temperature; and
X = distance between inflowing vapor e_2 and outflowing vapor e_1.

7. Kinetic Energy of Rain

From Fig. E9 or Table E11, obtain the average rainfall for your location. Use equation 6 to calculate the kinetic energy of falling rain.

$$K_e = P(\tfrac{1}{2}MV^2)(2.38 \times 10^{-7}) \qquad Cal/m^2 \cdot yr \quad (6)$$

where,

K_e = kinetic energy of rain, $Cal/m^2 \cdot yr$;
P = annual rainfall, cm/yr;
M = density of rain = 1 g/cm^3;
V = average velocity of raindrop, cm/s (see Table E12).

Example for calculating kinetic energy of rain:

Using an average raindrop diameter of 4 mm, the average falling velocity is approximately 762 cm/s (Table E12). This yields a kinetic energy of

$$\Delta K = \tfrac{1}{2}MV^2$$
$$= \tfrac{1}{2}(1\ g/cm^3)(762\ cm/s)^2(2.38 \times 10^{-11}\ Cal/erg)$$
$$= 6.91 \times 10^{-6}\ Cal/cm^3.$$

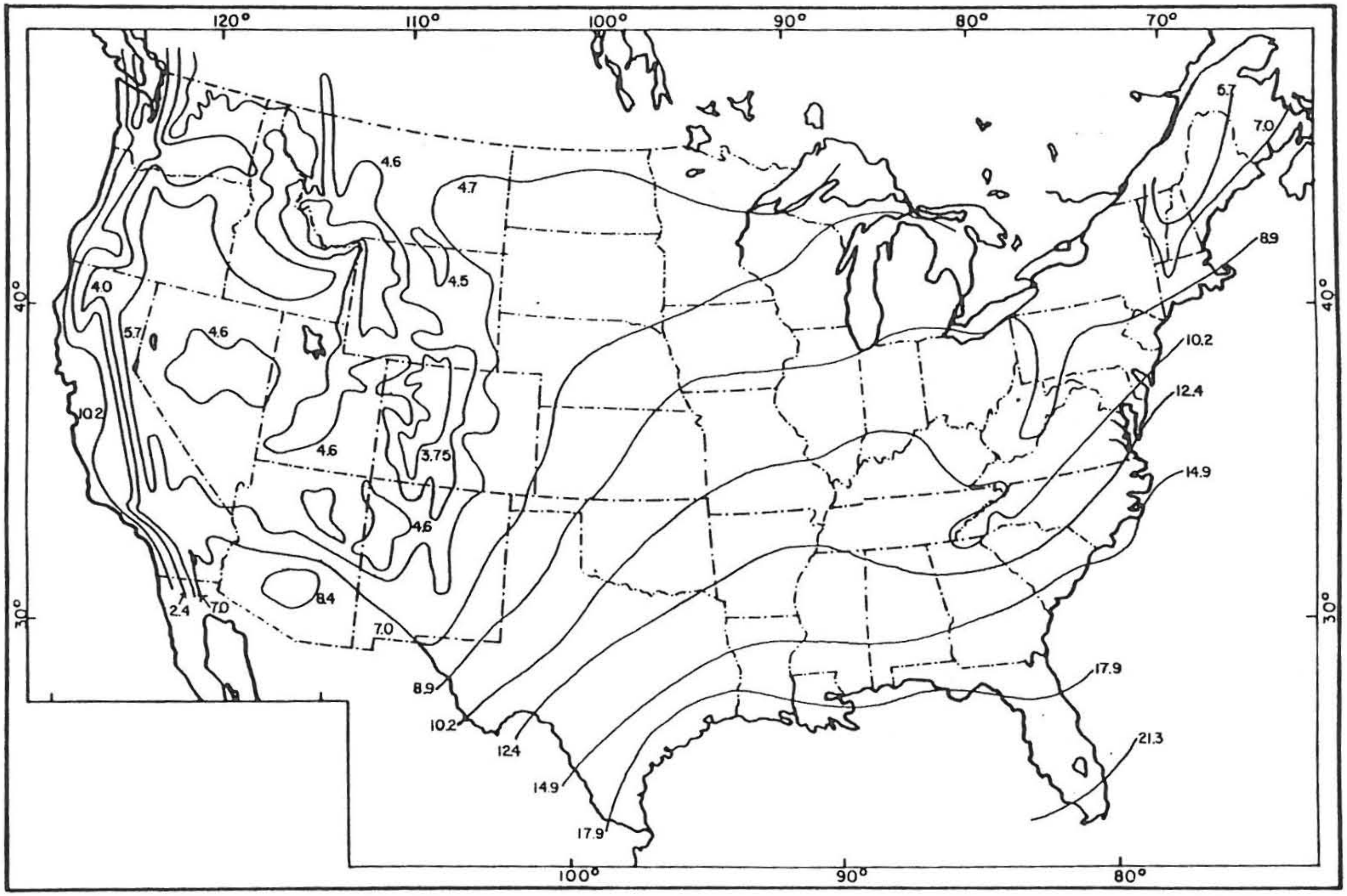

Figure E8. Average vapor pressure in mb (NOAA 1977).

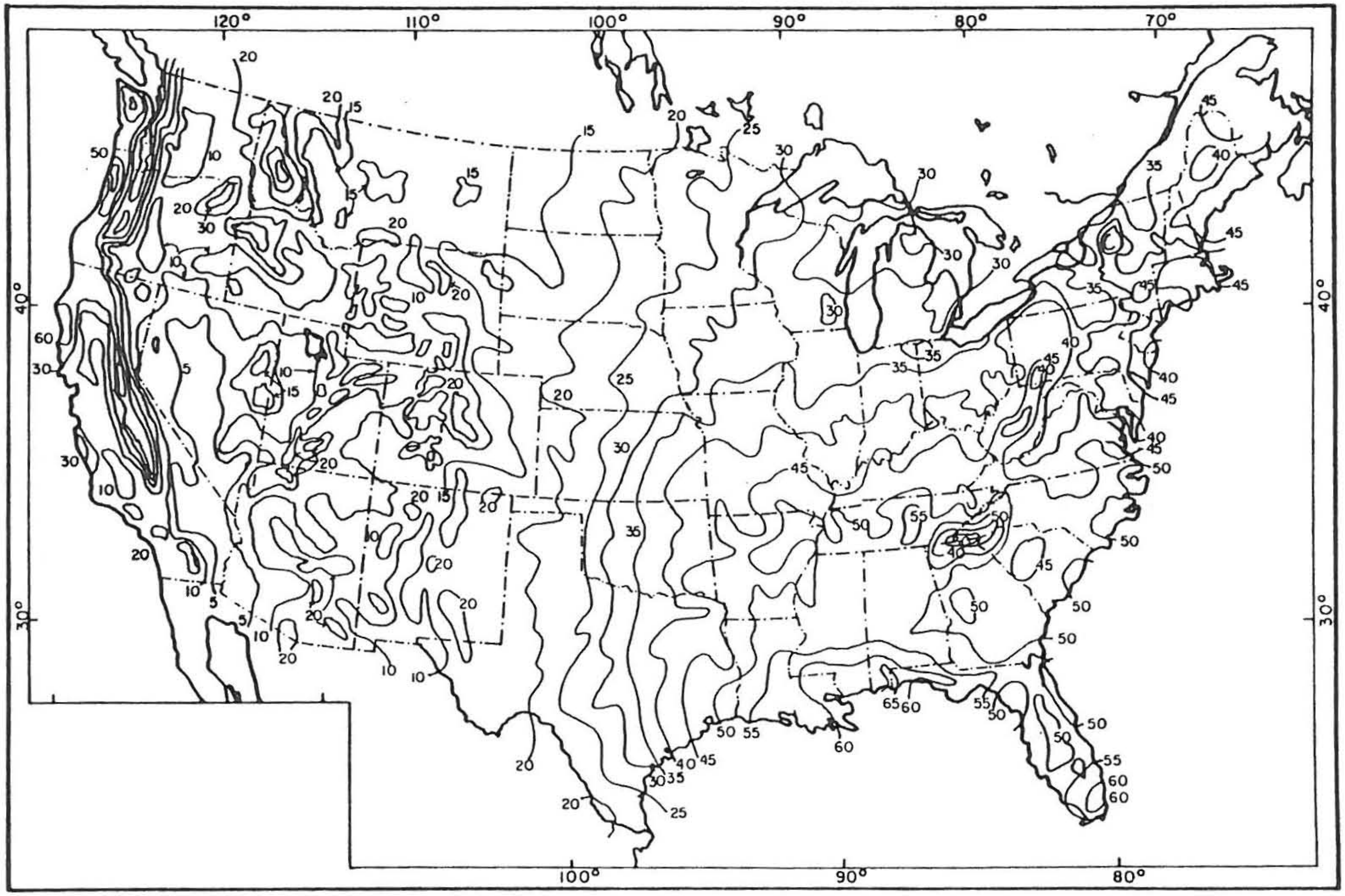

Figure E9. Average annual precipitation for the United States, in inches (NOAA 1977).

Table E11. Normal annual rainfall for selected cities of the United States (adapted from Todd [1970], p. 6).

Station	Average Annual Rainfall, P	
	Inches	Centimeters
Alabama, Mobile	68.13	173.05
Alaska, Juneau	54.62	138.73
Arizona, Phoenix	7.20	18.29
Arkansas, Little Rock	48.66	123.60
California, Sacramento	16.29	41.38
Colorado, Denver	14.81	37.62
Connecticut, Hartford	42.92	109.02
Delaware, Wilmington	44.56	113.18
D.C., Washington	40.78	103.58
Florida, Miami	59.76	151.79
Georgia, Atlanta	47.14	119.74
Hawaii, Honolulu	21.89	55.60
Idaho, Boise	11.43	29.03
Illinois, Peoria	34.84	88.49
Indiana, Indianapolis	39.25	99.70
Iowa, Des Moines	30.37	77.14
Kansas, Wichita	28.41	72.16
Kentucky, Louisville	41.32	104.95
Louisiana, New Orleans	53.90	136.91
Maine, Portland	42.85	108.84
Maryland, Baltimore	43.05	109.35
Massachusetts, Boston	42.77	108.64
Michigan, Detroit	30.95	78.61
Minnesota, Deluth	28.97	73.58
Mississippi, Jackson	50.82	129.08
Missouri, Kansas City	34.07	86.54
Montana, Great Falls	14.07	35.74

Table E11. (continued).

Station	Average Annual Rainfall, P	
	Inches	Centimeters
Nebraska, Omaha	27.56	70.00
Nevada, Reno	7.15	18.16
New Hampshire, Concord	38.80	98.55
New Jersey, Atlantic City	42.36	107.59
New Mexico, Albuquerque	8.13	20.65
New York, Albany	35.08	89.10
North Carolina, Charlotte	43.38	110.19
North Dakota, Bismarck	15.15	38.48
Ohio, Cleveland	35.35	89.79
Oklahoma, Oklahoma City	30.82	78.28
Oregon, Portland	37.18	94.44
Pennsylvania, Pittsburgh	36.14	91.80
Rhode Island, Providence	42.13	107.01
South Carolina, Columbia	46.82	118.92
South Dakota, Sioux Falls	25.16	63.91
Tennessee, Nashville	45.15	114.68
Texas, Houston	45.95	116.71
Utah, Salt Lake City	13.90	35.31
Vermont, Burlington	33.21	84.35
Virginia, Richmond	44.21	112.29
Washington, Seattle-Tacoma	38.94	98.91
West Virginia, Charleston	44.43	112.85
Wisconsin, Milwaukee	29.51	74.96
Wyoming, Cheyenne	15.06	38.25
Puerto Rico, San Juan	64.21	163.09

Table E12. Kinetic energy of rain according to drop size used for different parts of the country (adapted from Todd [1970], p. 55).

Raindrop Diameter, mm	Average Falling Velocity Ft/s	cm/s	Kinetic Energy, 10^{-6} Cal/cm^3
1.0	14	427	2.17
2.0	19	579	3.99
3.0	23	701	5.85
4.0	25	762	6.91
5.0	26	792	7.46

From Table E11, for example, the annual rainfall in Miami, Florida, is about 152 cm. The kinetic potential energy of rain is estimated as

$$K_e = P(\frac{1}{2}MV^2)$$

$$= (152 \text{ cm/yr})(100^2 \text{ cm}^2/\text{m}^2)(6.91 \times 10^{-6} \text{ Cal/cm}^3)$$
$$= 10.50 \text{ Cal/m}^2\cdot\text{yr}.$$

The relationship of kinetic energy of rain versus raindrop size for different annual rainfall is tabulated in Table E13 and plotted in Fig. E10.

8. Potential Energy of Rain at Surface

Read difference between receiving and outflow elevation for the area from Fig. E11 or Table E14 (or from local data). Use equation 7 to calculate the potential energy of rain.

Table E13. Kinetic energy of rain versus raindrop size for different annual rainfall (from equation 6 and Table E12).

Annual Rainfall Inch	cm	Raindrop Diameter, mm	Kinetic Energy Cal/m$^2\cdot$yr
60	152.4	1.0	3.31
		2.0	6.08
		3.0	8.92
		4.0	10.53
		5.0	11.37
50	127.0	1.0	2.76
		2.0	5.07
		3.0	7.43
		4.0	8.78
		5.0	9.47
40	101.6	1.0	2.20
		2.0	4.05
		3.0	5.94
		4.0	7.02
		5.0	7.58
30	76.2	1.0	1.65
		2.0	3.04
		3.0	4.46
		4.0	5.27
		5.0	5.68
20	50.8	1.0	1.10
		2.0	2.03
		3.0	2.97
		4.0	3.51
		5.0	3.79
10	25.4	1.0	0.55
		2.0	1.01
		3.0	1.49
		4.0	1.76
		5.0	1.89

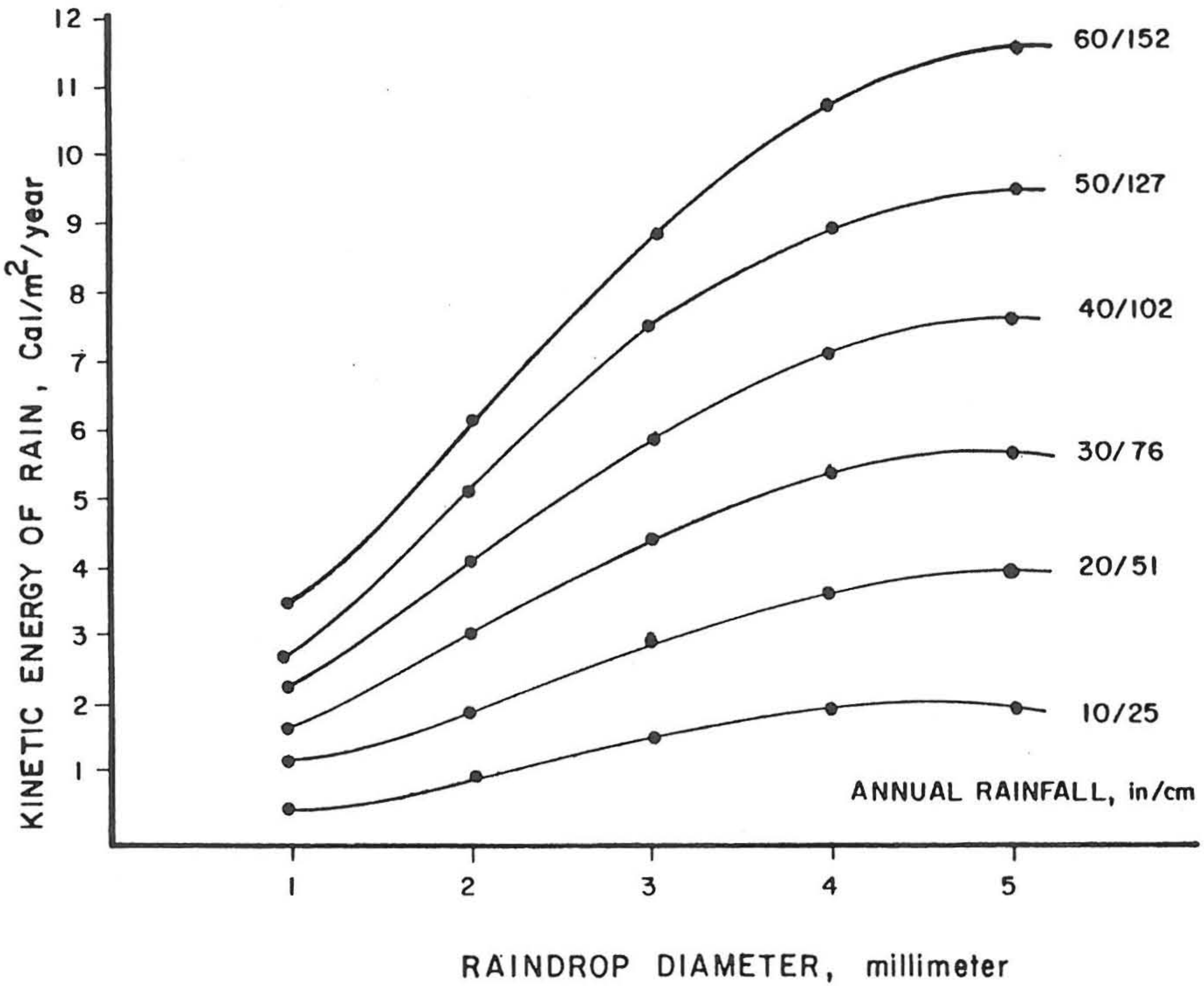

Figure E10. Kinetic energy of rain versus raindrop size for different annual rainfall (calculated using equation 6).

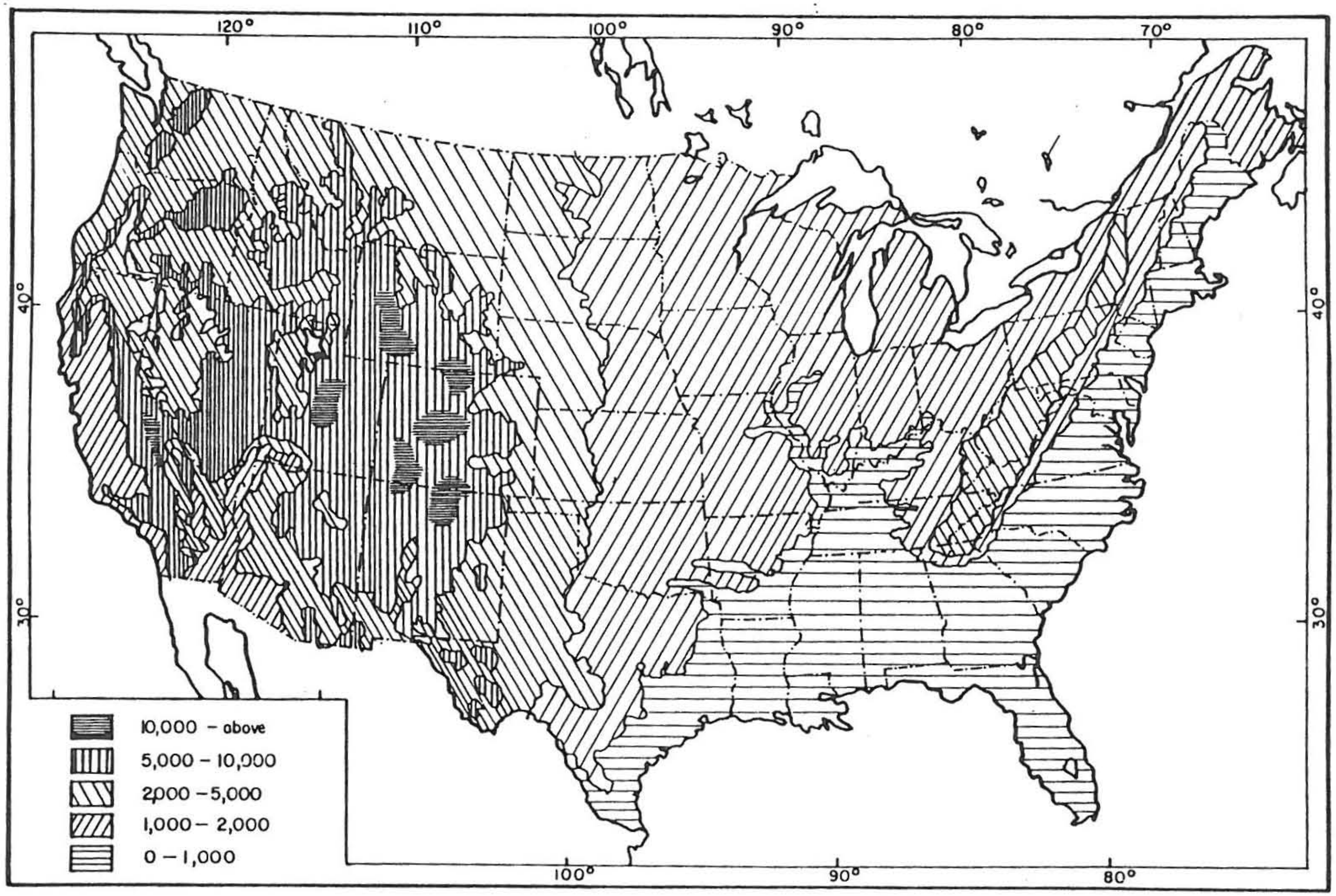

Figure E11. Map of elevation of the United States, in feet (from Hunt 1967).

Table E14. Mean and extreme altitudes of the United States (Hunt 1974).

State or Province	Highest Point		Lowest Point		Approximate Mean Altitude, ft
	Point	Altitude, ft	Point	Altitude, ft	
Alabama	Cheaha Mountain	2,406	Gulf of Mexico	Sea Level	500
Alaska	Mount McKinley, S. Peak	20,320	Pacific Ocean	Sea Level	1,900
Alberta	Mount Columbia	12,294	Liard River	1,000	5,000
Arizona	Humphreys Peak	12,633	Colorado River	70	4,100
Arkansas	Magazine Mountain	2,753	Ouachita River	55	650
British Columbia	Mount Fairweather	15,300	Pacific Ocean	Sea Level	5,000
California	Mount Whitney	14,494	Death Valley	- 282	2,900
Colorado	Mount Elbert	14,433	Arkansas River	3,350	6,800
Connecticut	Mount Frissell, S. Slope	2,380	Long Island Sound	Sea Level	500
Delaware	On Ebright Road	422	Atlantic Ocean	Sea Level	60
District of Columbia	Tenleytown	410	Potomac River	1	150
Florida	Sec. 30, T. 6N, R. 20W	345	Atlantic Ocean	Sea Level	100
Georgia	Brasstown Bald	4,784	Atlantic Ocean	Sea Level	600
Hawaii	Mauna Kea	13,786	Pacific Ocean	Sea Level	1,990
Idaho	Borah Peak	12,662	Snake River	710	5,000
Illinois	Charles Mound	1,235	Mississippi River	279	600
Indiana	Franklin Township	1,257	Ohio River	320	700
Iowa	Ocheyedan Mound	1,675	Mississippi River	480	1,100
Kansas	Mount Sunflower	4,039	Verdigris River	680	2,000
Kentucky	Black Mountain	4,145	Mississippi River	257	750
Louisiana	Driskill Mountain	535	New Orleans	- 5	100
Maine	Mount Katahdin	5,268	Atlantic Ocean	Sea Level	800
Manitoba	Baldy Mountain	2,727	Hudson Bay	Sea Level	1,200
Maryland	Backbone Mountain	3,360	Atlantic Ocean	Sea Level	350
Massachusetts	Mount Greylock	3,491	Atlantic Ocean	Sea Level	500
Michigan	Mount Curwood	1,980	Lake Erie	572	900
Minnesota	Eagle Mountain	2,301	Lake Superior	602	1,200
Mississippi	Woodall Mountain	806	Gulf of Mexico	Sea Level	300
Missouri	Taum Sauk Mountain	1,772	St. Francis River	230	800
Montana	Granite Peak	12,799	Kootenai River	1,800	3,400
Nebraska	Johnson Township	5,426	SE corner of state	840	2,600
Nevada	Boundary Peak	13,140	Colorado River	470	5,500
New Brunswick	Mount Carlton	2,690	Gulf of St. Lawrence	Sea Level	1,200
Newfoundland (Island)	Lewis Hills	2,672	Atlantic Ocean	Sea Level	1,200
Newfoundland	Torngat Mountains	5,500	Atlantic Ocean	Sea Level	2,200

Table E14. (continued).

State or Province	Highest Point: Point	Highest Point: Altitude, ft	Lowest Point: Point	Lowest Point: Altitude, ft	Approximate Mean Altitude, ft
New Hampshire	Mount Washington	6,288	Atlantic Ocean	Sea Level	1,000
New Jersey	High Point	1,803	Atlantic Ocean	Sea Level	250
New Mexico	Wheeler Peak	13,161	Red Bluff Reservoir	2,817	5,700
New York	Mount Marcy	5,344	Atlantic Ocean	Sea Level	1,000
North Carolina	Mount Mitchell	6,684	Atlantic Ocean	Sea Level	700
North Dakota	White Butte	3,506	Red River	750	1,900
Northwest Territories	Baffin Island	8,500	Atlantic Ocean	Sea Level	1,000
Nova Scotia	North Barren	1,747	Atlantic Ocean	Sea Level	500
Ohio	Campbell Hill	1,550	Ohio River	433	850
Oklahoma	Black Mesa	4,973	Little River	287	1,300
Ontario	Tip Top Mountain	2,120	Hudson Bay	Sea Level	500
Oregon	Mount Hood	11,235	Pacific Ocean	Sea Level	3,300
Pennsylvania	Mount Davis	3,213	Delaware River	Sea Level	1,100
Puerto Rico	Cerro de Punta	4,389	Atlantic Ocean	Sea Level	2,200
Quebec	Mount Jacques Cartier	4,160	Hudson Bay	Sea Level	2,000
Rhode Island	Jerimoth Hill	812	Atlantic Ocean	Sea Level	200
Saskatchewan	Cypress Hills	4,546	Slave River	600	1,000
South Carolina	Sassafras Mountain	3,580	Atlantic Ocean	Sea Level	350
South Dakota	Harney Peak	7,742	Big Stone Lake	962	2,200
Tennessee	Clingmans Dome	6,643	Mississippi River	182	900
Texas	Guadalupe Peak	8,751	Gulf of Mexico	Sea Level	1,700
Utah	Kings Peak	13,528	Beaverdam Creek	2,000	6,100
Vermont	Mount Mansfield	4,393	Lake Champlain	95	1,000
Virginia	Mount Rogers	5,729	Atlantic Ocean	Sea Level	950
Virgin Islands	Crown Mountains	1,556	Atlantic Ocean	Sea Level	750
Washington	Mount Rainier	14,410	Pacific Ocean	Sea Level	1,700
West Virginia	Spruce Knob	4,862	Potomac River	240	1,500
Wisconsin	Timms Hill	1,952	Lake Michigan	581	1,050
Wyoming	Gannett Peak	13,785	Belle Fourche River	3,100	6,700
Yukon	Mount Logan	19,850	Artic Ocean	Sea Level	3,500

$$G_e = P(\rho gh)(2.38 \times 10^{-7}) \quad Cal/m^2 \cdot yr \quad (7)$$

where,

G_e = potential energy of rain, $Cal/m^2 \cdot yr$;
P = annual rainfall, cm/yr;
ρ = density of water = 1 g/cm^3;
g = acceleration of gravity = 980 cm/s^2;
h = average height of land, cm.

Example for calculating potential energy of rain:

If the difference in elevation between receiving and outflow area is 10 m (1000 cm), the potential energy is computed as

$$\begin{aligned}\Delta G &= \rho gh \\ &= (1\ g/cm^3)(980\ cm/s^2)(1000\ cm) \\ &\quad (2.38 \times 10^{-11}\ Cal/erg) \\ &= 2.33 \times 10^{-5}\ Cal/cm^3.\end{aligned}$$

From Table E11, the annual rainfall in Miami, Florida, is about 60 inches (152 cm). The potential energy of rain is estimated as

$$\begin{aligned}G_e &= P(\rho gh) \\ &= (152\ cm/yr)(100^2\ cm^2/m^2) \\ &\quad (2.33 \times 10^{-5}\ Cal/cm^3) \\ &= 35.5\ Cal/m^2 \cdot yr.\end{aligned}$$

The relationship between potential energy of rain and land elevation difference for different annual rainfall is tabulated in Table E15 and plotted in Fig. E12.

Table E15. Potential energy of rain versus land elevation for different annual rainfall (from equation 7).

Annual Rainfall Inch	Annual Rainfall cm	Difference in Land Elevation m	Potential Energy $Cal/m^2 \cdot yr$
60	152.4	10	35.5
		20	71.0
		30	106.7
		40	142.2
		50	177.7
50	127.0	10	29.6
		20	59.2
		30	88.9
		40	118.5
		50	148.1
40	101.6	10	23.7
		20	47.4
		30	71.1
		40	94.8
		50	118.5
30	76.2	10	17.8
		20	35.5
		30	53.3
		40	71.1
		50	88.9
20	50.8	10	11.8
		20	23.7
		30	35.6
		40	47.4
		50	59.2
10	25.4	10	5.9
		20	11.8
		30	17.8
		40	23.7
		50	29.6

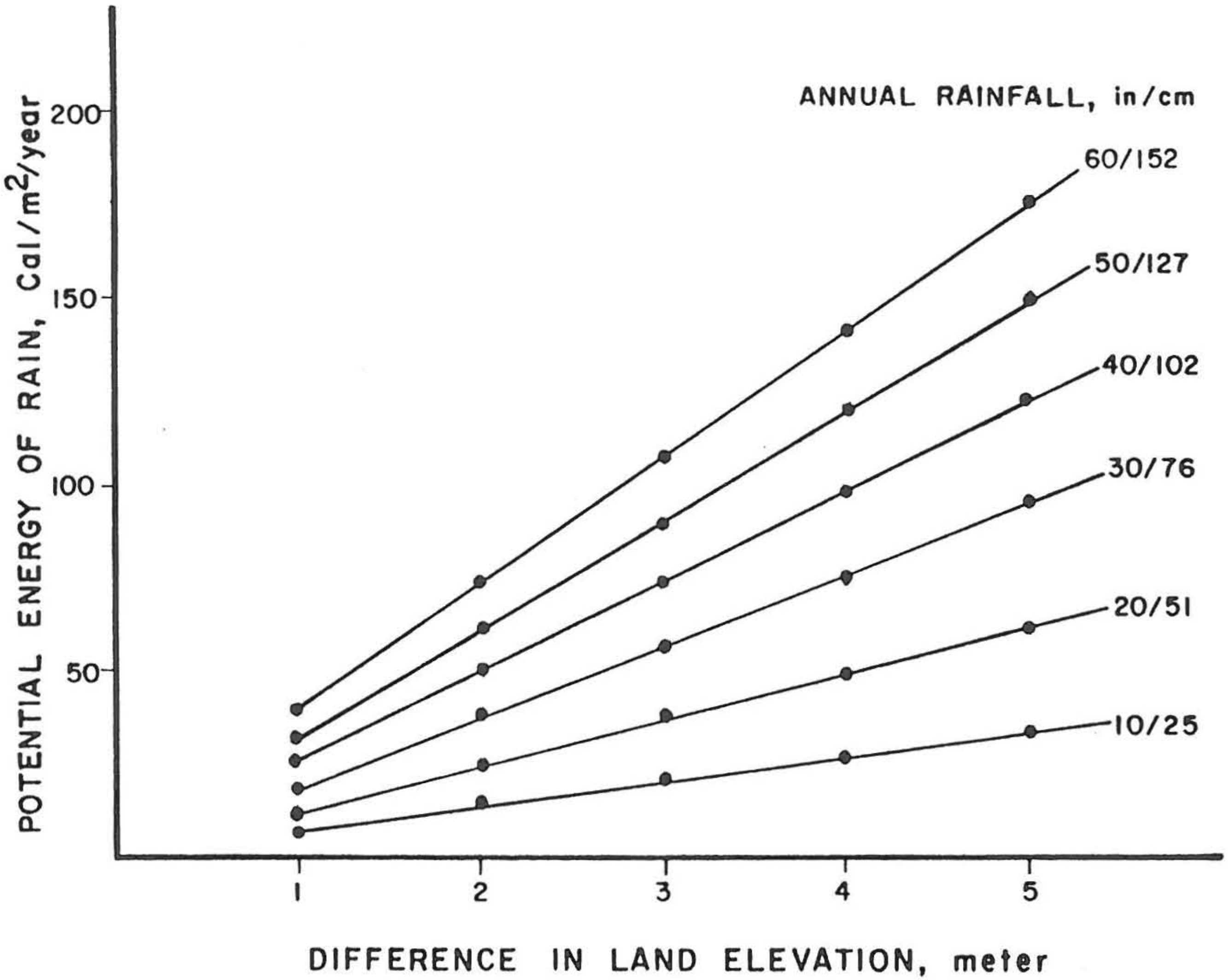

Figure E12. Potential energy of rain versus land elevation difference for different annual rainfall (calculated using equation 7).

9. Chemical Potential Energy of Rainfall

First, obtain the average annual rainfall from Fig. E9 or Table E11. Then read the average total dissolved solids concentration (in ppm) in rainfall from Fig. E13. Subtract this from 1,000,000 ppm to get the water concentration. Call this C_2. Use equation 8 to calculate the total free energy from chemical potential in rainfall for your site.

$$F_r = P(nRT)(C_2)\ln(\frac{C_2}{C_1}) \qquad Cal/m^2\cdot yr \qquad (8)$$

where,

- F_r = chemical potential energy based on water concentration, Cal/m2.yr;
- P = annual rainfall, m/yr;
- n = number of moles of water = 1/18 mole/g;
- R = universal gas constant = 1.99×10^{-3} Cal/°K·mole;
- T = temperature in degrees Kelvin = 300°K;
- C_1 = seawater concentration = 1,000,000 ppm - 35,000 ppm = 965,000 ppm; and
- C_2 = rainwater concentration.

Example for calculating chemical potential energy of rainfall:

An average of 10 ppm rainwater and 35,000 ppm seawater are assumed. The free energy per gram of water is given by

$$\Delta F = (nRT)\ln(\frac{C_2}{C_1})$$

$$= \frac{(1.99 \times 10^{-3}\ Cal/°K\cdot mole)(300°K)}{18\ g/mole}\ln(\frac{999,990}{965,000})$$

$$= (3.31 \times 10^{-2}\ Cal/g)(0.0356)$$

$$= 1.18 \times 10^{-3}\ Cal/g\ water.$$

From Table E11, the annual rainfall in Miami, Florida, is 1.52 m/yr, so the chemical potential energy of rain is estimated as

$$F_r = PC_2\Delta FP(nRT)(C_2)\ln(\frac{C_2}{C_1})$$

$$= (1.52\ m/yr)(999,990\ g/m^3)(1.18 \times 10^{-3}\ Cal/g)$$

$$= 1.79 \times 10^3\ Cal/m^2\cdot yr.$$

10. Rain Chemical Potential of Nutrients

First, obtain the average annual rainfall from Fig. E9 or Table E11. Second, read the average nitrogen and phosphorus concentration (in ppm) in rainfall from Figs. E14 and E15 or Tables E16 and E17. Call these C_2 and C_3, respectively.

Use equations 9 and 10 to calculate the chemical potential of nitrogen and phosphorus, respectively.

$$F_n = P(nRT)(C_2)\ln(\frac{C_2}{C_1}) \qquad Cal/m^2\cdot yr \qquad (9)$$

where,

- F_n = chemical potential of nitrogen as NO_3^- and NH_4^+;
- P = annual rainfall, m/yr;
- n = number of moles of nitrogen as NO_3^- and NH_4^+ per gram = 1/40;
- R = universal gas constant = 1.99×10^{-3} Cal/°K·mole;
- T = temperature in degrees Kelvin = 300°K;
- C_1 = average nitrogen concentration in seawater = 0.5 ppm;

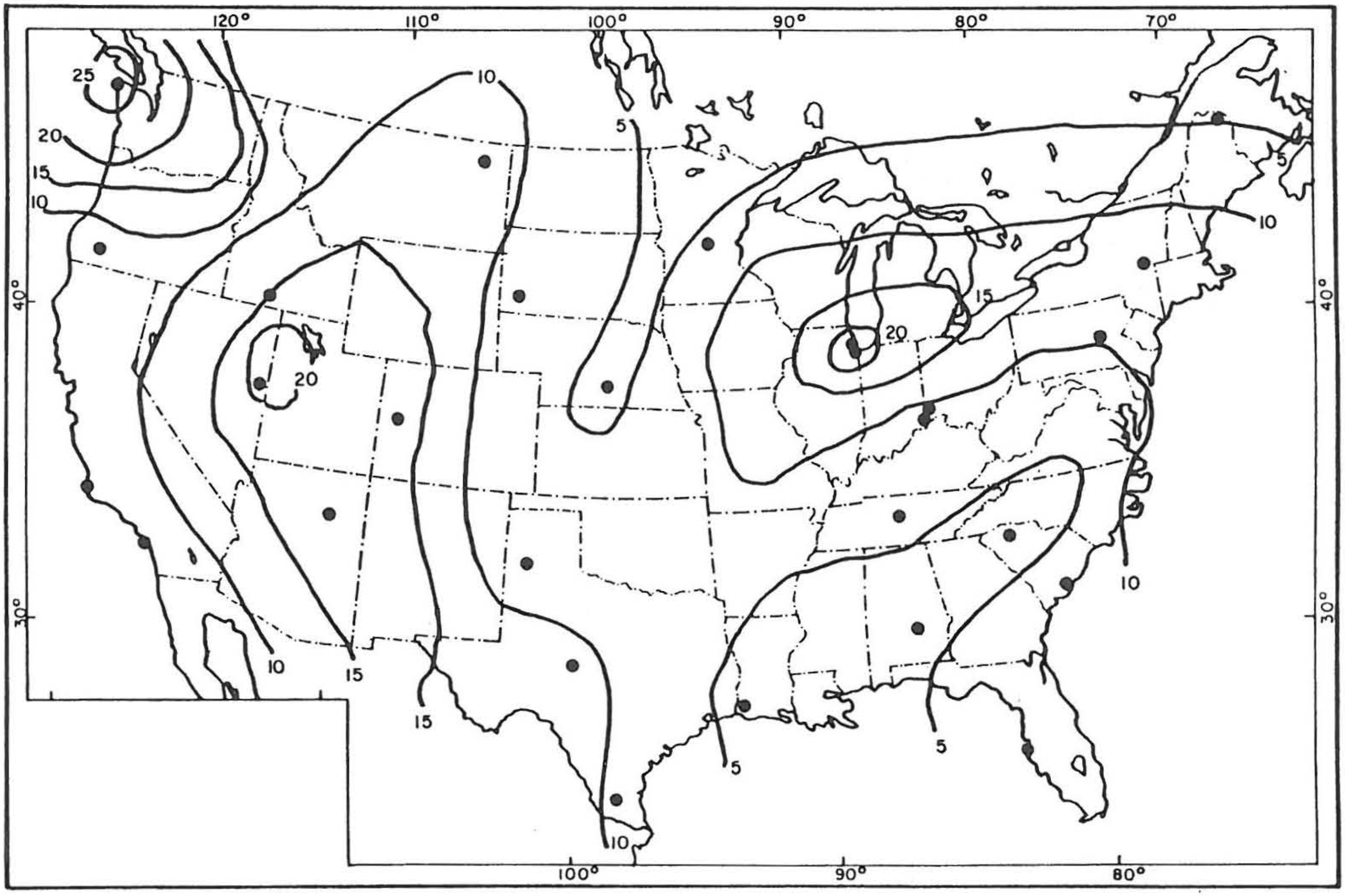

Figure E13. Estimated total dissolved solids in rainfall in ppm (from Likens 1976; Lodge et al. 1968).

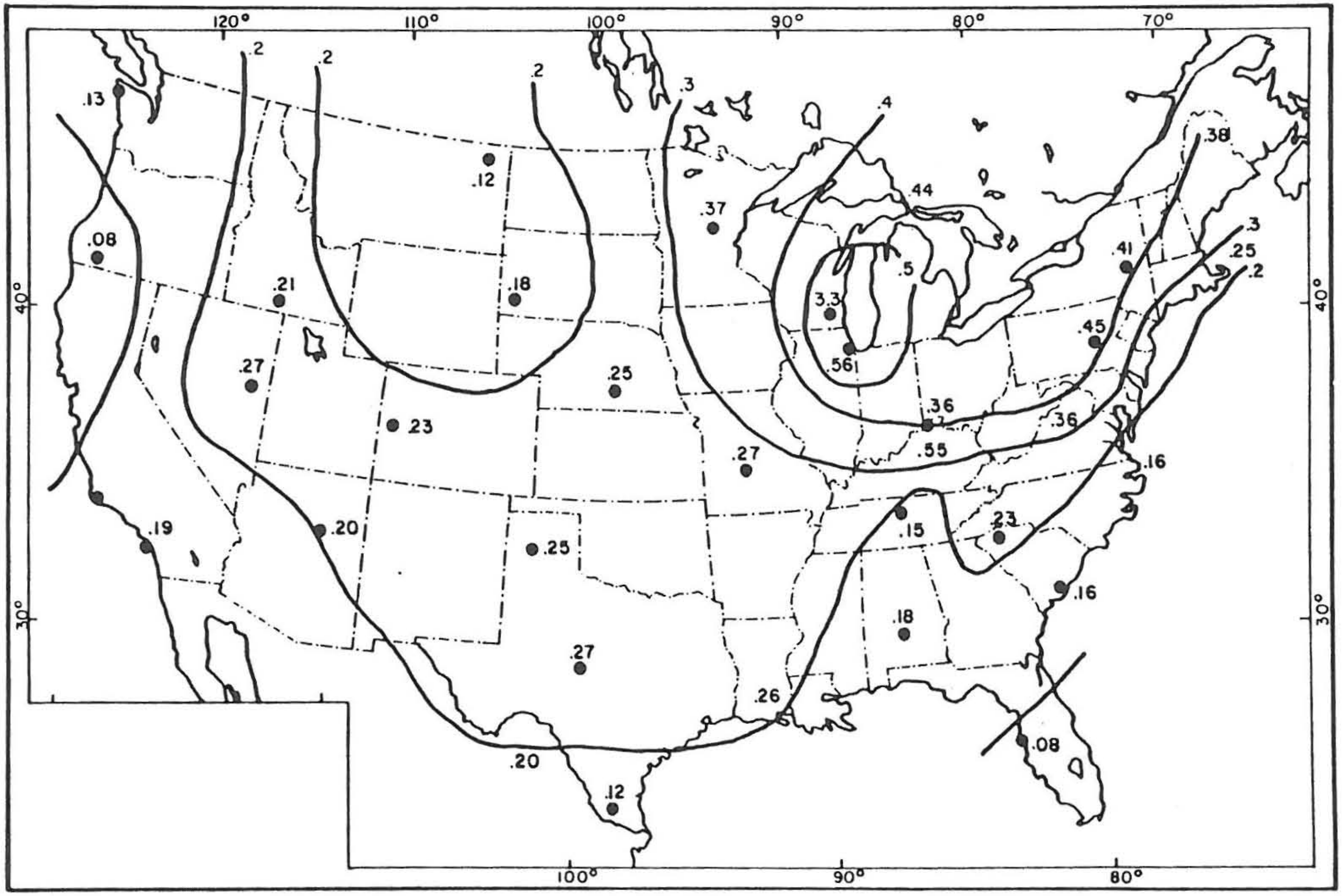

Figure E14. Total inorganic nitrogen concentration in rainfall (NO_3^- and NH_4^+) in ppm (from Lodge et al. 1968; see Table E16).

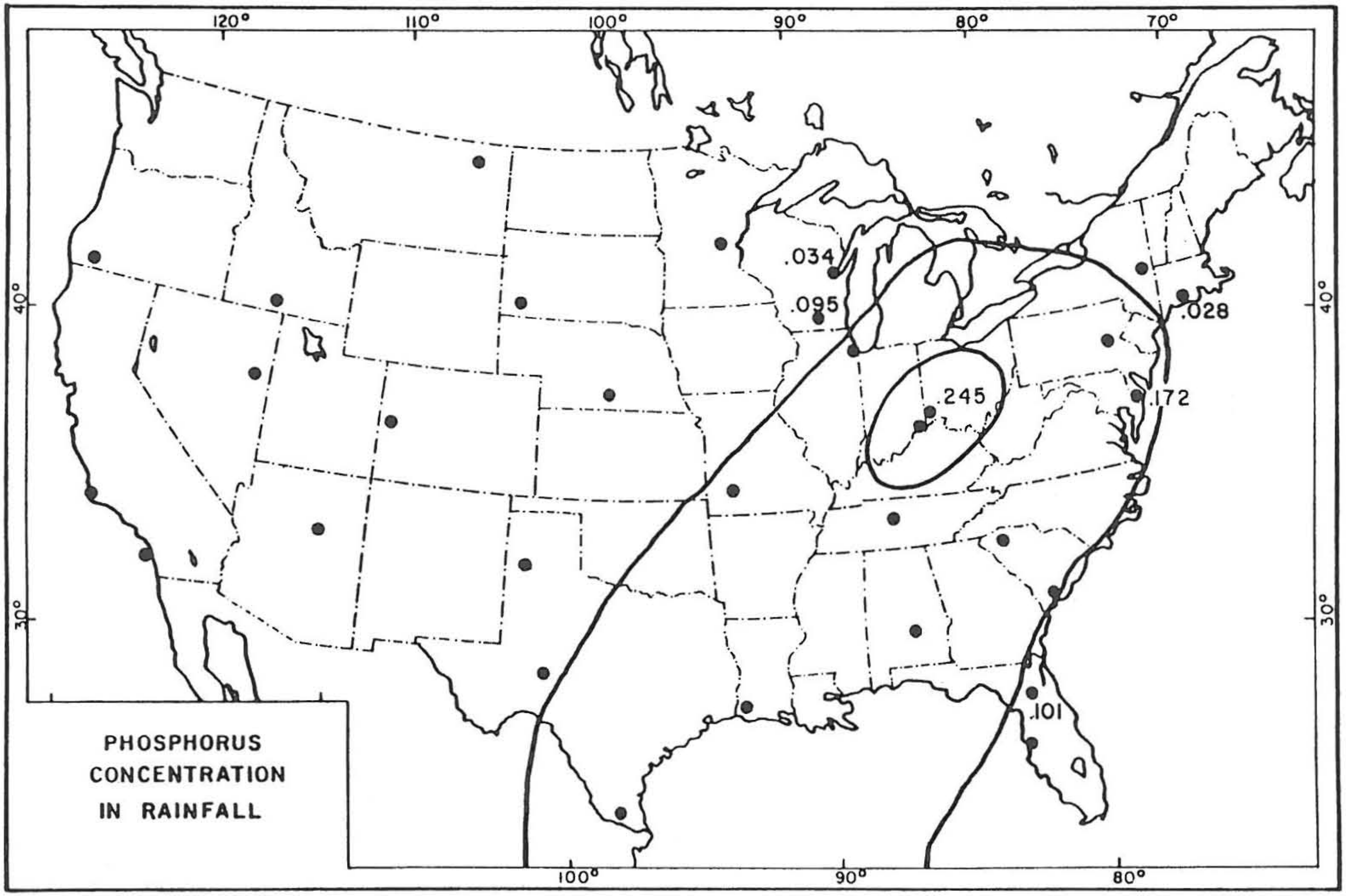

Figure E15. Phosphorus concentration in rainfall (PO_4^{3-}) in ppm (for sources see Table E17).

Table E16. Major chemical substances dissolved in rainfall for 32 U.S. stations in ppm.

Station	H^{+}[b]	Annual Average for 1960–1966[a] Ca^{++}	Na^{+}	Mg^{++}	K^{+}	SO_4^{--}	NH_4^{+} + NO_3^{-}	Cl^{-}	PO_4^{-3}	Total
1 Caribou, Maine	0.09	0.39	0.23	0.18	0.14	3.47	0.38	0.26	0.01	5.15
2 Nantucket, Massachusetts	0.12	0.40	2.66	0.63	0.21	2.99	0.25	5.35	0.02	12.63
3 Albany, New York	0.10	1.97	0.46	0.20	0.45	8.66	0.41	1.08	0.05	13.38
4 Philadelphia, Pennsylvania	0.01	1.15	0.91	0.34	0.29	8.71	0.45	1.26	0.12	13.24
5 Boonsville, Kentucky	0.01	1.28	0.54	1.16	0.24	5.40	0.55	0.63	0.25	10.06
6 Cincinnati, Ohio	0.01	1.81	0.34	0.25	0.16	6.11	0.36	0.85	0.25	10.14
7 Cape Hatteras, North Carolina	0.01	0.40	3.44	0.67	0.25	2.26	0.16	6.07	0.10	13.36
8 Montgomery, Alabama	0.01	0.71	0.45	0.19	0.15	1.75	0.18	0.58	0.13	4.15
9 Tampa, Florida	0.01	1.61	1.01	0.20	0.15	3.34	0.08	1.54	0.10	8.04
10 Greenville, South Carolina	0.05	0.30	0.26	0.12	0.15	1.52	0.23	0.35	0.15	3.13
11 Charleston, South Carolina	0.05	0.44	1.06	0.82	0.22	2.75	0.16	1.43	0.10	7.03
12 Nashville, Tennessee	0.01	1.17	0.72	0.09	0.10	3.65	0.15	0.38	0.17	6.04
13 Midway Airport, Chicago, Illinois	*	6.34	1.88	2.67	0.54	23.9	0.56	4.58	0.10	40.57
14 O'Hare Airport, Chicago, Illinois	*	4.32	0.75	1.81	0.36	12.1	3.39	1.44	0.10	24.27
15 Sault Ste. Marie, Michigan	0.01	1.00	0.34	0.19	0.18	4.20	0.44	0.49	0.04	6.89
16 St. Cloud, Minnesota	*	1.12	0.25	0.34	0.14	3.38	0.37	0.33	0.10	6.03
17 Sterling, Virginia	0.01	0.67	0.34	0.44	0.27	3.40	0.36	0.52	0.15	6.16
18 Springfield, Missouri	0.01	4.51	0.59	0.13	0.40	3.30	0.29	0.78	0.10	10.11
19 Grand Island, Nebraska	*	0.96	0.22	0.14	0.18	2.13	0.25	0.32	0.10	4.30
20 Lake Charles, Louisiana	*	0.56	0.58	0.07	0.12	1.25	0.21	1.03	0.10	3.92
21 Amarillo, Texas	*	2.26	0.44	0.18	0.27	2.89	0.25	0.59	0.10	6.98
22 Brownsville, Texas	*	1.52	1.70	0.62	0.39	2.43	0.12	3.71	0.10	10.59
23 San Angelo, Texas	*	3.72	1.19	0.38	0.21	2.29	0.27	3.67	0.10	11.83
24 Grand Junction, Colorado	*	7.25	0.98	0.61	0.39	7.47	0.23	0.86	0.10	17.90
25 Pocatello, Idaho	*	3.31	0.98	1.00	0.45	3.91	0.21	0.17	0.10	11.13
26 Ely, Nevada	*	6.17	1.85	2.35	0.52	10.00	0.27	1.65	0.10	22.91
27 Neah Bay, Washington	*	0.88	12.97	0.20	0.67	5.00	0.13	25.20	0.10	45.15
28 Glasgow, Montana	*	1.22	2.19	0.11	0.27	5.79	0.12	1.67	0.10	11.47
29 Santa Catalina, California	*	0.48	0.96	0.23	0.14	1.42	0.19	4.98	0.10	8.50
30 Medford, Oregon	*	1.39	0.43	0.28	0.54	1.76	0.08	0.44	0.10	5.02
31 Rapid City, South Dakota	*	6.47	0.52	0.18	0.29	1.06	0.18	0.43	0.10	9.23
32 Winslow, Arizona	*	7.93	2.03	0.62	0.74	4.35	0.20	2.16	0.10	18.13

[a]Lodge et al. (1968).
[b]Likens (1976).
*Less than 0.005 ppm.

C_2 = average nitrogen concentration in rainwater, ppm.

$$F_p = P(nRT)(C_3)\ln(\frac{C_3}{C_1}) \quad Cal/m^2 \cdot yr \quad (10)$$

where,

F_p = chemical potential of phosphorus as PO_4^{3-} $Cal/m^2 \cdot yr$;
P = annual rainfall, m/yr;
n = number of moles of phosphorus as PO_4^{3-} per gram = 1/95;
T = temperature in degrees Kelvin = 300°K;
C_1 = average phosphorus concentration in seawater = 0.07 ppm;
C_3 = average phosphorus concentration in rainwater, ppm.

Table E17. Phosphorus content of rainfall for U.S. locations.

Location	P, $g/m^2 \cdot yr$	Rainfall m/yr	PO_4^{-3}* ppm	Source
Green Bay, Wisconsin	0.008	0.70	0.034	Sridharam 1971
Madison, Wisconsin	0.023	0.75	0.095	Kluesener 1972
Cincinnati, Ohio	0.080	1.00	0.245	Weibel et al. 1966
New Haven, Connecticut	0.010	1.09	0.028	Voight 1960
Delaware	0.056	1.00	0.172	Reimbold and Daiber 1967
Gainesville, Florida	0.045	1.36	0.101	Brezonik et al. 1969
AVERAGE			0.11	

*If all P as PO_4^{-3}.

11. Chemical Potential of Acidity in Rain

To calculate the chemical potential energy of mixing acid substances in rain, equation 11 is used with data in Figs. E6, E9, and E16 (Castellan 1964).

$$F_a = P(nRT)(X_H^+)\ln X_H^+ \quad Cal/m^2 \cdot yr \quad (11)$$

where,

F_a = chemical potential of acid substance, $Cal/m^2 \cdot yr$;
P = annual rainfall, m/yr (Fig. E9);
n = number of moles of water per gram = 1/18 g/mole = 55.6 moles H_2O/l;
R = universal gas constant = 1.99×10^{-3} Cal/°K·mole;
T = average surface temperature in degrees Kelvin, °K (Fig. E6);
X_H^+ = mole fraction of H_2O with H^+/pure H_2O

$$= \frac{55.6 \text{ moles } H_2O/l - \text{moles } H^+/l}{55.6 \text{ moles } H_2O/l} \quad \text{(Fig. E16);}$$

$\ln X_H^+$ = natural log of the mole fraction (when X_H^+ is near 1, $\ln X_H^+ = X_H^+ - 1$).

12. Physical Energy in Tidal Absorption

The average total tidal energy passing shelf can be estimated by equation 12 with tidal range data from Fig. E17.

$$E_t = N \cdot A(\frac{1}{2}\rho g h^2)(2.38 \times 10^{-11}) \quad Cal/yr \quad (12)$$

where,

E_t = tide energy passing the shelf, Cal/yr;

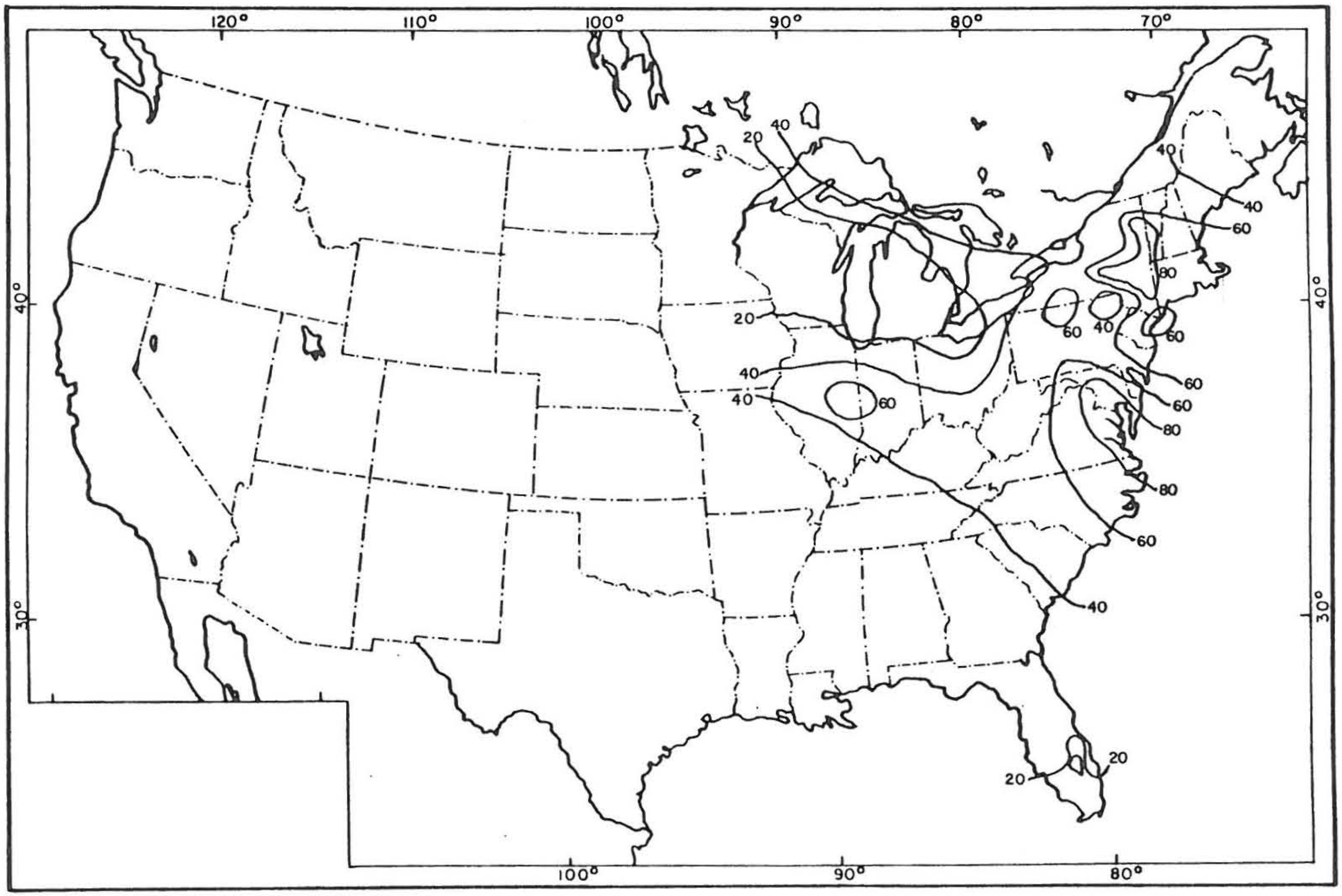

Figure E16. Acid substance in rainfall for 1975-1976 in 10^{-6} moles of H^{+} per liter (unpublished data from Butler and Likens 1968).

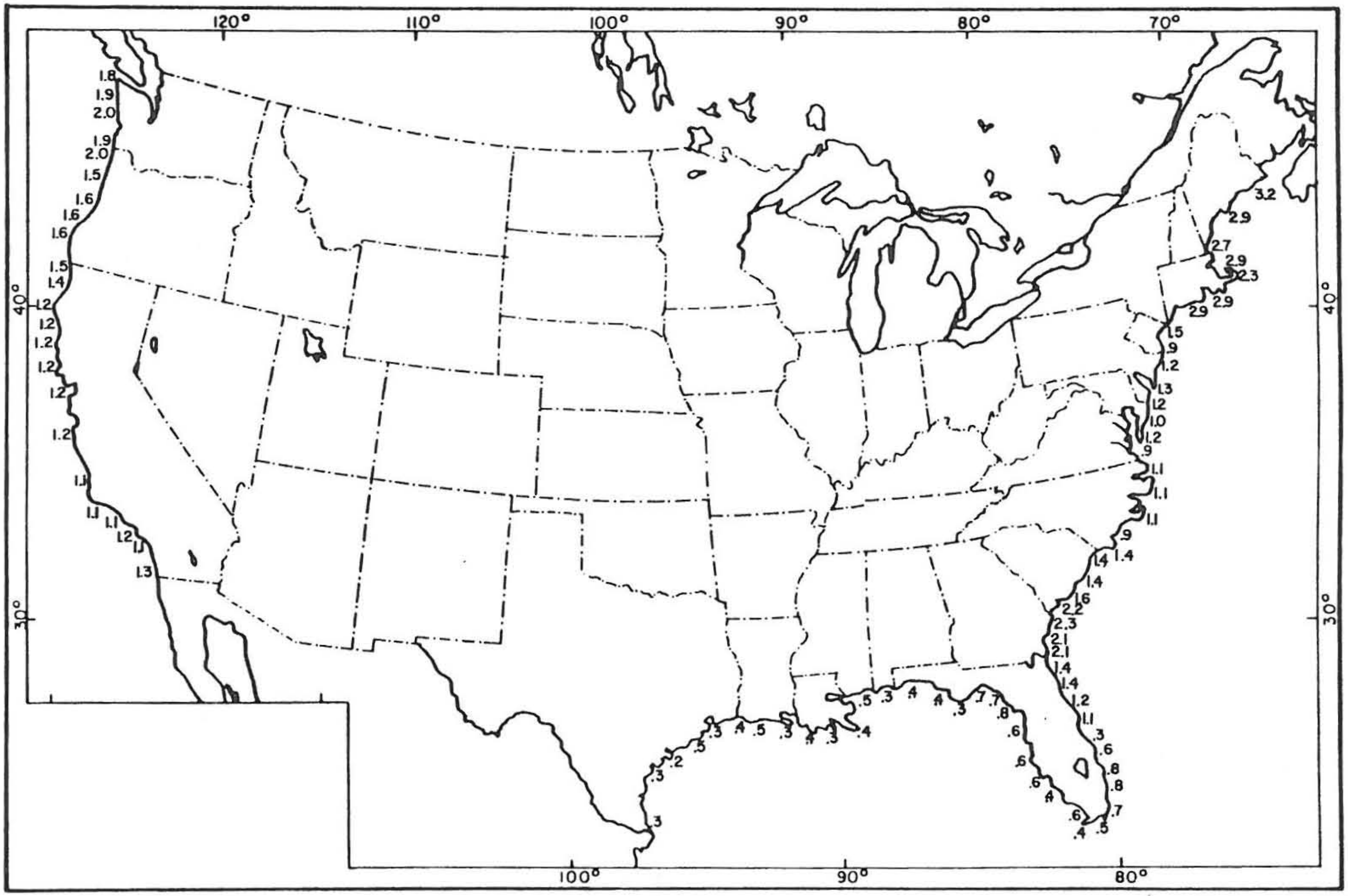

Figure E17. Mean tidal range on the coast of the United States in meters (data from U.S. Coastal and Geodetic Survey 1956).

N = number of tides per year;
A = tide absorbing area, cm^2;
ρ = density of seawater = 1.025 g/cm^3;
g = acceleration of gravity = 980 cm/s^2;
h = mean tidal range as shown in Fig. E17, expressed in cm.

Example for calculating tidal energy absorbed over shelf:

The mean tidal range in the vicinity of Miami Beach (Fig. E17) is about 0.75 m. The number of tides per year is 706. The absorbing area is assumed equal to shelf to 100 m and estuaries, about 75 m^2 = 75 x 10^4 cm^2. Tide absorbed over shelf is taken as 50% of tide energy passing shelf. Thus, tidal absorption in the estuary is estimated as

$$E_t = 0.5\ N \cdot A \cdot \frac{1}{2} \rho g h^2 (2.38 \times 10^{-11})$$

$$= 0.5(706\ \text{tides/yr})(75 \times 10^4\ cm^2)(\tfrac{1}{2})$$

$$(1.025\ g/cm^3)(980\ cm/s^2)(75\ cm^2)$$

$$(2.38 \times 10^{-11}\ \text{Cal/erg})$$

$$= 1.78 \times 10^4\ \text{Cal/yr.}$$

13. and 14. Chemical Free Energy Due to Differences in Salt in Tidal Inflow and Outflow

Estimate the annual tidal inflow (J_1) from data for your site (in m^3/yr) and the average salinity (C_1) of the inflow (in ppm). Estimate the annual outflow (J_2) for your site (in m^3/yr) and the average salinity (C_2) of the outflow (in ppm). Estimate the river discharge (J_3) from Table E18 or more detailed data (in m^3/yr) and the average salinity (C_3) of the river discharge (in ppm) (Table E19). Use equation 13 to calculate the total chemical free energy.

Table E18. Average annual discharge of larger rivers in the United States (Chow 1964).

River	Average Annual Discharge, ft^3/s	Drainage Area, sq mi	Length, mi
Mississippi	620,000	1,243,700	3,892
St. Lawrence	400,000	565,000	2,150
Ohio (T)*	255,000	203,900	1,306
Columbia	235,000	258,200	1,214
Mississippi (T)	91,000	171,600	1,170
Missouri (T)	70,000	529,400	2,714
Tennessee (TT)*	63,700	40,600	900
Mobile	59,000	42,300	758
Red (T)	57,300	91,400	1,300
Arkansas (T)	45,200	160,500	1,450
Snake (T)	44,500	109,000	1,038
Susquehanna	35,800	27,570	444
Alabama (T)	31,600	22,600	720
White (T)	31,000	28,000	690
Willamette (T)	30,700	11,250	270
Wabash (TT)	30,400	33,150	475
Cumberland (TT)	27,800	18,080	720
Illinois (T)	27,400	27,900	420
Tombigbee (T)	27,000	19,500	525
Sacramento	26,000	27,100	382
Apalachicola	25,000	19,500	500
Pend Oreilla (T)	24,600	25,820	490
Colorado	23,000	246,000	1,450
Hudson	21,500	13,370	306
Allegheny (TT)	19,200	11,700	325
Delaware	19,000	12,300	390

*T = first-order tributary; TT = second-order tributary.

Table E19. Dissolved and suspended load in selected rivers in different climatic regions of the United States (Leopold et al. 1964).

River and Location	Elevation, ft	Drainage Area, sq mi	Average Discharge, ft^3/s	Discharge per Drainage Area $ft^3/s \cdot sq\ mi$	Years of Record in Sample	Average Suspended Load 10^6 ton/yr	Average Dissolved Load 10^6 ton/yr	Suspended and Dissolved Load 10^6 ton/yr	Average Load per Area tons/sq mi·yr	Dissolved Load as Percent of Total Load %
Little Colorado, Woodruf, Arizona	5,129	8,100	63.3	0.0078	6	1.6	0.02	1.62	193	1.2
Canadian, near Amarillo, Texas	2,989	19,445	621	0.032	1	6.41	0.124	6.53	336	1.9
Colorado, near San Saba, Texas	1,096	30,600	1,449	0.047	5	3.02	0.208	3.23	105	6.4
Bighorn, Kane, Wyoming	3,609	15,900	2,391	0.150	1	1.60	0.217	1.82	114	12
Green, Green River, Utah	4,040	40,600	6,737	0.166	20-26	19	2.5	21.5	530	12
Colorado, near Cisco, Utah	4,090	24,100	8,457	0.351	20-25	15	4.4	19.4	808	23
Iowa, Iowa City, Iowa	627	3,271	1,517	0.464	3	1.184	0.485	1.67	510	29
Mississippi, Red River Landing, Louisiana		1,144,500	569,500	0.497	3	284	101.8	385.8	337	26
Sacramento, Sacramento, California	0	27,000	25,000	0.926	3	2.85	2.29	5.14	190	44
Flint, near Montezuma, Georgia	256	2,900	3,528	1.22	1	0.400	0.132	0.53	183	25
Juniata, near New Port, Pennsylvania	364	3,354	4,329	1.29	7	0.322	0.566	0.89	265	64
Delaware, Trenton, New Jersey	8	6,780	11,730	1.73	4-9	1.003	0.830	1.83	270	45

$$F_t = (nRT)J_1C_1\ln\left(\frac{C_1}{C_2}\right) + J_3C_3\ln\left(\frac{C_3}{C_2}\right); \text{ Cal/yr} \quad (13)$$

where,

- F_t = total chemical free energy, Cal/yr;
- n = number of moles per gram of salt = 1/35;
- R = universal gas constant = 1.99×10^{-3} Cal/°K·mole;
- T = temperature in degrees Kelvin = 300°K;
- J_1 = annual tidal inflow, m^3/yr;
- J_2 = annual tidal outflow, m^3/yr;
- J_3 = annual river discharge, m^3/yr;
- C_1 = average salinity of total inflow, ppm;
- C_2 = average salinity of total outflow, ppm;
- C_3 = average salinity of river discharge, ppm.

15. Energy in Waves Breaking

The wave energy transmitting toward shoreline is the product of energy per unit area of wave front (Ippen 1966) and the velocity of the waves. Read mean elevation of waves striking shore in map in Fig. E18 or Table E20, and using equation 14 to calculate the wave energy.

$$E_w = \frac{1}{8}\rho g h^2 \cdot C \cdot 2.38 \times 10^{-11} \quad \text{Cal/m·yr} \ (14)$$

where,

- E_w = wave energy transmitting toward shoreline, Cal/m·yr;
- ρ = density of seawater = 1.025 g/cm^3;
- g = acceleration of gravity = 980 cm/s^2;
- h = mean wave height as shown in Fig. E18 or Table E20, cm;
- C = wave celerity = $(gd)^{1/2}$ = $(9.8 \text{ m/s·d})^{1/2}$, m/s;
- d = mean water depth at wave gauge, m.

Example for calculating wave energy coming ashore:

The mean wave height in the vicinity of Daytona Beach from Fig. E18 is about h = 0.66 m. The energy per unit of wave front is

$$\begin{aligned}\Delta E_w &= \frac{1}{8}\rho g h^2 \\ &= \frac{1}{8}(1.025 \text{ g/cm}^3)(980 \text{ cm/s}^2)(66 \text{ cm})^2 \\ &\quad (100^2 \text{ cm}^2/\text{m}^2)(2.38 \times 10^{-11} \text{ Cal/erg}) \\ &= 0.130 \text{ Cal/m}^2.\end{aligned}$$

Assuming the shoaling depth (d) is 10 m, the wave celerity is

$$\begin{aligned}C &= (gd)^{1/2} \\ &= ((9.8 \text{ m/s}^2)(10 \text{ m}))^{1/2} = 9.90 \text{ m/s} \\ &= (9.90 \text{ m/s})(3.15 \times 10^7 \text{ s/yr}) \\ &= 3.12 \times 10^8 \text{ m/yr}.\end{aligned}$$

The total wave energy transmitting toward shoreline is estimated per meter of wave front as

$$\begin{aligned}E_w &= \Delta E_w \cdot C \\ &= (0.130 \text{ Cal/m}^2)(3.12 \times 10^8 \text{ m/yr}) \\ &= 4.06 \times 10^7 \text{ Cal/m·yr}.\end{aligned}$$

The relationship of wave power per unit length of exposed coast versus mean water depth for different mean wave height is tabulated in Table E21.

Waves striking beaches are assumed to be absorbed into turbulence, beach work, and long

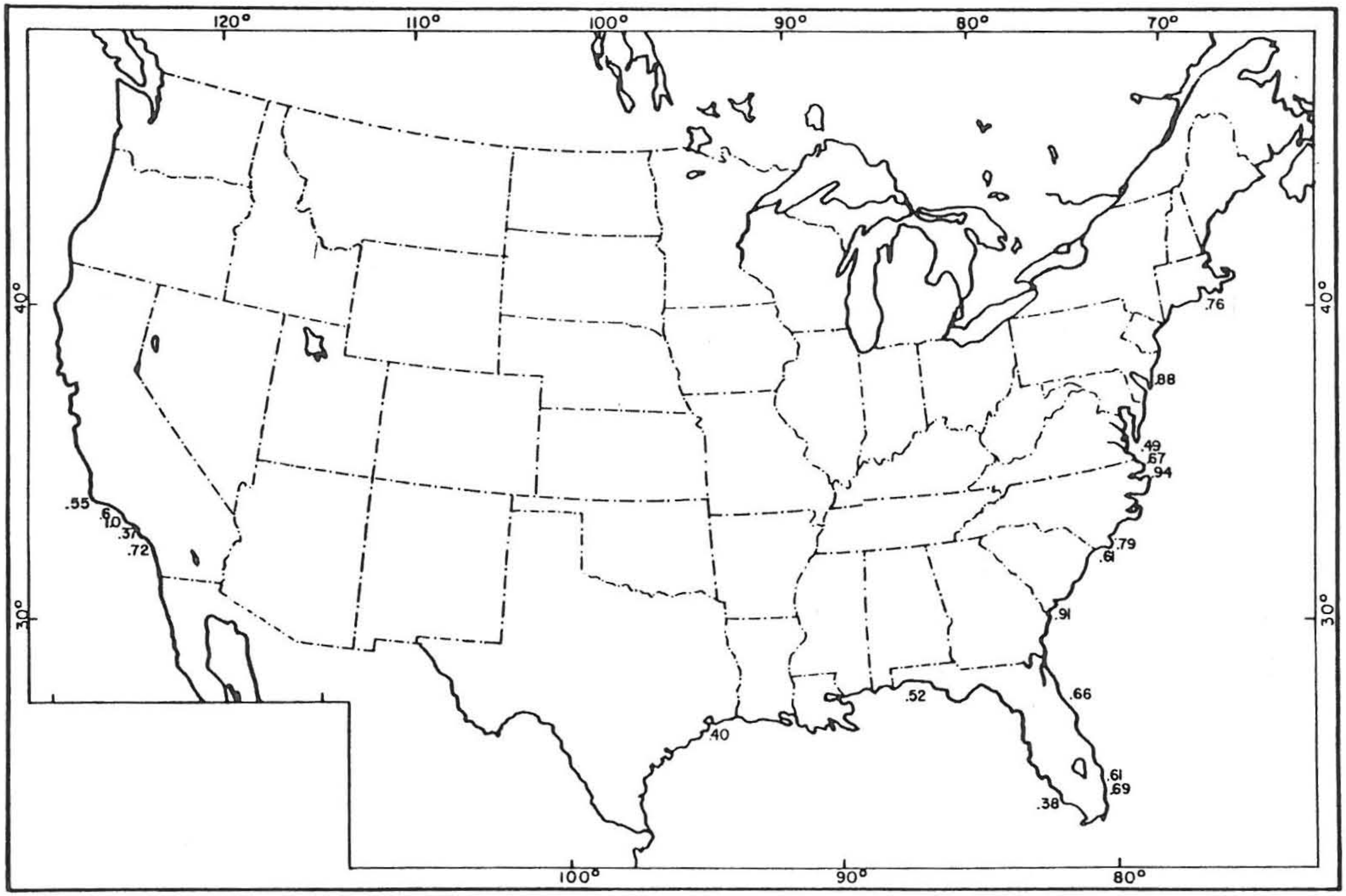

Figure E18. Mean wave height on the coast of the United States in meters (data from Coastal Engineering Research Center 1977).

shore currents. Multiply energy per unit wave fron E_W by length of perpendicular shore absorbing waves to obtain total energy received on shore or into estuaries. Waves striking rocky coasts are partly reflected.

Table E20. Wave heights and periods for selected locations along U.S. coast (Thompson 1977).

Location	Average Wave Height, m	Average Period, s
Buzzards Bay, Massachusetts	0.76	7.39
Atlantic City, New Jersey	0.88	8.43
Chesapeake Bay Bridge, Virginia	0.49	3.70
Virginia Beach, Virginia	0.67	8.32
Nags Head, North Carolina	0.94	8.59
Wrightsville Beach, North Carolina	0.79	7.79
Holden Beach, South Carolina	0.61	7.38
Savannah Light Tower, Georgia	0.91	6.64
Daytona Beach, Florida	0.66	6.11
Palm Beach, Florida	0.61	6.42
Lake Worth, Florida	0.67	6.21
Naples, Florida	0.38	4.55
Destin, Florida	0.58	5.79
Galveston, Texas	0.40	5.71
Point Conception, California	0.72	
Port Hueneme, California	0.37	10.04
Point Miyu, California	1.00	11.01
Venice, California	0.64	10.45
Huntington Beach, California	0.55	12.84

16. Energy in Sand Supply

Energy in sand supply has two components, chemical free energy in sand flux and elevated potential energy in sedimentation.

Table E21. Wave power per unit length of exposed coast.

Mean Wave Height (H), m	Mean Water Depth (d), m	Wave Power (P), 10^7 Cal/m·yr
0.40	1	0.47
	5	1.05
	10	1.49
	15	1.83
	20	2.11
0.50	1	0.74
	5	1.65
	10	2.33
	15	2.85
	20	3.29
0.60	1	1.06
	5	2.37
	10	3.35
	15	4.11
	20	4.74
0.70	1	1.44
	5	3.23
	10	4.57
	15	5.59
	20	6.46
0.80	1	1.89
	5	4.22
	10	5.96
	15	7.30
	20	8.43
0.90	1	2.39
	5	5.34
	10	7.55
	15	9.24
	20	10.67
1.00	1	2.95
	5	6.59
	10	9.32
	15	11.41
	20	13.18

Organic chemical potential in sand flux. Estimate the average organic matter content of sediments from Table E22 and the average littoral drift from Table E23. Use equation 15 to calculate the organic chemical free energy in sand flux.

$$F_s = O \cdot Q \cdot \rho \cdot K \cdot 10^6 \qquad \text{Cal/m} \cdot \text{yr} \quad (15)$$

where,

- F_s = chemical potential in sand flux, Cal/yr;
- O = sediments organic matters content, %;
- Q = average littoral drift along coastline, m^3/yr (Table E23);
- ρ = density of sand = 1.47 g/cm^3 (Leibowitz 1979);
- K = free energy of organic matter = 5.4 Cal/g (Regan 1977).

To estimate contribution of drift to an area subtract estimated outflow drift from inflow drift and divide by area involved.

Elevated potential energy in sedimentation. Estimate the average rate of sediment accumulation from Table E24 and use equation 16 to calculate the flux of potential energy against gravity in sediment.

$$G_s = A \cdot \rho g h \cdot d(2.38 \times 10^{-11}) \qquad \text{Cal/yr} \quad (16)$$

where,

- G_s = elevated potential energy from sedimentation, Cal/yr;
- A = coastal area affected by sedimentation, m^2;
- ρ = bulk density of sand = 1.47 g/cm^3;
- g = acceleration of gravity = 980 cm/s^2;
- h = average sedimentation rate, cm/yr (Table E24);
- d = distance to the center of gravity = h/2, cm.

17. Physical Energy in Stream Flow

Find drop in elevation within area drained and average runoff for the area from Fig. E19. Use equation 17 to calculate the physical energy in stream flow.

$$G_q = q \cdot \rho g h(2.38 \times 10^{-11}) \cdot 10^4 \qquad \text{Cal/m}^2 \cdot \text{yr} \quad (17)$$

where,

- G_q = physical energy in stream flow, Cal/m^2·yr;
- q = average runoff for the area, cm/yr (Fig. E19);
- ρ = density of water = 1 g/cm^3;
- g = acceleration of gravity = 980 cm/s^2;
- h = drop in elevation within area drained, cm.

Example for calculating physical energy in stream flow.

In Florida, the average surface runoff is about 10 in./yr; assuming the average drop in elevation is 10 m, then the potential energy of water flow against gravity is estimated as

$$G_q = (10 \text{ in./yr})(2.54 \text{ cm/in.})(1 \text{ g/cm}^3)(980 \text{ cm/s}^2)(10 \text{ m})(100 \text{ cm/m})(100^2 \text{ cm}^2/\text{m}^2)(2.38 \times 10^{-11} \text{ Cal/erg})$$
$$= 5.9 \text{ Cal/m}^2 \cdot \text{yr}.$$

Table E22. Sediment data to use to estimate Gibbs free energy (Gebelen 1977).

Type	Median Grain Size*	Weight Percentage Less than 62 micron	Percent Calcium Carbonate	Percent Organic	Percent Insoluble
Beach	2 mm (0.025 mm-25 mm)	4 (0-40)	92 (90-99)	1 (0.5-7)	7 (3-9)
Marine lagoon including tidal flats	3 microns (<1 micron-10 mm)	80 (74-91)	75 (64-91)	6 (4-9)	19 (14-28)
Inland lagoon	3 microns (<1 micron-7 mm)	83 (20-95)	63 (20-88)	30 (5-70)	7 (1-10)

*Range of values in parentheses.

Table E23. Annual littoral drift along coast (Komar 1976).

Location	Drift Rate, m^3/yr	Predominant Direction	Years of Record
Atlantic Coast			
Suffolk County, New York	255,000	W	1946-1955
Sandy Hook, New Jersey	377,000	N	1885-1933
Sandy Hook, New Jersey	334,000	N	1933-1951
Asbury Park, New Jersey	153,000	N	1922-1925
Shark River, New Jersey	255,000	N	1947-1953
Manasquan, New Jersey	275,000	N	1930-1931
Barnegat Inlet, New Jersey	191,000	S	1939-1941
Absecon Inlet, New Jersey	306,000	S	1935-1946
Ocean City, New Jersey	306,000	S	1935-1946
Cold Springs Inlet, New Jersey	153,000	S	
Ocean City, Maryland	115,000	S	1934-1936
Atlantic Beach, North Carolina	22,600	E	1850-1908
Hillsboro Inlet, Florida	57,000	S	
Palm Beach, Florida	115,000 to 172,000	S	1925-1930
Gulf of Mexico			
Pinellas County, Florida	38,000	S	1922-1950
Perdido Pass, Alabama	153,000	W	1934-1953
Galveston, Texas	334,700	E	1919-1934
Pacific Coast			
Santa Barbara, California	214,000	E	1932-1951
Oxnard Plain Shore, California	756,000	S	1938-1948
Port Hueneme, California	382,000	S	1938-1948
Santa Monica, California	207,000	S	1936-1940
El Segundo, California	124,000	S	1936-1940
Redondo Beach, California	23,000	S	
Anaheim Bay, California	115,000	E	1937-1948
Camp Pendleton, California	76,000	S	1950-1952
Great Lakes			
Milwaukee County, Wisconsin	6,000	S	1894-1912
Racine County, Wisconsin	31,000	S	1912-1949
Kenosha, Wisconsin	11,000	S	
State Line to Waukegan, Illinois	69,000	S	
Waukegan to Evanston, Illinois	44,000	S	
South of Evanston, Illinois	31,000	S	
Outside the United States			
Monrovia, Liberia	383,000	N	1946-1954
Port Said, Egypt	696,000	E	
Port Elizabeth, South Africa	459,000	N	
Duban, South Africa	293,000	N	1897-1904
Madras, India	566,000	N	1886-1949
Mucuripe, Brazil	327,000	N	1946-1950

18. Energy in Dissolved Substances in Streams

Obtain stream inflow volume (J_1) and total dissolved solids concentration (C_1) from local data or Table E19. Obtain stream outflow volume (J_2), total dissolved solids concentration (C_2), and stream temperature from local data. Then, the free energy of dissolved substances in stream is estimated by the following equation.

Table E24. Approximate rates of sediment accumulation in some marine and estuarine systems (Oviatt and Nixon 1975).

System	Accumulation Rates, mm/yr	Source
Open ocean	0.01	Sverdrup et al. 1942
San Francisco Bay, California	0.1-1.3	Graham 1974
Narragansett Bay, Rhode Island	0.3-0.4	Farrington 1971
Delaware Bay, Delaware	1.5	Ovstdam and Jordan 1972
James River Estuary, Virginia	1.5-3.0	Nicholas 1972
Temperate estuaries	2-4	Ruseak 1967
Salt Marsh, S. Potens Zone, Connecticut	2.0-6.5	Harrison and Bloom 1974
Mobile Bay, Alabama	5-6	Ryan and Goodell 1972
Upper Chesapeake Bay, Maryland	5-8	Schvbel 1971
Port Valdez, Prince William Sound, Alaska	17	Sharma and Burbank 1973

$$F_d = (nRT)(J_1C_1\ln(\frac{C_1}{C_0}) - J_2C_2\ln(\frac{C_2}{C_0}))\ \text{Cal/yr} \quad (18)$$

where,

F_d = free energy of dissolved substance in stream, Cal/yr;

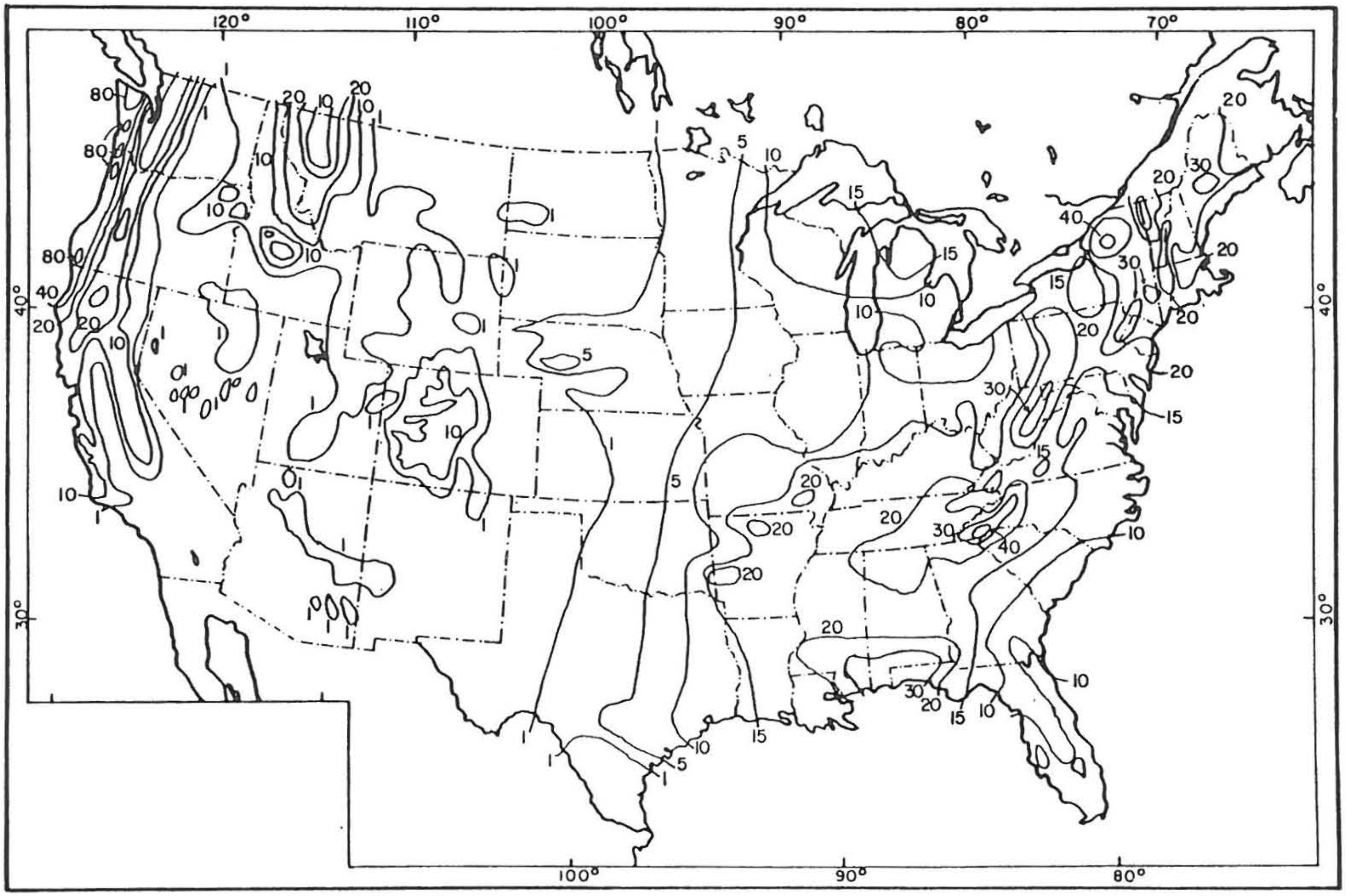

Figure E19. Average runoff for the United States in inches (from Chow 1964).

n = number of moles of dissolved substance per gram = 1/35;
R = universal gas constant = 1.99×10^{-3} Cal/°K·mole;
T = temperature in degrees Kelvin = 300°K;
J_1 = annual stream inflow, m^3/yr;
J_2 = annual stream outflow, m^3/yr;
C_0 = average total dissolved solids concentration in seawater = 35,000 ppm;
C_1 = total dissolved solids concentration of stream inflow, ppm;
C_2 = total dissolved solids concentration of stream outflow, ppm.

19. Chemical Potential Energy in Sediments in Streams

Obtain average discharge and total sediment load of stream flow from your local area or Table E19. With the help of Table E22, estimate the organic matter content of sediments. Use equation 19 to calculate the organic chemical potential energy in sediments.

$$F_o = O \cdot J \cdot Q \cdot K \qquad \text{Cal/yr (19)}$$

where,

F_o = chemical potential energy in sediments, Cal/yr;
O = organic matter content of sediments, %;
J = average annual stream flow, m^3/yr;
Q = total sediment load in stream flow, g/m^3;
K = free energy of organic matter = 5.4 Cal/g.

20. Physical Potential Energy in Materials in Stream Flow

Obtain the stream flow from your local area. Estimate the density or weight of particulate and dissolved material flow borne by water (see Table E19). Find the change in elevation of your drainage area. Use equation 20 to calculate the potential energy of materials in stream flow against gravity.

$$G_m = J \cdot \rho g h (2.38 \times 10^{-11}) \qquad \text{Cal/yr (20)}$$

where,

G_m = physical potential energy in materials in stream flow, Cal/yr;
J = average annual stream flow, m^3/yr;
ρ = density of particulate and dissolved materials, g/m^3;
g = acceleration of gravity = 980 cm/s^2;
h = drop in elevation of drainage area, cm.

21. Energy Inflow in Catastrophes

Energy inflow in catastrophes for earthquake, tornado, hurricane, and flood are calculated as follows.

Earthquake energy. Using the effective peak acceleration map in Fig. E20 obtain the peak acceleration in g's for the site of interest (note the map is in percent of 1 g). To find probabilistic frequency of occurrence per 100 years, locate area of interest by seismic zone from Fig. E21. Read seismic zone number and use it to look up frequency per 100 years on Table E25. Use equation 21 to calculate the average energy per unit area.

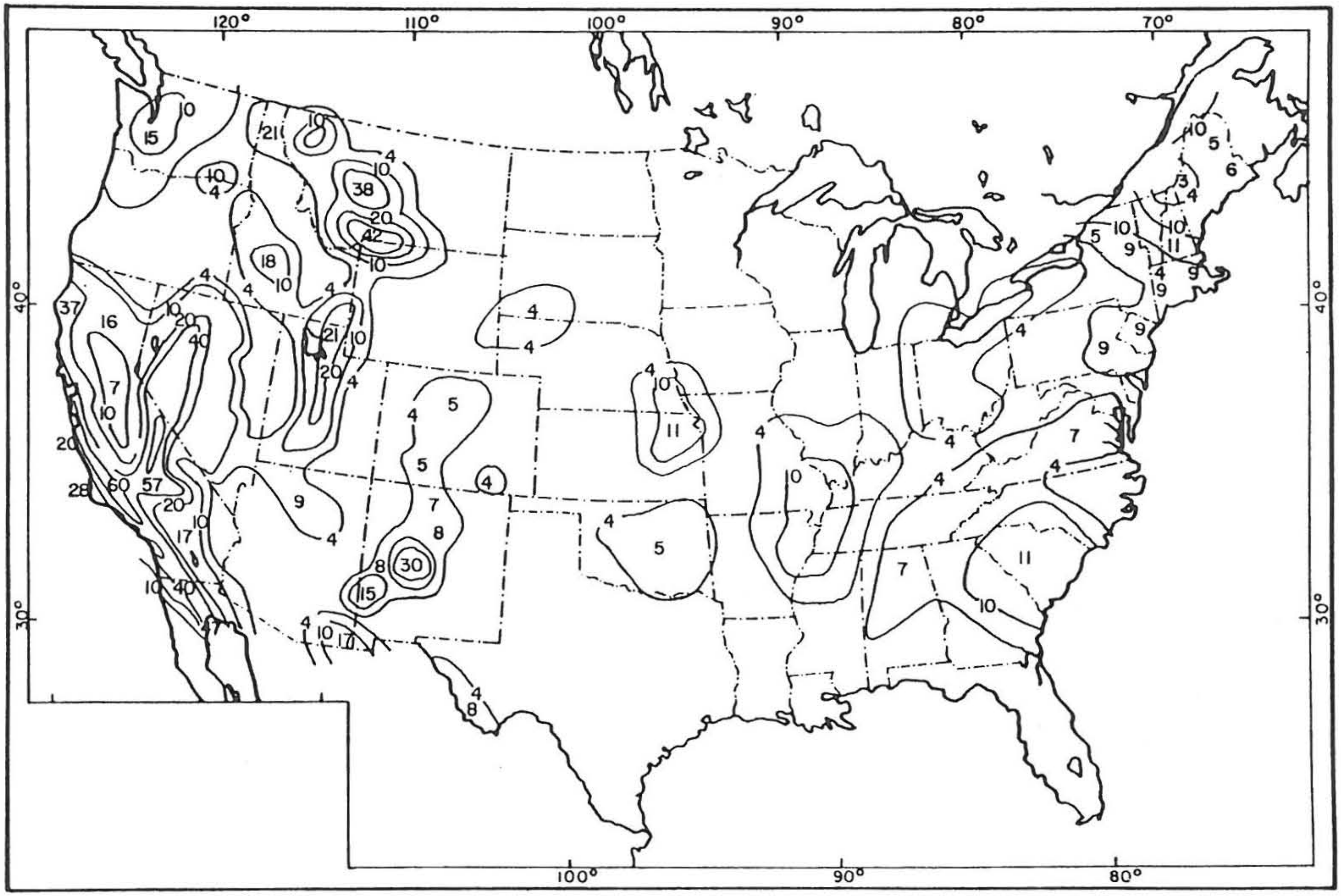

Figure E20. Effective peak acceleration map of the United States. Numbers are in percent of one g acceleration (from Algermissen and Perkins 1976).

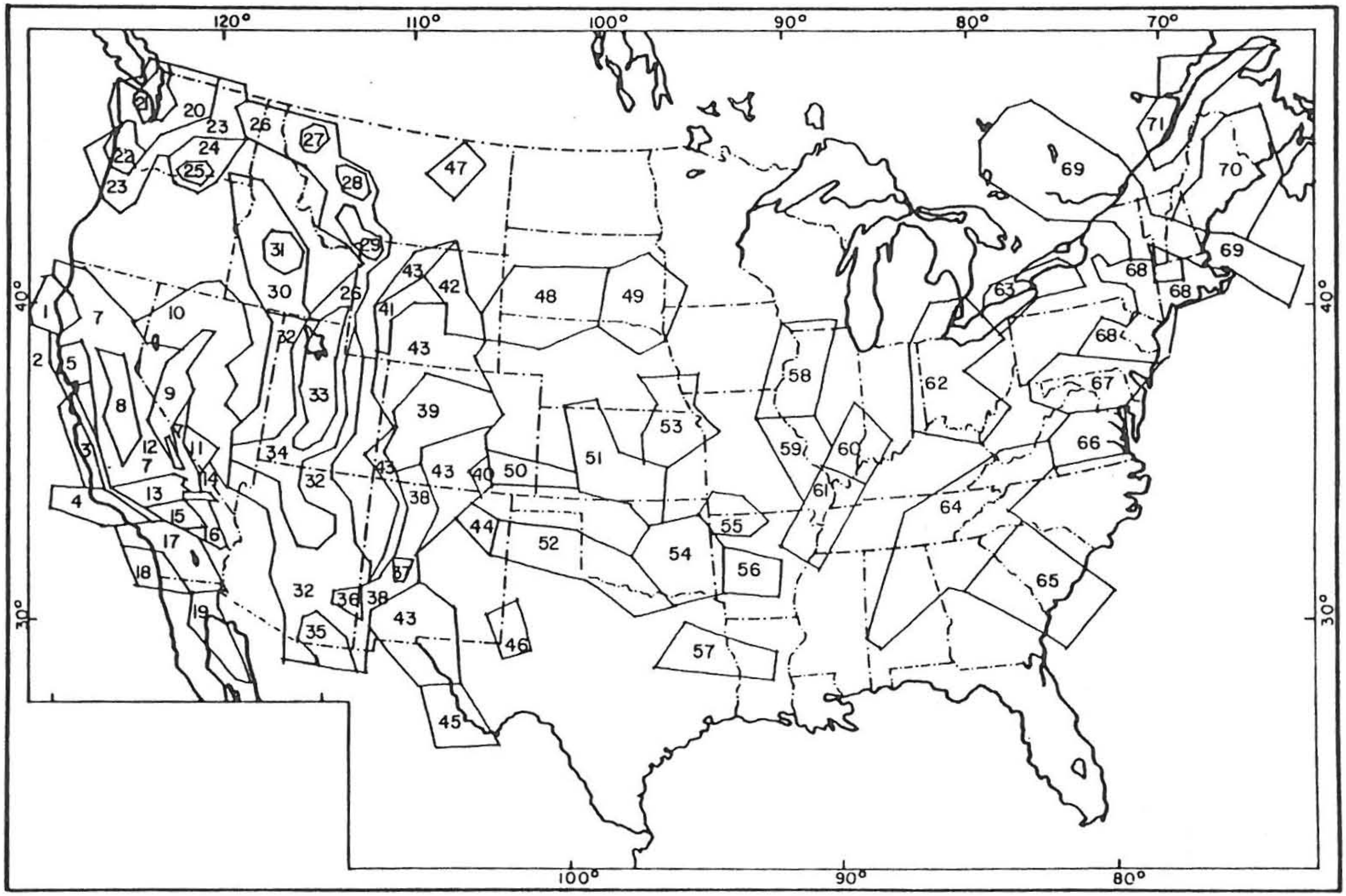

Figure E21. Seismic zone map of the United States. See Table E21 for frequency of occurrence by zone (Algermissen and Perkins 1976).

Table E25. Seismic parameters for source zones (after Algermissen and Perkins 1976).

Zone* No.	Number of Modified Mercalli Maximum Intensity V's Number/100 yr	b_I	Maximum I_0	Maximum M_c
1	245.2	-0.50	X	7.3
2	110.0	-0.40†	XII	8.5
3	27.2	-0.45	XI	7.9
4	75.1	-0.45	XI	7.9
5	14.9	-0.50	X	7.3
6	44.4	-0.45	XI	7.9
7	299.6	-0.53	VIII	6.1
8	7.3	-0.49	VI	4.9
9	208.0	-0.40	XI	7.9
10	125.0	-0.51	VIII	6.1
11	80.1	-0.53	VIII	6.1
12	43.0	-0.43†	XII	8.5
13	99.4	-0.45	XI	7.9
14	34.9	-0.45	XI	7.9
15	0.0	-0.53	VIII	6.1
16	33.9	-0.50	X	7.3
17	223.0	-0.45	XI	7.9
18	2.8	-0.50	X	7.3
19	613.6	-0.52	X	7.3
20	14.8	-0.29	VIII	7.1
21	79.8	-0.59	VII	5.5
22	80.1	-0.76	VI	4.9
23	12.7	NA	V	4.3
24	6.0	do	V	4.3
25	8.5	-0.59	VII	5.5
26	137.1	-0.72	VI	4.9
27	99.9	-0.67	VII	5.5
28	35.3	-0.32	IX	6.7
29	90.4	-0.36	X	7.3
30	10.5	-0.26	VII	5.5
31	84.6	-0.63	VII	5.5
32	17.0	-0.56	VI	4.9
33	126.8	-0.56	IX	6.7
34	71.0	-0.56	VII	5.5
35	23.0	-0.56	VIII	6.1
36	15.3	-0.54	VII	5.5
37	15.6	-0.31	VIII	6.1
38	31.1	-0.54	VII	5.5
39	21.5	-0.54	VII	5.5
40	2.7	-0.40	VI	4.9
41	27.6	NA	V	4.9
42	11.1	-0.40	VI	4.9
43	23.0	NA	V	4.3
44	13.8	do	V	4.3
45	6.7	-0.31	VIII	6.1
46	2.7	-0.40	VI	4.9
47	2.7	-0.40	VI	4.9
48	14.7	-0.54	VII	5.5
49	10.3	NA	V	4.3
50	4.6	do	V	4.3
51	7.4	-0.53	VI	4.9
52	13.0	-0.40	VI	4.9
53	9.3	-0.24	VIII	6.1
54	21.2	-0.55	VII	5.5
55	1.7	NA	V	4.3
56	5.7	-0.53	VI	4.9
57	7.8	-0.55	VII	5.5
58	0.6	-0.50	VII	5.5
59	16.0	-0.50	VIII	6.1
60	16.0	-0.50	VIII	6.1
61	84.5	-0.50	X	7.3
62	22.0	-0.50	VIII	6.1
63	22.1	-0.64	VIII	6.1
64	54.4	-0.59	VIII	6.1
65	19.9	-0.33	X	7.3
66	13.0	-0.59	VIII	6.1
67	7.8	-0.59	VII	5.5
68	69.1	-0.67	VIII	6.1
69	117.6	-0.59	IX	6.7
70	33.5	-0.65	VIII	6.1
71	21.7	-0.49	X	7.3

*The zones are shown in Fig. E20.
†up to XI then flat.

$$E_e = K_e \cdot a^2 \cdot f \qquad \text{Cal/m}^2\cdot\text{yr} \quad (21)$$

where,

E_e = average earthquake energy, Cal/m^2·yr;
K_e = a constant derived from the case study of Guatemala earthquake of February 4, 1976 = 4168 (Alexander 1978);
a = percent of one g acceleration;
f = expected frequency per 100 yr.

Example for calculating catastrophic energy in earthquake.

The peak acceleration in South Carolina from Fig. E20 is 11%, or 0.11; read the seismic zone number at the same area from Fig. E21 (which is 65) and use it to look up frequency per 100 years on Table E25, 19.9/100 yr. The earthquake energy is estimated as

$$\begin{aligned} E_e &= K_e \cdot a^2 \cdot f \\ &= 4168 \cdot 0.11^2 \cdot 19.9/100\ \text{yr} \\ &= 10.04\ \text{Cal/m}^2\cdot\text{yr.} \end{aligned}$$

Tornado energy. Obtain the average number of tornadoes per year from Fig. E22. Use equation 22 to compute the average tornado energy.

$$E_t = f \cdot e_t \qquad \text{Cal/m}^2\cdot\text{yr} \quad (22)$$

where,

E_t = average tornado energy for study area, Cal/m^2·yr;
f = expected frequency = number of tornadoes/2.6 x 10^{10} m^2·yr (from Fig. E22; Abbey 1977);
e_t = average energy per tornado per unit area;
A_t = average energy per tornado = 3.7 x 10^7 Cal (Sellers 1965);
A_d = average damage path area = 7.5 x 10^6 m^2 (Thom 1963);

$$\begin{aligned} e_t &= \frac{A_t}{A_d} \\ &= \frac{3.7 \times 10^7\ \text{Cal}}{7.5 \times 10^6\ \text{m}^2} \\ &= 4.9\ \text{Cal/m}^2. \end{aligned}$$

Hurricane energy. Read the probability that a hurricane will occur for the site from Fig. E23. Use equation 23 to calculate the annual energy released from the hurricane.

$$E_h = e_h \cdot P \qquad \text{Cal/m}^2\cdot\text{yr} \quad (23)$$

where,

E_h = average hurricane energy, Cal/m^2·yr;
e_h = average energy released per hurricane, Cal/m^2 = 5 x 105 Cal/m^2 (see calculation in the following);
P = probability that a hurricane will occur (Fig. E23).

Hughes (1952) and Miller (1958) estimated that the hurricane energy varied from 2 to 6 x 10^{26} ergs/day = 4.78 to 14.34 x 10^{15} Cal/day, or an average of 9.6 x 10^{15} Cal/day. Hurricane size is considered as 100 miles in diameter = 1.6 x 10^5 m (Dunn and Miller 1964). Thus the hurricane area is

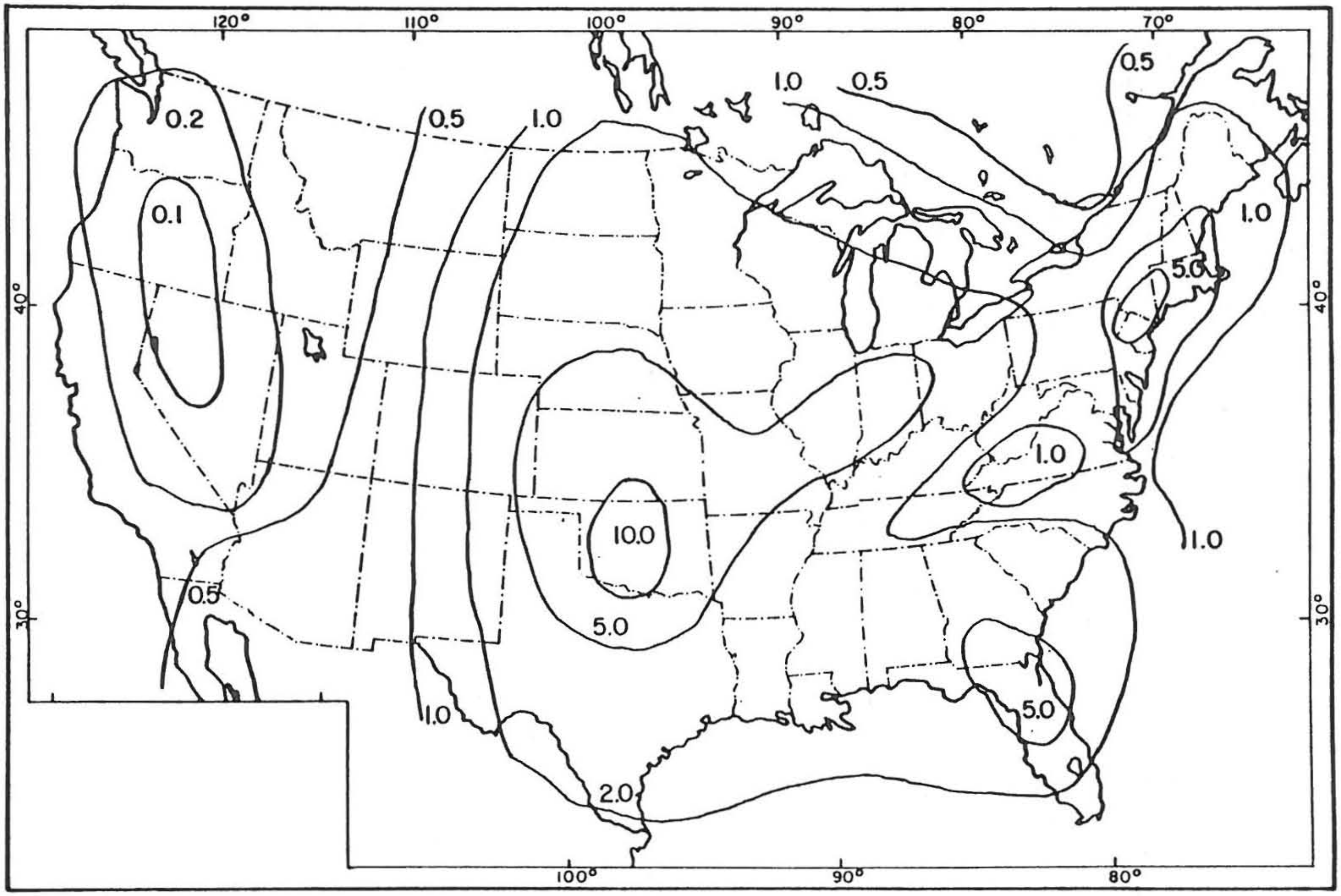

Figure E22. Average number of tornadoes per year per 2.6 x 10^{10} meters^2 (Abbey 1977).

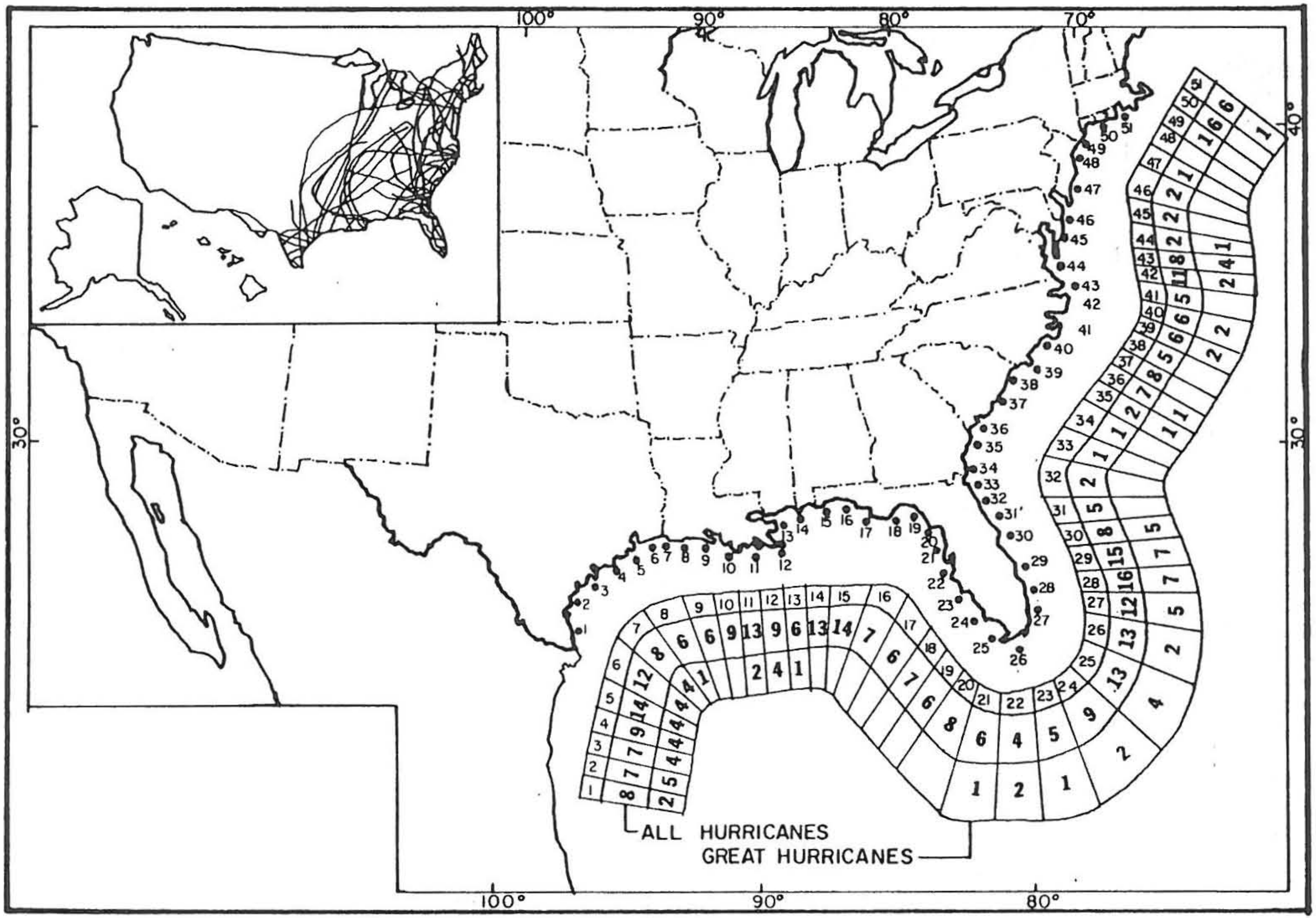

Figure E23. Probability (percentage) that a hurricane (winds exceeding 73 mph) or great hurricane (winds in excess of 125 mph) will occur in any one year in a 50-mile segment of coastline (Simpson and Lawrence 1971).

$$A = \pi r^2$$
$$= 3.14\left(\frac{1.6 \times 10^5\ m}{2}\right)^2$$
$$= 2 \times 10^{10}\ m^2.$$

Hurricane energy/m^2 equals:

$$\frac{9.6 \times 10^{15}\ Cal/day}{2 \times 10^{10}\ m^2}$$

$$= 4.8 \times 10^5\ Cal/m^2 \cdot day.$$

Using an average forward velocity of 100 miles/day for average 100-mile-diameter hurricanes yields approximately 5×10^5 Cal/m^2 per hurricane = e_h.

Flood energy. Flood energy is calculated from the gravitational potential energy of runoff, assuming 1% of the rainfall is involved in flood events. The elevation for the study site is acquired from Fig. E11 and the mean annual rainfall from Fig. E9. The potential flood energy is calculated from equation 24.

$$E_f = P \cdot p \cdot \rho g h (2.38 \times 10^{-5}) \quad Cal/m^2 \cdot yr \quad (24)$$

where,

E_f = average flood energy, Cal/$m^2 \cdot$yr;
P = annual rainfall, cm/yr (Fig. E9);
p = percentage of rainfall involved in flood events, 1% is assumed;
ρ = density of water = 1 g/cm^3;
g = acceleration of gravity = 980 cm/s^2;
h = average height of land, m (Fig. E11).

Figure E24 shows the areas of seasonal flooding in the United States.

22. Energy in Species Inflow

Using Table E26, estimate the approximate quantity of DNA per species propagule. The value of Calories of DNA per speices propagule may be estimated by assuming 1 g DNA = 5 Cal as shown in Table E26, column 3.

Table E26. Approximate quantity of DNA per species propagule (Canoy 1972).

Category (1)	mg DNA/propagule[a] (2)	Cal/propagule[b] (3)
Algae	6.5×10^{-7}	3.25×10^{-9}
Microscopic invertebrates	6.5×10^{-4}	3.25×10^{-6}
Vascular plant seeds	5×10^{-5}	2.50×10^{-7}
Insects	6.5×10^{-2}	3.25×10^{-4}
Vertebrates	100	0.50

[a]Values are calculated from estimated average propagule size and DNA content of 50, 5 or 0.5 mg DNA/g dry weight for microorganisms, consumers, and plants, respectively.
[b]Values of Calories are estimated by assuming 1 g DNA = 5 Cal.

23. Human Exchange

For systems having a component of human activity, estimate actual energy of human service at 2500 Cal/person·day. For systems that have a flux of fuels, estimate volumes of fuel flow, and using Table E27, convert to Calories. For systems that have a flux of goods, estimate weights of various basic commodities listed in Table E28 and convert to Calories.

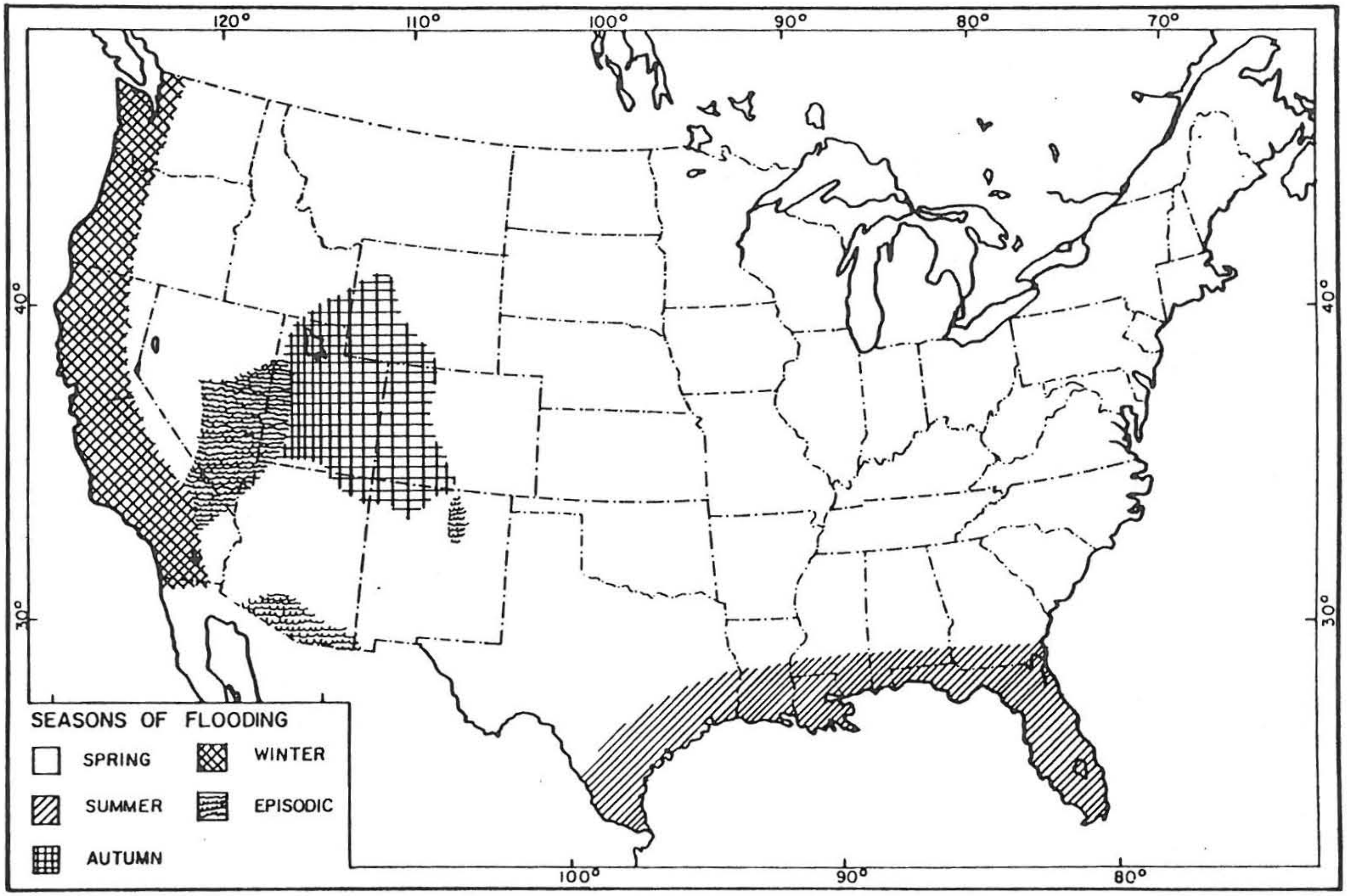

Figure E24. Location map of seasonal flooding in the United States (White and Haasl 1975).

24. Money Flow

The actual energy in money is negligible, but the embodied energy developing its buying power is large. Record the dollar flow per time of purchased goods and services and of exports that cross the system boundary. Then, with the help of Table E4, convert it to the solar equivalent Calories embodied in its buying power. In this calculation, dollar flow is converted to embodied energy equivalents without calculating the actual energy of the money.

Table E27. Calorie contents of fuels used in human activity (Merill 1974).

Fuel	Calorie Content per unit	Unit
Alcohol		
Ethanol	23,929	gal
Methanol	16,877	gal
Biogas (60% methane)	160	ft^3
Butane	775	ft^3
Coal		
Anthracite	3,200	lb
Bituminous	3,300	lb
Lignite	1,688	lb
Coal coke	3,275	lb
Coal gas	120	ft^3
Crude oil	34,761	gal
Fuel oil	37,431	gal
Gasoline	36,225	gal
Kerosene/diesel fuel	34,030	gal
Lp gas	23,929	gal
Natural gas	264	ft^3
Propane	600	ft^3
Wastes		
Municipal organic refuse	1,125	lb
Paper	1,914	lb
Dry plant biomass	2,015	lb
Wood	1,458	lb

Table E28. Chemical potential energies of representative commodities.

Commodity	Potential Energy, Cal/lb	Footnote
Cement	20	a
Glass	1900	b
Metal (steel)	700	c
Organic		b
Food	1500	
Natural fiber	1500	
Paper	1900	
Wood	1500	
Plastic	3000	d

[a] Assumes cement consisting of two-thirds limestone and one-third sand. Assumes the free energy of sand is negligible.
[b] Merill (1974), p. 110.
[c] The oxidation of 55.85 g of iron to ferric oxide releases 177 g. The potential energy of 1 lb (454 g) of steel is 700 Cal/lb.
[d] Two-thirds of fossil fuel.

25. Potential Energy in Land Uplift

Potential energy in land uplift is calculated as the product of mass, acceleration, and height of uplift. Estimate the rate of uplift from Table E29 and the density of land materials from Table

Table E29. Estimates of upheaval rates under (a) orogenic, (b) isostatic, and (c) epeirogenic conditions (based on data from Schumm 1968; Carson and Kirkby 1972).

Location	Uplift/1000 yr m	ft	Source
(a) Orogenic			
California	4.8-12.6	16-42	Gilluly 1949
Southern California	3.9-6.0	13-20	Stone 1961
Japan	0.8-75	3-250	Tsuboi 1933
Persian Gulf	3.0-9.9	10-33	Lees 1955
(b) Isostatic			
Fennoscandia	10.8	36	Gutenberg 1941
Southern Ontario	4.8	16	Gutenberg 1941
(c) Epeirogenic	0.1-3.6	0.3-12	Cailleux 1952

E30. Use equation 25 to calculate the flux of potential energy against gravity in the supply of land to the system.

$$E_u = \rho g h \cdot d(2.38 \times 10^{-7}) \qquad Cal/m^2 \cdot yr \quad (25)$$

where,

E_u = potential energy in land uplift, $Cal/m^2 \cdot yr$;

ρ = density of land materials (Table E31), g/cm^3;

g = acceleration of gravity = 980 cm/s^2;

h = rate of uplift (Table E30), cm/yr;

d = center of gravity of uplifted land, 0.5(height of uplift) = 0.5 h, cm.

26. Chemical Potential Energy of Land Uplift

Estimate the rate of geologic uplift from Table E29 and the density of rock type from Table E30. Read the Gibbs free energy of land components from Table E31 and use equation 26 to find the heat equivalents of chemical potential energy of land uplift.

$$F_u = \rho \cdot h \cdot G_f \cdot 10^4 \qquad Cal/m^2 \cdot yr \quad (26)$$

where,

F_u = chemical potential energy of land uplift, $Cal/m^2 \cdot yr$;

ρ = density of land materials (Table E30), g/cm^3;

h = rate of geologic uplift (Table E29), cm/yr;

G_f = Gibbs free energy of land components (Table E31), Cal/g.

Example for calculating the chemical potential energy of land uplift.

The density of granite = 2.61 g/cm^3, the average land uplift = 3.6 cm/1000 yr, or 3.6×10^{-3} cm/yr, and the Gibbs free energy of granite = 0.012 Cal/g. The chemical potential energy of land uplift is estimated as

$$F_u = (2.61\ g/cm^3)(3.6 \times 10^{-3}\ cm/yr)(0.012\ Cal/g)(10^4\ cm^2/m^2) = 1.13\ Cal/m^2 \cdot yr.$$

Table E30. Representative strength parameters for some rocks (Statham 1977).

Rock Type	Intact Rock: Unit Weight g/cm^3	Intact Rock: S_c Compressive Strength, kg/cm^2	Intact Rock: H_c Critical Height of Vertical Cliff, m	Rock with Discontinuities: c' Cohesion kg/cm^2	Rock with Discontinuities: Φ Degrees	Rock with Discontinuities: Critical Height* m
Granite	2.614	1,000-2,500	4,000-10,000	1-3	30-50	12-65
Sandstone	1.950	200-1,700	1,000-9,000	0.5-1.5	30-45	9-40
Shale	2.400	100-1,000	400-4,000	0.2-1.0	27-45	4-20
Limestone	3.169	300-2,500	900-8,000	0.25-1.0	30-50	5-25
Quartzite	2.614	1,500-3,000	6,000-11,000	1-3	30-50	12-65

*Based on Culmann method, assuming material behaves as isotropic continuum of discontinuities and assuming tension crack develops.

Step IV. Evaluate Long-Term Storages

Storages with time constants longer than a year are included in the main diagram Fig. E2. Evaluation of actual energy is done by multiplying Calories per unit by the number of units. Use the format given in Table E5.

Table E31. Chemical potential energy of components of land (Gilliland et al. 1978).

Land Component	Estimated Formation Time, $g/m^2 \cdot yr$	Heat Equivalent,* Cal/g of rock
Granite	0.692	0.012
Basalt	0.795	0.041
Shale	1.909	0.024
Limestone	1.672	0.146
Sandstone	NA	0.012

*Gibbs free energy between rock and its weathered state after reacting with rainwater.

Storages of solar energy, heat, wind, and water are short term and are shown on the diagram as small storage symbols. These are not evaluated since they are small relative to their inflows, which were calculated above. Storages evaluated below are keyed to Fig. E2 by capital letters.

A. Energy Stored in Dominant Biomass

Use representative data of biomass and energy content for each type of forest land from Table E32. Multiply the energy content of wood biomass per unit area by the area of each type of forest land as shown in Fig. E25 (or from local data) to obtain the energy stored in dominant biomass.

B. Energy Stored in Soil

Soil energy storage is measured here as the chemical potential of the organic matter in soil. Identify the soil type of your study area from the soil map in Fig. E26, and obtain the average soil nitrogen content from Table E33. Use equation 27 or 28 to calculate the actual heat energy storage of soil.

$$E_s = K \cdot O \qquad \text{Cal/m}^2 \quad (27)$$

where,

E_s = energy stored in soil, Cal/m^2;
K = an empirical constant = 5.4 Cal/g organic matter (Regan 1977);
O = organic matter content of soil = 20 x N;
N = soil nitrogen content, g/m^2 (Table E33; divide grams per hectare by 10^4 m^2/ha.)

$$E_s = K \cdot R \cdot B \cdot D \qquad (28)$$

where,

K = an empirical constant;
R = ratio of organic weight to total weight;
B = bulk density of soil, g/m^3;
D = depth of soil, m (Table E33).

Table E32. Energy in wood biomass on an areal basis.

Forest Type	Age, yr	Location	Wood Biomass, kg/m^2	Energy Content* of Wood Biomass, 10^4 Cal/m^2	Source
Dry					
Slash pine plantation	5-6	North Carolina	0.40	0.2	Nemeth 1973
Slash pine plantation	7-8	North Carolina	1.79	0.8	Nemeth 1973
Loblolly pine plantation	5-6	North Carolina	0.33	0.1	Nemeth 1973
Loblolly pine plantation	7-8	North Carolina	0.34	0.2	Nemeth 1973
Loblolly pine plantation	9	North Carolina	1.28	0.6	Nemeth 1973
Loblolly pine plantation	10-11	North Carolina	5.35	2.4	Nemeth 1973
Loblolly pine plantation	12	North Carolina	7.39	3.3	Nemeth 1973
Northern pine-oak	mixed	Minnesota	12.08	5.4	Reiners 1972
Old-field pine stand	17	Virginia	6.64	3.0	Madgwick 1968
Oak-pine-hazel	mixed	Minnesota	3.03	1.4	Ovington et al. 1963
Oak-pine	45-58	Minnesota	16.11	7.2	Ovington et al. 1963
Oak-pine	mixed	New York	5.96	2.7	Whittaker and Woodwell 1971
Spruce-fir	mixed	Smokey Mountains	34.88	14.3	Whittaker and Woodwell 1971
Pine flatwood	mixed	North-central Florida	6.2	2.8	Hood pers. comm.
Moist					
Oak-hickory	mixed	Missouri	10.13	4.6	Rochow 1974
Post oak-black jack oak	mixed	Oklahoma	17.44	7.8	Johnson and Risse 1974
Marginal fern	mixed	Minnesota	9.41	4.2	Reiners 1972
Cove forest	mixed	Smokey Mountains	49.59	22.3	Whittaker and Woodwell 1971
Mixed oak-hickory	mixed	Georgia	13.79	6.2	Monk et al. 1970
Liriodendron forest	mixed	Tennessee	6.79	3.1	Reichle et al. 1973a
Wet					
White cedar swamp	mixed	Minnesota	15.12	6.8	Reiners 1972
Cypress strand	mixed	South Florida	17.0	7.7	Burns 1978
Cypress dome	>100	Florida	21.2	9.5	Brown 1978
Cypress dome	50	Florida	17.0	7.7	Brown 1978
Scrub cypress	100	South Florida	2.4	1.1	Brown 1978
Cypress floodplain forest	mixed	North-central Florida	28.1	12.6	Brown 1978
Bottomland hardwood forest	mixed	Louisiana	16.5	7.4	Connors 1975
Cypress tupelo gum	mixed	Louisiana	37.2	16.7	Connors 1975
Cypress swamp	mixed	Georgia	29.8	13.4	Schlesinger 1976
Red mangrove	mixed	South Florida	0.03	0.01	Stanford 1976
Black mangrove	mixed	South Florida	0.009	0.004	Stanford 1976
White mangrove	mixed	South Florida	0.08	0.04	Stanford 1976

*Calculated by multiplying wood biomass numbers by 4.5 Cal/g.

FOREST VEGETATION
(WESTERN)

SPRUCE-FIR (N. CONIFEROUS FOREST)

"CEDAR"-HEMLOCK (N.W. CONIFEROUS FOREST)

- Western Larch-Western White Pine
- Pacific Douglas-Fir
- Redwood

PINYON JUNIPER
(S.W. CONIFEROUS WOODLAND)

CHAPARRAL
(S.W. BROADLEAVED WOODLAND)

PONDEROSA PINE-DOUGLAS-FIR
(WESTERN PINE FOREST)

- Ponderosa Pine-Sugar Pine
- Ponderosa Pine-Douglas-Fir
- Lodgepole Pine

FOREST VEGETATION
(EASTERN)

SPRUCE-FIR (N. CONIFEROUS FOREST)

JACK, RED, AND WHITE PINES
(N.E. PINE FOREST)

BIRCH-BEECH-MAPLE-HEMLOCK
(N. HARDWOODS)

OAK (S. HARDWOOD FOREST)

- Chestnut-Chestnut Oak-Yellow Poplar
- Oak-Hickory
- Oak-Pine

CYPRESS-TUPELO-SWEETGUM
(RIVER BOTTOM FOREST)

LONGLEAF-LOBLOLLY-SLASH PINE
(S.E. PINE FOREST)

MANGROVE (SUBTROPICAL FOREST)

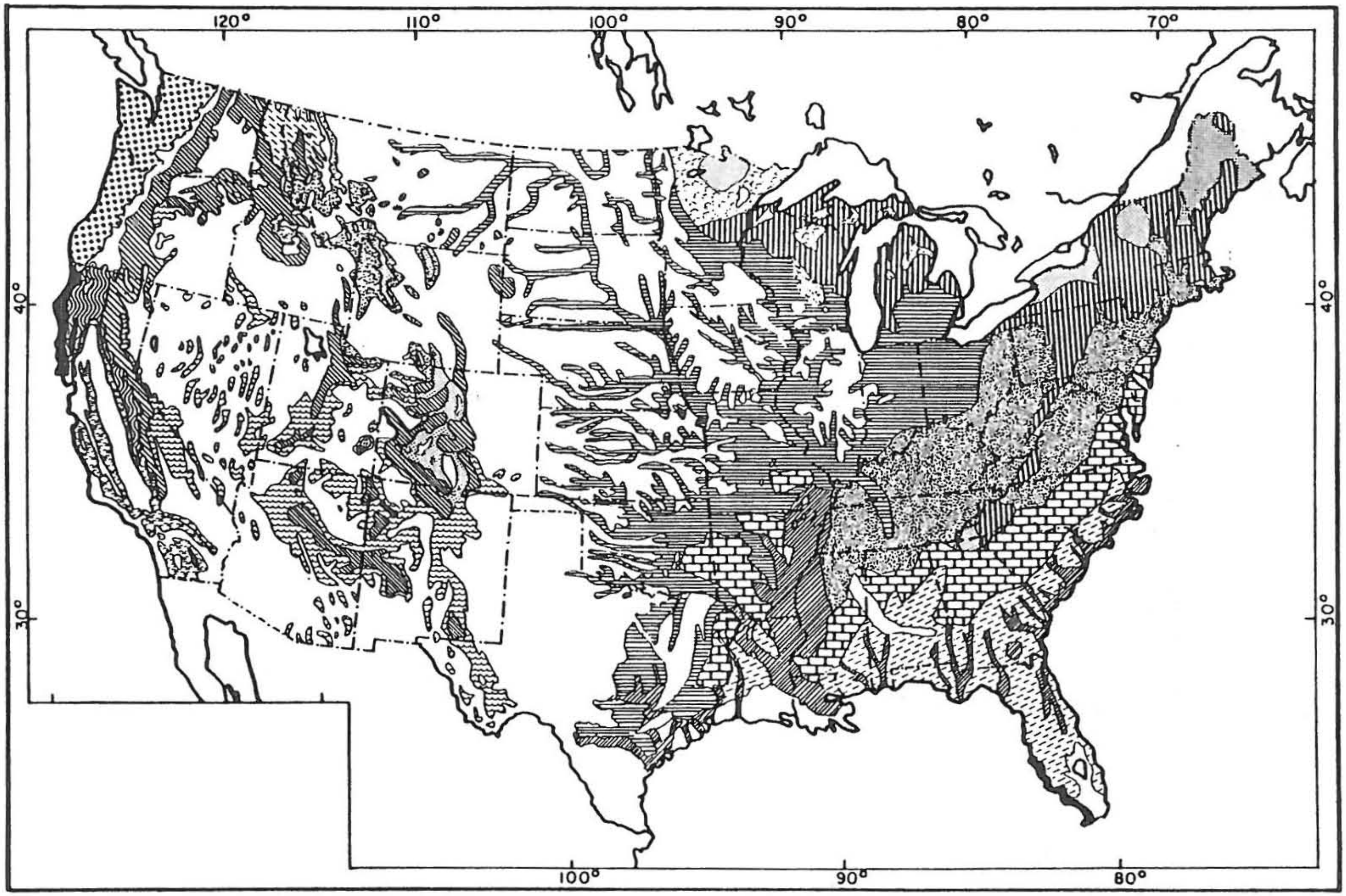

Figure E25. Forest vegetation map of the United States (from USDA 1949).

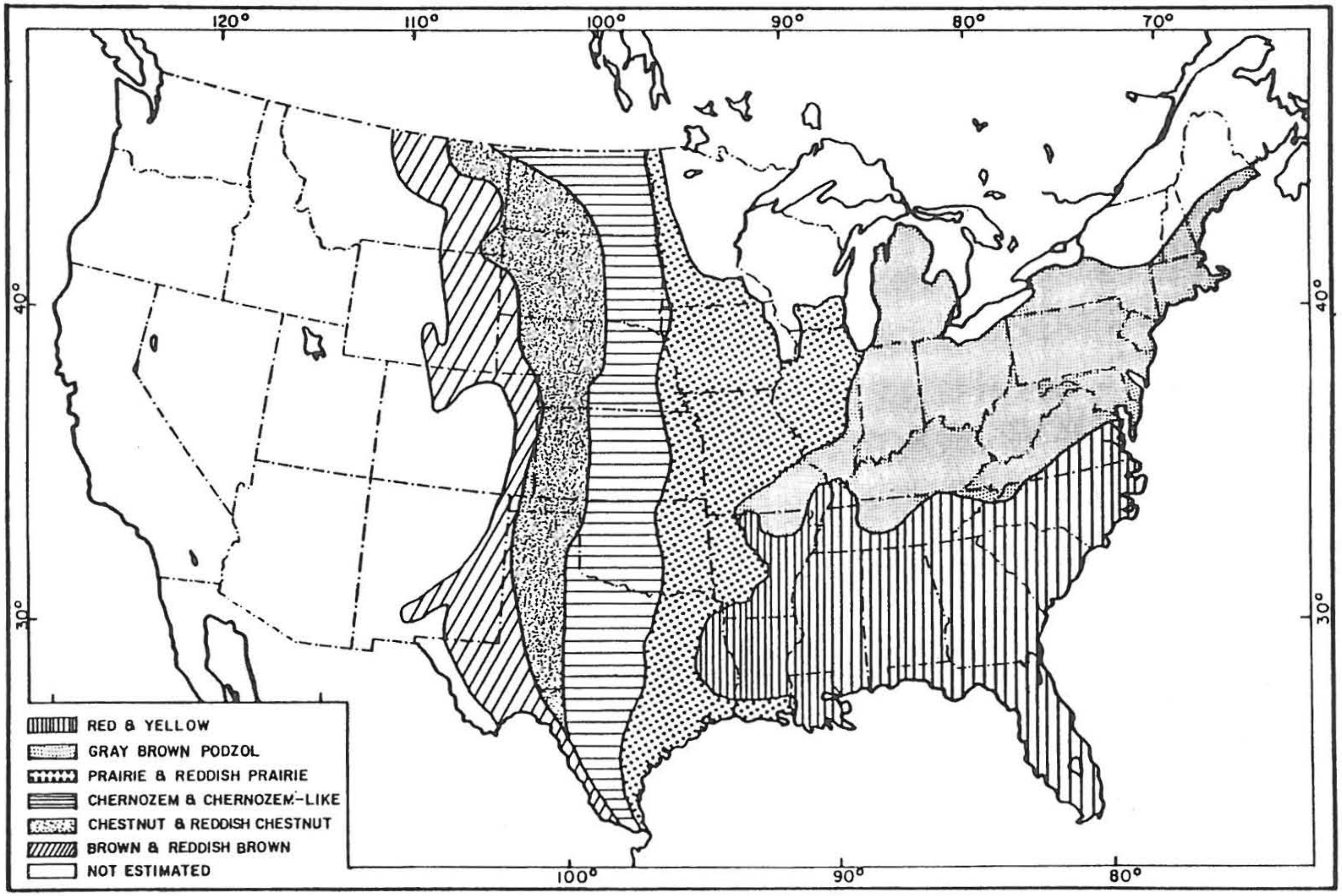

Figure E26. Map showing the distribution of six U.S. soil types (adapted from Hunt 1972).

Example for computing energy stored in soil:

The soil type in the southeastern United States is classified as Red and Yellow soils (Fig. E26). The nitrogen content is 4.47×10^6 g/ha, or 4.47×10^2 g/m^2, and the soil depth is 1.07 m (Table E33). The organic matter in

Table E33. Average nitrogen value, soil depth, and area of six U.S. soil types (Hunt 1972).

Soil Type	Nitrogen, 10^6 g/ha	Depth, m	Area 10^8 ha
Red and Yellow	4.47	1.07	1.13
Gray Brown Podzol	7.16	0.76	1.21
Prairie and Reddish Prairie	16.80	0.91	0.66
Chernozem and Chernozem-like	17.94	0.91	0.56
Chestnut and Reddish Chestnut	11.98	0.91	0.69
Brown and Reddish Brown	8.97	0.91	0.51
Not estimated			2.93

soils is 8.94×10^3 g/m^2, and the total soil weight per unit area is 1.47×10^6 g/m^3 times 1.07 m, or 1.57×10^6 g/m^2. Thus, the ratio of weight of organic matter to the total soil weight is 8.94×10^3 g/m^2/1.57×10^6 g/m^2, or 5.69×10^{-3}. The chemical potential energy of the organic matter in soil (in heat equivalents) is estimated as

$$
\begin{aligned}
E_s &= K \cdot R \cdot B \cdot D \\
&= (5.4\ \text{Cal/g})(5.69 \times 10^{-3}) \\
&\quad (1.47 \times 10^6\ \text{g/m}^3)(1.07\ \text{m}) \\
&= 4.83 \times 10^4\ \text{Cal/m}^2.
\end{aligned}
$$

The total area of Red and Yellow soils in the Southeast is 1.13×10^8 ha, or 1.13×10^{12} m^2 (from Table E33). The total energy stored in the Red and Yellow soils is 4.83×10^4 Cal/m^2 times 1.13×10^{12} m^2, or 5.46×10^{16} Cal.

C. Energy in Information in Species

To estimate the energy in Calories stored in high-quality diversity and information, estimate the energy in the DNA of species with help from the data in Table E26 and multiply by the number of species. Table E34 represents the species

Table E34. Representative data of species flux rates for various general groups of organisms.

Category	Measured Species Flux	Source
Algae	46 species/6.25×10^{-4} m^2/4 d	Patrick 1967
Microscopic invertebrates	180 species/0.113 m^2/12 d	Maguire 1970
Vascular plant seeds	2.8 species/0.83 m^2/14 d	Wagner 1965
Insects	30 species/100 m^2/120 d	Wilson 1969
Vertebrates	30 species/50 km^2/37 yr	Hesse et al. 1957

flux rate for various general groups of organisms.

D. Energy Stored in Urban Structure

To calculate the chemical potential energy stored in urban structure, evaluate the area affected as to type of land use and determine from Table E35 the weight of different materials. Then, use Tables E27 and E28 for energy per pound of human assets, multiply weights of individual materials by the appropriate chemical potential energy factor. The value thus obtained is the chemical potential energy stored in urban structure.

The potential energy due to elevation is obtained by using the numbers in the last column of Table E36 that apply to the particular land use type being calculated.

The values given in Tables E35 and E36 are calculated based on representative land use types. If areas to be evaluated differ significantly from the land uses given in the tables, sufficient data are given in the footnotes to Table E35 to calculate more representative values. A map of the urban structure is given in Fig. E27.

E. Potential Energy in Uplifted Land

Estimate the land elevation above mean sea level from Fig. E11. Find the density of the land materials from Table E30, and use equation 29 to calculate the potential energy in uplifted land.

$$E_\ell = \rho g h^2 (2.38 \times 10^{-5}) \qquad \text{Cal/m}^2 \quad (29)$$

where,

E_ℓ = potential energy in uplifted land, Cal/m^2;
ρ = density of land materials (Table E29), g/cm^3;
g = acceleration of gravity = 980 cm/s^2;
h = land elevation above mean sea level, m.

F. Chemical Potential Energy in Base Rocks

From the map in Fig. E28 or local data determine base rock class. Find the land elevation from Fig. E11 and rock density from Table E30. Read the free energy per unit rock from Table E31, and use equation 30 to obtain the storage of chemical potential energy per unit area.

$$E_r = \rho h G_f \cdot 10^6 \qquad \text{Cal/m}^2 \quad (30)$$

where,

E_r = chemical potential energy in base rock, Cal/m^2;
ρ = density of land materials (Table E30), g/cm^3;
h = average land elevation, m, (distance above plane of elevation defined as the lower boundard of the system);
G_f = Gibbs free energy of land components (Table E31), Cal/g.

Table E35. Weights of assets of human activity[a] (Brown 1980).

	Buildings[b], 10^3 lb/acre		Miscellaneous Assets[c], 10^3 lb/acre			Road[d], 10^3 lb/acre	
	Wood	Concrete	Organic, 70%	Metal, 25%	Plastic, 5%	Asphalt	SubBase (rock)
Single-Family Residential							
Low Density[e]	260	680	16	6	1	68	243
Medium Density[f]	410	1,060	25	9	2	100	323
Multi-Family Residential							
Low Rise[g]	1,250	3,040	77	28	6	258	929
High Rise[h]		7,940	196	70	14	278	1,000
Commerical[i]		3,380	63	23	5	410	1,476
Industrial[j]		2,830	119	43	9	357	1,285
Central Business District[k]							
Average height 2 stories		7,480	182	65	13	311	1,120
Average height 6 stories		22,100	546	195	39	311	1,120

[a]Given in Table E35 are representative weights of assets per acre for types of urban land uses. They are given on an acre basis for easy calculation. If the actual areas affected by the proposed project are substantially different, multipliers may be derived from data given.

[b]Weight of buildings is calculated by assuming weights for one-story wood and concrete structures as 70 lb/sq ft and 180 lb/sq ft, respectively. Residential buildings greater than two stories are calculated by assuming weights of 65 lb/sq ft and 170 lb/sq ft for wood and concrete structures. Commercial and industrial structure is calculated by assuming a weight of 225 lb/sq ft; and central business district weights are calculated by assuming 170 lb/sq ft.

[c]Miscellaneous assets are defined as furnishings, machinery, and other goods stored within the structure. Weights were calculated by assuming that those assets occupied approximately 30% of the floor area of the building; and weigh 20 lb/sq ft of occupied space. Composition of miscellaneous assets was assumed to be 70% organic (wood, cloth, etc.), 25% metal, and 5% plastic.

[d]The area of roads and other impervious surfaces was measured from aerial photographs of typical urban systems. Areas were multiplied by 15 lb/sq ft to obtain gross weight per acre of asphalt, and by 54 lb/sq ft to obtain gross weight per acre of rock subbase.

[e]Low-density single-family residential is defined as two units per acre. Area of buildings per acre is based on studies of Florida residential systems by Alexander et al. (1976) where low density had 3.77×10^3 sq ft/acre of structure. Area of roads was measured as 4.5×10^3 sq ft/acre.

[f]Medium-density single-family residential is defined as three units per acre. Area of buildings per acre is based on studies of Florida residential systems by Alexander et al. (1976) where medium density had 5.91×10^3 sq ft/acre of structure. Area of roads was measured as 6.72×10^3 sq ft/acre.

^{g}Low-rise multi-family residential is defined as two stories high with 15 units per acre. Area of buildings per acre is based on studies of Florida residential systems by Alexander et al. (1976) where low-rise multi-family had 17.9 x 10^3 sq ft/acre of structure. Area of roads and other impervious surfaces was measured as 17.2 x 10^3 sq ft/acre.

^{h}High-rise multi-family residential is defined as six stories high with 40 units per acre. Area of buildings per acre is based on studies of Florida residential systems by Alexander et al. (1976) where high-rise multi-family had 46.7 x 10^3 sq ft/acre of structure. Area of roads and other impervious surfaces was measured as 18.5 x 10^3 sq ft/acre.

^{i}Commercial systems are defined as commercial strip developments and commercial malls. Area of buildings per acre is based on studies of Florida commercial systems by Brown and Genova (1973) where commercial systems had 15.0 x 10^3 sq ft/acre of structure. Area of roads and other impervious surfaces was measured as 27.3 x 10^3 sq ft/acre.

^{j}Industrial system values are representative Florida industrial systems that in many instances are less intensive than other areas. Area of structure is based on studies by Brown and Genova (1973) where industrial systems had 17.0 x 10^3 sq ft/acre of structure, and roads and other impervious surfaces were measured 23.8 x 10^3 sq ft/acre.

^{k}Central business district. Two values are given: the first where the average height of the CBD is two stories, and the second where the average height is six stories. These values are based on representative Florida CBDs, which in many cases are less intensive than other areas (coverage of buildings is approximately 50%) (see Brown and Genova [1973]). Floor area of structure for CBDs of two stories was 44.0 x 10^3 sq ft/acre; and for six-story CBDs, 130 x 10^3 sq ft/acre. Area of roads and other impervious surfaces was measured as 20.7 x 10^3 sq ft/acre for both types of CBDs.

G. Physical Potential Energy in Land Form

The physical potential energy in land form is in depressions and elevations of the land surface. For elevated land forms use item E. The potential energy in depressions and valleys is equivalent to the potential energy against gravity of the materials that formerly occupied the area. To find this value, estimate the volume of depressions and calculate energy as in item E.

Table E36. Gravitational potential energy due to elevation of urban structure.

	Weight per Acre 10^3 lbs	Average Height, ft	Total Gravitational Potential Energy,* 10^3 Cal/acre
Single-Family Residential			
Low Density	963	5	1.6
Medium Density	1,506	5	2.4
Multi-Family Residential			
Low Rise	4,401	12	17.1
High Rise	8,220	36	95.9
Commercial	3,471	8	9.0
Industrial	4,001	8	10.4
Central Business District			
Average height 2 stories	7,740	12	30.1
Average height 6 stories	22,880	36	266.9

*Calculated using the equation PE = mgh.

Step V. Determine Embodied Energy Flows and Storages

A solar energy transformation ratio is defined as the Calories of sunlight required to generate 1 Calorie of the energy flow of concern. Using the tables of solar energy transformation ratios in Table E1, multiply energy flows and storages that were written in formats of Table E4 and E5 by energy transformation ratios to express them as embodied solar energy. These are now expressed in units of solar Calories. These numbers, tabulated in the format of Table E4 and E5, may be written on the energy diagram of the system also.

The energy embodied in each flow in the same quality of energy (solar Calories) allows each flow to be compared for its relative importance in the sense of the energy required to replace it. If surviving systems are those that use high-energy—costing flows for interactions that have appropriately high amplifier actions, then the energy evaluation are one kind of measure of value.

Step VI. Estimate Dollar Equivalents

As indicated in Figs. E3 and E29 the work processes of the environment are responsible for

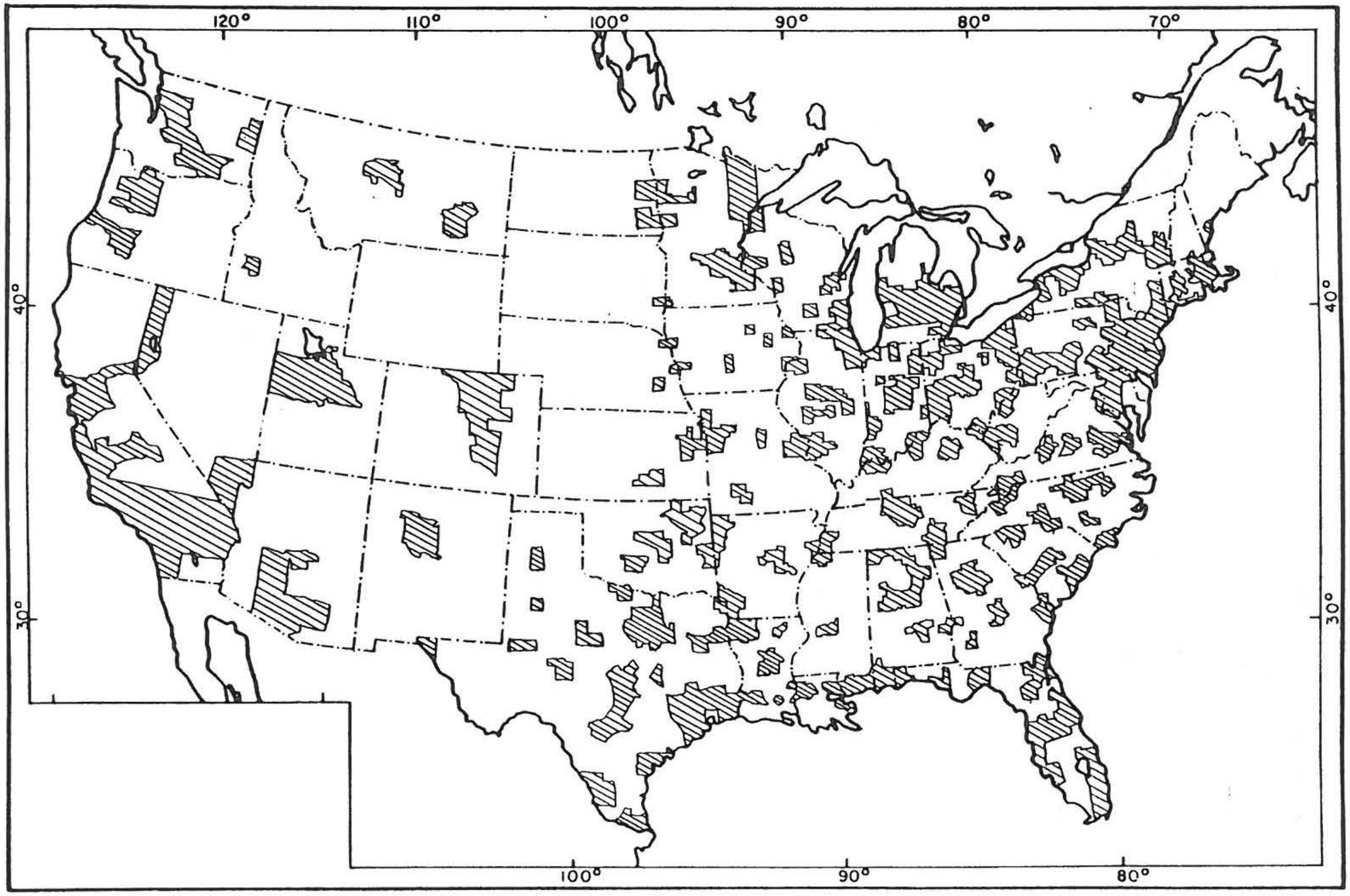

Figure E27. Areas of major urban structure concentration (based on Standard Metropolitan Statistical Areas) (from USDC 1977).

SEDENTARY DEPOSITS

- Residual
  - Clay from deeply weathered metamorphic rocks
  - Clay from deeply weathered, well-consolidated sedimentary and deeply weathered volcanic rocks
  - Sand, silt, and clay from deeply weathered, poorly consolidated sedimentary rocks
- Other
  - Evaporites, chemical precipitates at salt pans. (Travertine and caliche deposits too small to be shown)
  - Peat and other swamp and bog deposits
  - Clinker, baked shale and sandstone from burning of lignite beds

TRANSPORTED DEPOSITS

- Glacial
  - Glacial drift, a vast till plain with morainal ridges
  - Discontinuous drift in hills and valleys, locally thick
  - Mountain glacial deposits
- Lake
  - Beds of late Pleistocene lakes
- Eolian
  - Loess, wind-deposited silt
  - Wind-deposited sand (partially shown)
- Stream
  - Alluvium, deposits in floodplains (partially shown)
  - Valley fill, largely sand and gravel sloping to dry lake beds (many with salt pans) or alluvial bottoms
- Mixed
  - A variety of deposits, mostly stony and thin
- Marine and Littoral
  - Coastal, mostly sandy and silty, some limestone (includes marine, deltaic, estuarine, and fluvatile deposits)
  - Marl
- Desert
  - Sand between bare rock ledges
  - Shale, sandstone outcrops
- Volcanic
  - Ash

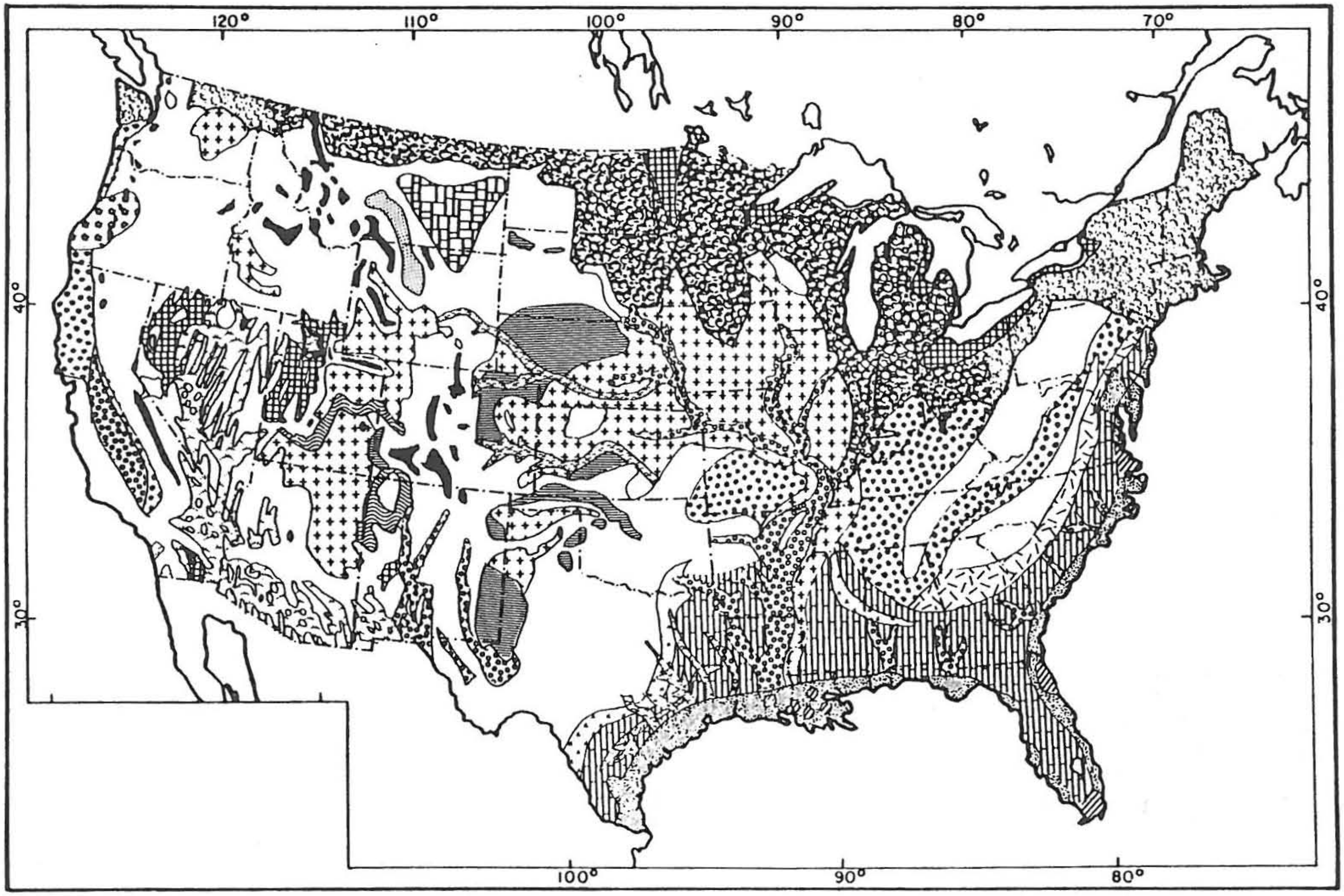

Figure E28. Basic rock types of the United States (from Hunt 1967).

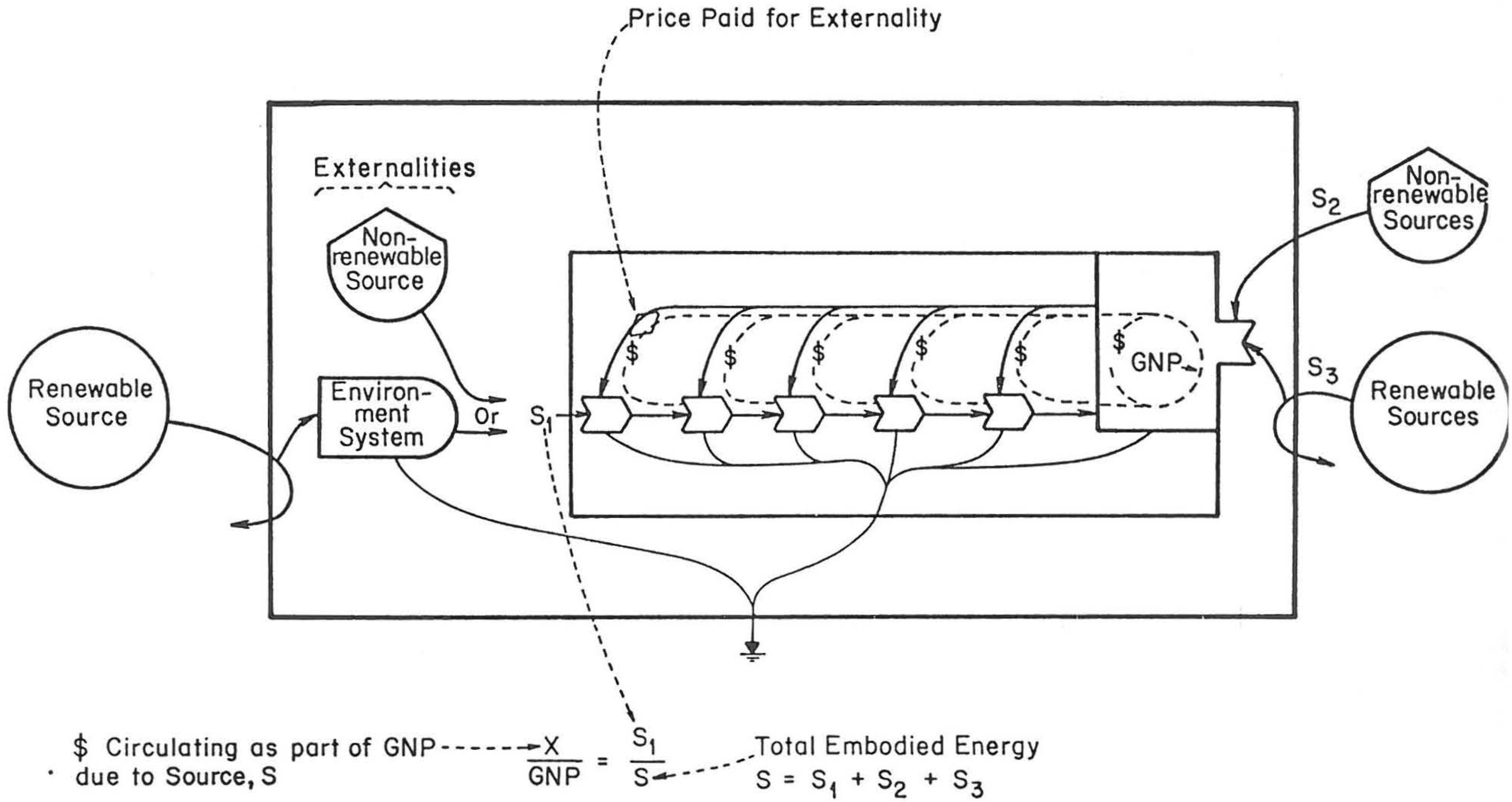

Figure E29. Diagram showing dollar circulation as part of gross national product (GNP) due to externalities of the environment. Dollar equivalents (X) may be estimated using the proportion shown. The ratios of GNP/S for different years are given in Fig. E4.

part of the buying power of the dollars circulating in the gross national product (GNP). With all energies driving the economy represented as solar equivalents, the proportion due to a particular environmental flow or storage may be estimated by proportion as shown in Fig. E29. The embodied energy of the environmental value of concern is to the total environmental energy flow as the dollar equivalent of the environmental resources is to the total energy basis of the economy. The ratio of embodied solar energy to dollars is given in Fig. E4 and Table E2.

Attracted Matching Energies

An environmental resource has a greater effect on the economy than its own share of the total energy budget of the economy. Because of the matching requirement of high-quality energy interacting with lower quality energy (Fig. E3). An environmental resource makes possible good utilization of high-quality energies that feed back through the economy ultimately from other sources. On the average in the United States, the ratio of high-quality matching energies interacting with renewable solar-based energies on a regional scale is about 3:1. Therefore an environmental resource's ultimate effect on the economy is 4 times its proportion of the economy. This is because the United States receives three-fourths of its solar equivalent energies from moderately high-quality fuels from the past that feed back as a matching interaction with the one-forth more dilute environmental energies.

To estimate attracted matching energy and dollars multiply the dollar equivalents calculated in the previous procedure (VI) by 4 (within the United States) to obtain maximum dollar impact.

This calculation is useful for determining a local area's environmental value's potential for attracting other energies and monies. These activities are also possible in the more distant city where the interaction of environmental products with fuel energies may actually occur. The ratio to be used differs for other countries where the ratio of environmental energies to attracted energies is different. Over the world the usual ratio of attracted high-quality energies (in solar equivalents) to local environmental values (in solar equivalents) is only 0.3:1.

Whatever the size of the system being analyzed, there is always a larger one that is in energy exchange with the one being studied. Decisions about the study area often depend upon its role in the next larger system and the larger surrounding economy. The procedure for estimating matching energy given in the paragraphs above is a way of estimating energy and dollar value in the next larger realm.

Step VII. Estimate Changes

If evaluating changes is desirable, select the pathways that will have changed energy flows and the storages that will be used up. Evaluate the energies, embodied energies, and dollar equivalents of these changes in the same procedures given in Steps I—VII.

Whereas the procedures given in Steps I–VII estimate energies and dollar equivalents for any storage or flow that may be important in a system, many energy analyses do not require total energy evaluation. Evaluation of expected or observed changes is sufficient to determine impacts or alternatives. For siting a power plant, for example, where the decision and justification of the plant have already been made, only the changes in environmental value are necessary to determine the impacts and the way they differ with alternative sites and means of cooling, etc.

EXAMPLE OF EVALUATION OF MAIN ENERGY FLOWS—AN AGRICULTURAL AREA WITH A POWER PLANT AT LASALLE, ILLINOIS

Flora C. Wang

The long procedure for evaluating environmental energy flows and storages given in the previous sections was applied to an agricultural area producing corn, LaSalle County, Illinois. Results are given here. The LaSalle area was analyzed because the environmental system of energy flows and storages was calculated as part of evaluating cooling alternatives when the power plant was constructed.

The procedure used for evaluating the environmental flows is given in Table E3. An energy diagram for agricultural land is shown in Fig. E30. Main flows and storages are identified by numbers and letters in Fig. E30. Tables E37 and E38 summarize the values of energy flows and storages. Their detailed computations are explained in the footnotes to the tables. On a per unit area basis, the total flows of man and nature of the agricultural land as expressed in embodied solar energy amount to 1.48×10^9 solar $Cal/m^2 \cdot yr$; and the embodied solar energy stored in the combined system of man and nature is equal to 3.60×10^{17} solar Cal/m^2.

SUMMARY

The procedures described here evaluate the environmental energy storages and flows in any selected area in actual Calories, then in embodied energies, and then in dollar equivalents. The procedure evaluates energy flows and storages or the changes in these due to a project.

This manual of energy analysis of environmental values may be used in many ways: for impact analysis, for choosing between alternative sites, for chosing between alternative public policies, for determining if a project should be done, and to help determine what will be economical, etc. The guiding principle in selecting alternatives is to select one with maximum useful power, the least wasteful energy diversion, and thus the one contributing most to a vital economy of man and nature.

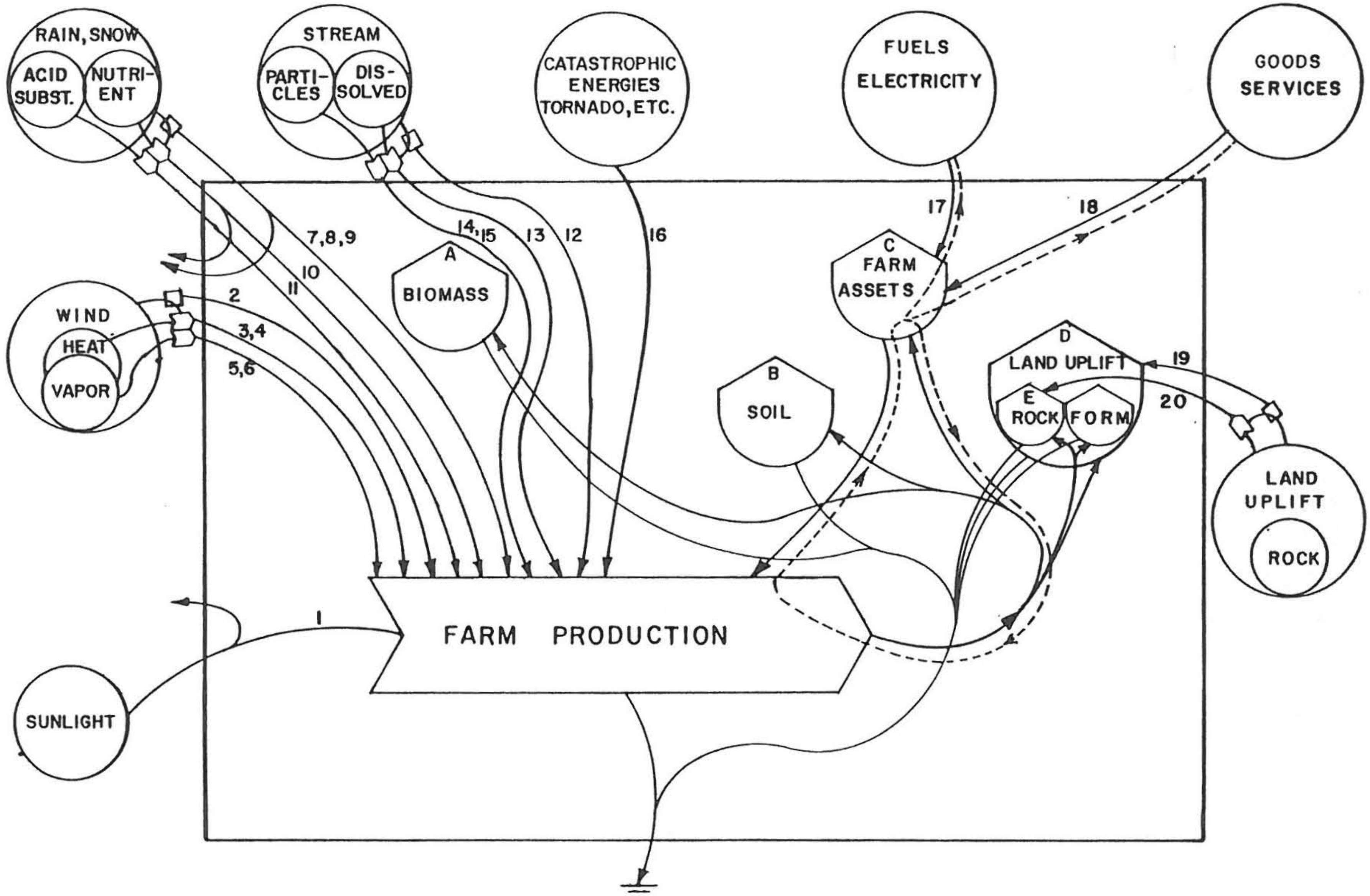

Figure E30. Environmental flows and storages of an agricultural area.

Table E37. Energy evaluation of environmental flows of an agricultural area.

Flows (Numbers in Fig. E30)	Name of Item	Heat Equivalents, $Cal/m^2 \cdot yr$	Transformation Ratio, Solar Cal/Cal	Solar Equivalents Solar $Cal/m^2 \cdot yr$	Footnote
1	Sunlight	1.01×10^6	1.0	1.01×10^6	1
2	Wind	6.83×10^3	56.7	3.87×10^5	2
3	Vertical heat exchange	1.86×10^6	12.9	2.40×10^7	3
4	Horizontal heat advection	3.03×10^6	5.3	1.61×10^7	4
5	Vertical vapor exchange	2.34×10^5	55.9	13.1×10^6	5
6	Horizontal vapor advection	2.19×10^5	55.9	12.2×10^6	6
7	Rain kinetic energy	6.43	2.38×10^5	1.53×10^6	7
8	Rain gravitational energy	1.49×10^2	4.0×10^3	5.96×10^5	8
9	Rain chemical potential over land	1.05×10^3	6.9×10^3	7.25×10^6	9
10a	Rain chemical potential of nitrogen	0.85×10^{-3}	2.91×10^9	2.46×10^6	10a
10b	Rain chemical potential of phosphorus	0.16×10^{-3}	2.61×10^{10}	4.18×10^6	10b
11	Rain chemical potential of acid	2.13×10^{-2}	1.09×10^9	23.2×10^7	11
12	Stream physical energy	3.43	1.06×10^4	3.64×10^4	12
13	Stream chemical potential of water	0.52	3.57×10^4	1.86×10^4	13
14	Stream chemical potential energy in sediments	2.60	0.88×10^6	2.29×10^6	14
15	Stream physical potential energy in materials	1.69×10^{-3}	2.33×10^7	0.39×10^5	15
16a	Catastrophic energy in earthquake	4.00×10^{-2}	3.98×10^6	1.59×10^5	16a
16b	Catastrophic energy in tornado	1.07×10^{-2}	2.61×10^{10}	2.79×10^8	16b
17a	Fuels (gasoline)	1.97×10^2	1.15×10^4	2.24×10^6	17a
17b	Electricity	7.65×10^1	2.72×10^4	2.08×10^6	17b
18	Goods and Services				
18a	Fertilizer	4.15×10^2	1.99×10^6	8.26×10^8	18a
18b	Machinery	1.04×10^2	6.8×10^3	7.07×10^5	18b
18c	Labor	1.21	8.87×10^5	1.07×10^6	18c
18d	Commodity	0.60×10^2	6.7×10^4	4.02×10^6	18d
19	Land uplift potential energy	2.31×10^{-9}	1.5×10^{12}	3.47×10^3	19
20	Land uplift chemical potential energy	1.19	4.03×10^7	4.80×10^7	20

[1] Sunlight: Representative value of solar radiation (S) for Illinois from Table E6; $S = 1.01 \times 10^6$ $Cal/m^2 \cdot yr$.

[2] Wind: Average value of winter and summer eddy diffusion coefficients (K_m) and wind velocity gradient (du/dZ) for Peoria, Illinois, from Table E7 and E8: $K_m = 27.7\ m^2/s$ in January, $1.78\ m^2/s$ in July; $du/dZ = 7.28 \times 10^{-3}/s$ in January, 1.70×10^{-3} in July. Average value of $K_m(du/dZ)^2 = 0.5[(27.7)(7.28 \times 10^{-3})^2 + (1.78)(1.70 \times 10^{-3})^2]$ $= 7.37 \times 10^{-4}\ m^2/s^3$. Turbulent kinetic energy: $P_m = Z_b\ \rho\ K_m(du/dZ)^2 = (1000\ m)(1.23\ kg/m^3)(7.37 \times 10^{-4}\ m^2/s^3)$ $(7534\ Cal/yr \cdot watt) = 6.83 \times 10^3\ Cal/m^2 \cdot yr$.

[3] Vertical heat exchange: Average value of winter and summer eddy diffusion coefficients, K_h, and potential temperature gradients, $d\theta/dZ$, for Peoria, Illinois, from Table E7 and E9: $K_h = 38.78\ m^2/s$ in January, $2.49\ m^2/s$ in July; $d\theta/dZ$ $= 9.84 \times 10^{-3}$ °K/m in January, 7.72×10^{-3} °K/m in July. Average value of $K_h(d\theta/dZ) = 0.5[(38.78)(9.84 \times 10^{-3})$

+ (2.49)(7.72 x 10^{-3})] = 200.41 x 10^{-3} °K·m/s. Turbulent heat flux: $J_h = C_p \rho K_h(d\theta/dZ)$ = (0.24 Cal/kg·°K) (1.23 kg/m^3)(200.41 x 10^{-3}°K·m/s) = (59.16 x 10^{-3} Cal/m^2·s)(3.15 x 10^7 s/yr) = 1.86 x 10^6 Cal/m^2·yr.

[4]Horizontal heat advection: Average horizontal temperature gradient, dT/dX, in the direction of local prevailing wind, u, for the LaSalle County Station (LSCS) is obtained from Table 2.3-1 (CEC 1977). LSCS average temperature = 58.9°F = 14.94°C = 287.94°K. Argonne average temperature = 55.6°F = 13.11°C = 286.11°K. Temperature difference, dT, = 1.83°K. ANL is located about 43 miles northeast of LSCS site, that is, horizontal distance dX = 43 miles = 68.8 km. Temperature gradient dT/dX = 1.83°K/68.8 km = 2.66 x 10^{-5}°K/m. From Fig. 2.3-2 (CEC 1977), northeast prevailing wind speed u_1 at 33-foot (10-m) levels equals u_1 = 7.0 m/s. At the half height of the boundary layer, the wind velocity is u = u_2 = $u_1(Z_2/Z_1)^{1/7}$ = (7.0 m/s)(500 m/10 m)$^{1/7}$ = 12.24 m/s. Horizontal transport of heat: $F_y = C_p \rho\ Z_b(dT/dX)u$ = (0.24 Cal/kg·°K)(1.23 kg/m^3)(1000 m)(2.66 x 10^{-5}°K/m)(12.24 m/s) = (9.61 x 10^{-2} Cal/m^2·s)(3.15 x 10^7 s/yr) = 3.03 x 10^6 Cal/m^2·yr.

[5]Vertical heat exchange: Average value of winter and summer eddy diffusion coefficient, K_w, and vapor pressure gradients, de/dZ, for Peoria, Illinois, from Tables E7 and E10: K_w = 38.78 m^2/s in January, 2.49 m^2/s in July. K_w = 0.5(38.78 + 2.50) = 20.64 m^2/s. de/dZ = 3.98 mb in January, 15.9 mb in July. Average vapor pressure, e = 0.5(3.98 + 15.9) = 9.94 mb. Average gradient of vapor pressure de/dZ = 0.5(13.99 + 49.91) x 10^{-4} = 31.95 x 10^{-4} mb/m. Height of boundary layer Z_b = 1000 m. d^2e/dZ^2 = d/dZ·de/dZ = 3.195 x 10^{-6} mb/m^2. Air density ρ = 1.23 kg/m^3. Gravitation acceleration g = 9.8 m/s^2. ρg/100 p = (1.23 kg/m^3)(9.8 m/s^2)/(100)(993 mb) = 1.21 x 10^{-4}/m. Gibbs free energy due to water vapor convection: $F_g = (2.38 \times 10^{-2})Z_bK_w[d^2e/dZ^2 + 2(\rho g/100\ p)de/dZ + 2(\rho g/100\ p)^2e][1 + \ln(e/p)]$ = (2.38 x 10^{-2}) (1000 m)(20.64 m^2/s)[3.195 x 10^{-6} + 2(1.21 x 10^{-4})(3.195 x 10^{-3}) + 2(1.21 x 10^{-4})^2(9.94)] mb/m^2[1 + ln(9.94/993)] = (4.91 x 10^2)(4.20 x 10^{-6})(-3.60) = (0.742 x 10^{-2} Cal/m^2·s)(3.15 x 10^7 s/yr) = 2.34 x 10^5 Cal/m^2/yr.

[6]Horizontal vapor advection: Average wind velocity, u_1; horizontal water vapor gradient, de/dZ; vapor pressure, e; and atmospheric pressure, p, near the LSCS site are obtained from Figs. E7 and E8 and Table E10: u_1 = 10 mph = 4.44 m/s. u = u_2 = $(Z_2/Z_1)^{1/7}u_1$ = (500/1)$^{1/7}$(4.44) = 10.79 m/s; de = 10.2 mb - 8.4 mb = 1.8 mb; dZ = (150 mile)(1.6 km/mile) = 240 km; de/dZ = 1.8 mb/240 km = 0.75 x 10^{-5} mb/m; e = 9.94 mb; p = 993 mb. Gibbs free energy due to water vapor advection: $F_g = (2.38 \times 10^{-2})Z_b[1 + \ln(e/p)]de/dZ \cdot u$ = (2.38 x 10^{-2})(1000 m)(1 + ln(9.94/993)(0.75 x 10^{-5} mb/m)(10.79 m/s) = (6.94 x 10^{-3} Cal/m^2·s)(3.15 x 10^7 s/yr) = 2.19 x 10^5 Cal/m^2·yr.

[7]Rain kinetic energy: Precipitation in the LSCS site area averages about 34 inches annually, and the area also receives an average of 27 inches of snow annually (CEC 1977). Assuming the snow flake density is 0.1 g/cm^3 (Eagleson 1970), giving 2.7 inches of rain-equivalent depth, and total rainwater equals 34 + 2.7 = 36.7 inches (93 cm). Assuming the average drop velocity is 25 ft/s (762 cm/s), then the kinetic energy of rain is: $K_e = p(0.5MV^2)$ = (93 cm/yr)0.5(1 g/cm^3) (762 cm/s)^2(100^2 cm^2/m^2)(2.38 x 10^{-11} Cal/erg) = 6.43 Cal/m^2·yr.

[8]Rain gravitation energy: Elevations range from approximately 710 feet above msl at the site to 484 feet msl along the Illinois River shoreline (CEC 1977). The difference between receiving and outflow elevation for the site is h = 710 - 226 ft = 68.9 m, then the gravitational energy of rain is: $G_e = p\rho gh$ = (93 cm/yr)(1 g/cm^3)(980 cm/s^2)(6890 cm) (100^2 cm^2/m^2)(2.38 x 10^{-11} Cal/erg) = 1.49 x 10^2 Cal/m^2·yr.

[9]Rain chemical potential energy: Average concentration of total dissolved solids in rainfall, C_2, and average rainfall for the site are obtained from Fig. E13 and from the report of CEC (1977). C_2 = 20 ppm, p = 93 cm/yr. Assuming seawater concentration C_1 = 35,000 ppm, Gibbs free energy of rain: $F_r = pnRTC_2\ln(C_2/C_1)$ = (0.93 m/yr)[(1.99 x 10^{-3} Cal/°K·mole) (288°K)]/(18 g/mole)(999,980 g/m^3)ln(999,980/965,000) = 1.05 x 10^3 Cal/m^2·yr.

[10a]Rain chemical potential of nitrogen: Average nitrogen concentration as NO_3^- and NH_4^+ in rainfall C_2 for the site is obtained from Fig. E13. C_2 = 0.56 ppm. Assuming average nitrogen concentration in seawater C_1 = 0.5 ppm, then the chemical potential of nitrogen is: $F_n = pnRTC_2 \ln(C_2/C_1)$ = (0.93 m/yr)[(1.99 x 10^{-3} Cal/°K·mole)(288°K)]/(40 g/mole)(0.56 g/m^3)$\ln$(0.56/0.50) = 0.85 x 10^{-3} Cal/m^2·yr.

[10b]Rain chemical potential of phosphorus: Average phosphorus concentration PO_4^{3-} in rainfall, C_3, for the site is obtained from Fig. E15. C_3 = 0.095 ppm. Assuming average phosphorus concentration in seawater C_1 = 0.07 ppm, then the chemical potential of phosphorus is: $F_p = pnRTC_3 \ln(C_3/C_1)$ = (0.93 m/yr)[(1.99 x 10^{-3} Cal/°K·mole)(288°K)]/(95 g/mole)(0.096 g/m^3)$\ln$(0.095/0.07) = 0.16 x 10^{-3} Cal/m^2·yr.

[11]Rain chemical potential of acid substance: Average acid substance H^+ in rainfall for the site is obtained from Fig. E16. Moles of H^+ = 40 x 10^{-6} moles H^+/1. Total mole = 55.6 moles H_2O/1. Mole fraction X_{H^+} = total mole - mole of H^+/total mole = 55.6 - 40 x 10^{-6}/55.6 = 1. $\ln X_{H^+} = X_{H^+} - 1$ = 40 x 10^{-6}/55.6 = -0.72 x 10^{-6}. Chemical potential of acid: $F_a = pnRT(X_{H^+})\ln X_{H^+}$ = (0.93 m/yr)[(1.99 x 10^{-3} Cal/°K·mole)(288°K)]/(18 g/mole)1(10^6 g/m^3)(0.72 x 10^{-6}) = 2.13 x 10^{-2} Cal/m^2·yr.

[12]Stream physical energy: Average drop in elevation h within area drained and average water flows q for the site are obtained from Fig. 3.3 (NRC 1978; AEC 1973, respectively). Average elevation drop h = 700 - 680 = 20 ft = 6.10 m. Approximately 11.7 square miles of surface runoff area will be intercepted by the cooling lake, which normally would have run off into the Illinois River. This runoff Q is estimated as average flow of 8.2 cfs (AEC 1973). Total runoff = (8.2 cfs)(1.98 ac-ft/day·cfs)(1230 m^3/ac-ft)(365 day/yr) = (8.2 cfs)(8.889 x 10^5 m^3/yr·cfs) = 72.89 x 10^5 m^3/yr. Area drained A = 11.7 square miles = 30.30 km^2 = 30.30 x 10^6 m^2. Average runoff: q = Q/A = (72.89 x 10^5 m^3/yr)/(30.30 x 10^6 m^2) = 0.241 m/yr = 9.49 in/yr. Physical energy in streamflow: $G_q = q\rho gh$ = (24.1 cm/yr)(1 g/cm^3)(980 cm/s^2)(610 cm)(10^2 cm^2/m^2)(2.38 x 10^{-11} Cal/erg) = 3.43 Cal/m^2·yr.

[13]Stream chemical potential of total dissolved solids: Average total dissolved solid concentration C is obtained from Tables 2.4 and 2.5 (NRC 1978), and the average stream temperature T is obtained from Table 2.6 (NRC 1978). Average total dissolved solids in the vicinity of the site (NRC 1978:2-12). C_1 = 444 ppm. Average total dissolved solids in South Kickapoo Creek (NRC 1978:2-13). C_2 = 484 ppm. Average temperature in the stream (NRC 1978:2-15). T = 56°F = 286°K. Average streamflow of the site (see footnote 12). J = q = 0.241 m/yr. Chemical potential energy in dissolved substances in stream: $F_a = nRT[JC_1 \ln(C_1/C_o) - JC_2 \ln(C_2/C_o)]$ = (1.99 x 10^{-3} Cal/°K·mole)(286°K)/(35 g/mole)(0.241 m/yr)[$C_1 \ln (C_1/C_o) - C_2 \ln(C_2/C_o)$] = (1.62 x 10^{-2} Cal/g)(0.241 m/yr)[(444 g/m^3)$\ln$(444/35,000) - (484 g/m^3)$\ln$(484/35,000) = 0.52 Cal/m^2·yr.

[14]Stream chemical potential energy in sediments: Average total organic carbon C in South Kickapoo Creek is obtained from Table 2.5 (NRC 1978). C = 2 ppm = 2 g/m^3. Assume free energy of organic matter K = 5.4 Cal/g. Heat equivalent of total chemical potential in sediment flux: F_o = JCK = (0.241 m/yr)(2 g/m^3)(5.4 Cal/g) = 2.50 Cal/m^2·yr.

[15]Stream physical potential energy in materials: Average concentration of materials in South Kickapoo Creek is obtained from Table 2.5 (NRC 1978). Average total dissolved solids = 484 ppm. Average total suspended solids = 7.5 ppm. Total materials in stream: ρ = 491.5 ppm = 491.5 x 10^{-6} g/cm^3. Average streamflow J = 24.1 cm/yr. Physical potential energy from mass of materials and height is: $G_m = J\rho gh$ = (24.1 cm/yr)(491.5 x 10^{-6} g/cm^3)(980 cm/s^2)(610 cm)(10^2 cm^2/m^2)(2.38 x 10^{-11} Cal/erg) = 1.69 x 10^{-3} Cal/m^2·yr.

[16a]Catastrophic energy in earthquake: Average peak acceleration a for the site is obtained from Fig. E20, a = 4% g = 0.04 g. Seismic zone number for the site is located from Fig. E21 to be 58, and is used to look up frequency f per 100 yr on Table E24. f = (0.6/100)/yr. Catastrophic energy in earthquake is: $E_e = K_e a^2 f$ = (4168)$(0.04)^2$(0.6 x 10^{-2}) Cal/m^2·yr = 4.00 x 10^{-2} Cal/m^2·yr.

[16b]Catastrophic energy in tornado: The recurrance interval of 460 yr was calculated for tornadoes at the site (NRC 1978), f = 1/460 yr. Catastrophic energy in tornado: $E_t = e_t f$ = (4.9 Cal/m^2)(1/460 yr) = 1.07 x 10^{-2} Cal/m^2·yr.

[17a]Fuels: Average fuel (gasoline) used for corn production is obtained from Pimentel et al. (1973): F_G = 22 gal/acre·yr = (22 gal/acre·yr)(1 acre/4050 m^2) = 5.43 x 10^{-3} gal/m^2·yr. From Pimentel et al. (1973) the heat equivalent of 1 gallon gasoline = 36,225 Cal, thus: F_G = (5.43 x 10^{-3} gal/m^2·yr)(36,225 Cal/gal) = 1.97 x 10^2 Cal/m^2·yr.

[17b]Electricity: Average electricity used for corn production is obtained from Pimentel et al. (1973): E_c = 310,000 Cal/acre·yr = 76.54 Cal/m^2·yr.

[18a]Fertilizer: Average fertilizer used for corn production is obtained from Pimentel et al. (1973): F_C = 200 lb/acre·yr = 4.94 x 10^{-2} lb/m^2·yr = (4.94 x 10^{-2} lb/m^2·yr)(8400 Cal/lb) = 4.15 x 10^2 Cal/m^2·yr. Average fertilizer cost is obtained from Brooke (1977): S_d = $42.07/acre = $0.21/lb. From Table 4, the energy-dollar ratio is 27.6 x 10^6 Solar Cal/$, thus, S = ($0.21/lb)(27.6 x 10^6 Solar Cal/$) = 5.80 x 10^6 Solar Cal/lb.

[18b]Machinery: Average energy for corn production and repair of farm machinery is obtained from Pimentel et al. (1973): M_E = 420,000 Cal/acre·yr = (4.2 x 10^5 Cal/acre·yr)(1 acre/4050 m^2) = 1.04 x 10^2 Cal/m^2·yr. ETR = 6800 global solar Cal/Cal.

[18c]Labor: Average farm labor contribution for corn production is obtained from Pimentel et al. (1973): L_E = 4900 Cal/acre·yr = (4.9 x 10^3 Cal/acre·yr)(1 acre/4050 m^2) = 1.21 Cal/m^2·yr.

[18d]Commodity flows: Average population density is obtained from CEC (1977). The 1970 population within 10 miles of the LSCS site was 15,624, which corresponds to a population density of 49.73 persons/square mile. Average flux of goods at the vicinity of the site is estimated by assuming the following representative commodity flows for a typical town of an area of 314 square miles = 804 km^2. Representative commodity flows for a typical town:

Commodity	Commodity Flow: Person, lb/person·day (1)	Commodity Flow: City, 10^6 lb/yr (2)	Potential Energy Flow: Cal/lb (3)	Potential Energy Flow: 10^7 Cal/yr	Embodied Solar Energy: 10^6 Cal/lb (4)	Embodied Solar Energy: 10^{12} Cal/yr
Cement	0.1	0.57	20	1.14	10.2	5.8
Glass	0.3	1.71	1900	324.90	30.6	52.3
Steel	0.3	1.71	700	119.70	81.6	139.5
Organic						
Food	3.0	17.11	1500	2566.50	163.2	2792.4
Fiber	0.05	0.29	1500	43.50	47.6	13.8
Paper	1.5	8.55	1900	1624.50	27.2	232.6
Wood	0.1	0.57	1500	85.50	13.6	7.7
Plastic	0.05	0.29	3000	87.00	13.6	3.9
TOTAL				4852.74		3238

(1)Commodity weight from ReVelle and ReVelle (1974).

(2)Population from CEC (1977), (15,624 people)(365 day/yr) = 5.703 x 10^6 person·day/yr.

(3)From Table E28.

(4)From Steinhart and Steinhart (1974); multiplied by 3.4 to convert direct solar equivalents to global equivalents.

Thus, total commodity flow = $(4.85 \times 10^{10}$ Cal/yr)/$(8.04 \times 10^8\ m^2)$ = 0.60×10^2 Cal/$m^2\cdot$yr and embodied solar energy = $(32.4 \times 10^{14}$ Cal/yr)/$(8.04 \times 10^8\ m^2)$ = 4.03×10^6 Solar Cal/$m^2\cdot$yr. Energy transformation ratio: Q = $(4.03 \times 10^6)/(0.60 \times 10^2) = 6.7 \times 10^4$ Solar Cal/Cal.

[19]Potential energy in land uplift: Bedrock at the LSCS site consists of Pennsylvanian sandstone, shale, and saltstone (Dames and Moore 1972). The weight for sandstone and shale are 1.95 g/cm^3 and 2.40 g/cm^3, respectively (from Table E30). Assuming the rate of uplift is about 3 cm/1000 yr (average for land), we obtain the gravitational work of land uplift: $E_u = \rho ghd = (2.2\ g/cm^3)(980\ cm/s^2)(.003\ cm/yr)(0.5)(0.003\ cm)(100^2\ cm^2/m^2)(2.38 \times 10^{-11}\ Cal/erg) = 2.31 \times 10^{-9}\ Cal/m^2\cdot yr$.

[20]Chemical potential energy of land uplift: Gibbs free energy values of sandstone and shale are 0.012 Cal/g and 0.024 Cal/g, respectively (Table E31), giving an average value of 0.018 Cal/g. Chemical potential energy of land uplift: $F_u = \rho hG_f = (2.2\ g/cm^3)(0.003\ cm/yr)(0.018\ Cal/g)(100^2\ cm^2/m^2) = 1.19\ Cal/m^2\cdot yr$. ETR is average of shale and sandstone, $(5.22 \times 10^7$ solar Cal/Cal + 2.83×10^7 solar Cal/Cal)/2 = 4.03×10^7 solar Cal/Cal.

Table E38. Energy evaluation of environmental storage of an agricultural area.

Storages (Letters in Fig. E3)	Name of Item	Heat Equivalents, Cal/m^2	Transformation Ratio, Solar Cal/Cal	Global Solar Equivalents Solar Cal/m^2	Footnote
A	Energy stored in crop biomass	3.86×10^3	2.17×10^3	8.38×10^6	A
B	Energy stored in soil	1.81×10^5	6.93×10^4	1.25×10^{10}	B
C	Farm assets	---	---	2.82×10^7	C
D	Energy stored in uplifted land	2.40×10^5	1.50×10^{12}	3.60×10^{17}	D
E	Energy stored in base rock	5.06×10^6	2.83×10^7	1.43×10^{14}	E

[A]Energy stored in crop biomass: Average weight taken as half the biomass at end of growing season (19.3 dry tonne/ha; from Slesser and Lewis [1979] who quoted Roller, Keener, Kline, Mederski, and Curry). $(19.3 \times 10^6$ g dry/ha)(4 Cal/g dry)/ $(10^4$ m^2/ha)(2) = 3860 Cal/m^2. For ETR see footnote 34 in Table E1a.

[B]Energy stored in soil: Average nitrogen content for Prairie and Reddish Prairie soil type is obtained from Table E33, $N = 16.80 \times 10^6$ g/ha $= 16.8 \times 10^2$ g/m^2.

Heat equivalents in soil $E_s = K \cdot 20N = (5.4\ Cal/g)(20)(16.8 \times 10^2\ g/m^2) = 1.81 \times 10^5\ Cal/m^2$.

Energy transformation ratio for Prairie and Reddish Prairie soil (footnote 28, Table E1a): $Q = 6.93 \times 10^4$ Solar Cal/Cal.

[C]Farm assets: Average value of farmland and buildings for corn-belt region in 1976 (USDA 1977, Table 590, p. 427) was $\$102,241 \times 10^6$, and the area planted for corn production in 1976 (USDA 1977, Table 35, p. 28) was $84,121 \times 10^3$ acres, thus,

$$\text{farm assets} = \frac{\$102,241 \times 10^6}{84,121 \times 10^3\ \text{acres}} = \$1215/\text{acre}$$
$$= (\$1215/\text{acre})(1\ \text{acre}/4050\ m^2)$$
$$= \$0.30/m^2$$
$$= (\$0.30/m^2)(1.38 \times 10^4\ \text{CE Cal}/\$)(6800\ \text{global solar Cal/CE Cal})$$
$$= 2.82 \times 10^7\ \text{global solar Cal}/m^2.$$

[D]Energy stored in uplifted land: The LSCS site is relatively flat, varying from approximately 700 to 720 ft (CEC 1977), the average elevation of the site: h = 710 ft = 216.4 m.

Average density of land material from Table E30, $\rho = 2.20\ g/cm^3$.

Potential energy stored in uplifted land: $E_p = \rho g h^2 = (2.20\ g/cm^3)(980\ cm/s^2)(2.164 \times 10^4\ cm)^2(100^2\ cm^2/m^2)$ $(2.38 \times 10^{-11}\ Cal/erg) = 2.40 \times 10^5\ Cal/m^2$.

[E]Energy stored in base rock: Average land elevation of the site is obtained from CEC (1977): h = 216.4 m.

The density for sandstone (from Table E29) and the Gibbs free energy (Table E30) are: $\rho = 1.95\ g/cm^3$; $G_f = 0.012$ Cal/g.

Energy stored in base rock: $E_r = \rho h G_f = (1.95\ g/cm^3)(2.164 \times 10^4\ cm)(0.012\ Cal/g)(100^2\ cm^2/m^2) = 5.06 \times 10^6\ Cal/m^2$.

APPENDIX F

PROCEDURE FOR DEVELOPING ENERGY CIRCUIT MODELS OF COMPLEX SYSTEMS

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An essential step in developing energy circuit models of systems of man and nature is diagraming the system. Over the past several years a step-by-step methodology has been developed for construction of energetics models and is summarized in this appendix to aid the evaluation of alternatives (Alexander, Alexander, and Sipe 1980; Alexander, Swaney, Rognstad, and Hutchison 1980).

The methodology to be presented is made up of the following 11 steps:

1. mapping the general area of interest;
2. identifying the system boundary;
3. identifying energy flows across the boundary;
4. organizing the major system components;
5. identifying interactions between subsystems and sources;
6. connecting the group symbols with external sources;
7. diagraming the subsystems;
8. evaluating the model;
9. translating energy circuit diagrams to differential equations;
10. simulating the energy circuit model;
11. validation of the model.

These steps are discussed below in more detail.

Step 1: Mapping the General Area of Interest

Energetics maps of the land use and ecosystems of the area of interest and the surrounding watersheds have been shown to be of considerable value in understanding the systems of man and nature. The use of color infrared photographs has been found to be useful in the identification of major physical features and in determining the spatial arrangement of energetic subsystems. Figure 6 is an example of an energetics subsystem map for LaSalle County station, plant site, and pipeline corridor before construction.

Step 2: Identifying the System Boundary

In modeling open systems it is necessary to clearly identify a system boundary so that a differentiation can be made between energy flows and storages within the system and the flows of energy from outside the system. Energetic subsystems maps as described in step 1 are helpful in this process since they can be used in determining the boundary in such a way that the significant natural subsystems are not unnecessarily divided. The system boundary is denoted by a large rectangle as may be seen in the complex diagram in Fig. 4.

Step 3: Identifying Energy Flows Across the Boundary

Once the system boundary is defined, flows of energy into and out of the system can be identified. Normally these flows include solar energy in the form of sun, rain, and wind; fossil fuel energy in the form of electricity, petroleum, goods and services, and information; combinations of solar and fossil fuel energy in the form of people; and money.

This step in the modeling process involves drawing a large rectangle that symbolizes the system boundary. The flows of energy across the boundary are represented as energy sources and are symbolized by a set of circles. These circles (energy sources) are arranged around the rectangle beginning in the lower left-hand corner and continuing clockwise in order of increasing energy quality. Thus the dilute energy sources such as the sun, wind, and rain would be located in the lower left of the rectangle, while the more concentrated sources such as fossil fuel, petroleum, and information would be located on the top or right side of the rectangle.

Step 4: Organizing the Major System Components

Energy circuit language contains several group symbols that may be used in diagraming the internal components of a system. Of particular interest is the bullet-shaped symbol and the hexagon-shaped symbol. As noted in Fig. 1 the bullet symbol represents producer systems that concentrate low-quality energy. Examples of such systems would be forests, swamps, estuaries, and farms. The hexagon symbol represents consumer systems requiring high-quality energy for their operation. Examples of these systems would include industries, towns, and people. Experience has shown that arranging these symbols within the diagram from upper left to lower right in order of fossil fuel dependency provides some order to the model.

In the illustrative example, (Fig. 4) producer (bullet) group symbols were used to represent the fallow lands and agriculture while the consumer (hexagon) group symbol is used to represent human settlements.

Step 5: Identifying the Interactions between Subsystems and Sources

This step involves the identification of the interactions between the group symbols within the system being studied and the external energy sources and sinks. To systematically identify these flows a matrix is used. On the vertical axis are listed the energy sources with the internal sources listed first, followed by the external sources. On the horizontal axis are listed the internal energy sinks followed by the external sinks. Once the axes are completed it is necessary to identify the flow between the sources and sinks. If there is an interaction, an "x" is placed in the box to denote a flow of energy between a given source and a sink.

Step 6: Connecting the Group Symbols with the External Sources

Based on the matrix completed in the last step, the group symbols, or subsystems, are connected to the external energy sources. Arrowheads are placed on each pathway to denote the direction of the energy flow. The energy flows intersecting the group symbols are arranged clockwise around the symbol in order of increasing energy quality. With respect to outputs from the group symbols, the degraded energy, which is no longer usable to any of the other subsystems, is shown by a pathway at the bottom of the group symbol, while the energy outputs that can be used by other subsystems are shown leaving the group symbol from the right. Figure 4 illustrates the energy circuit diagram of the LaSalle study area. This model should be thought of as an organizational overview model of the study area. The next step in the process involves looking at the detailed interactions that take place within the subsystems.

Step 7: Diagraming the Subsystems

Developing models of the various subsystems is done in much the same way that the overall model is developed. The significant difference between the two processes lies in the use of two new symbols. In diagraming the subsystems, group symbols are no longer used (although they are often times shown for clarification). Instead, they are replaced with an energy storage symbol that resembles a "water storage tank" and an interaction symbol that looks like an arrow. Within the interaction symbol is placed a mathematical function symbol specifying the type of interaction. For each of the group symbols, the appropriate energy storage tanks should be placed from the upper left to the lower right in order of increasing energy quality. Interaction symbols should be placed in a convenient location, usually to the left of the energy storage symbol into which the energy is flowing.

As was the case with the overall diagram, a matrix should be developed to aid in identifying all of the possible energy interactions. To keep the process simple, separate matrices should be developed for each of the subsystems. After the subsystem matrices are completed, the appropriate pathways can be added to the diagram.

As illustrated in Fig. 4 the completed subsystem diagrams can be put back into the overall model for a completed detailed model of the study area. While the detailed model shows interactions of energy within the system being studied as well as among the system and the outside energy sources, no mention has been made of the quantity of these flows. This leads to the next step in the energy circuit modeling process, that of model evaluation.

Step 8: Evaluating the Model

While the evaluation of the model can be done at the overall level, it is much simpler to undertake this step at the subsystem level. The interdisciplinary nature of systems tends to make model evaluation difficult; however, working at the subsystem level tends to minimize this problem. For example, evaluation of energy flows and storages in the natural system can be based on the wealth of information found in ecological literature, just as information on agricultural systems can be found in the agricultural literature. Care should be taken to see that all the flows of energy adhere to the laws of thermodynamics. That is, energy may not be created or destroyed in any process, and some energy must be degraded in any real process. The first law simply states that the sum of the flows into and out of any interaction must be equal, while the second law or principle requires that all interactions must have heat sinks or losses of unusable degraded energy. It is suggested that a separate evaluation table be set up for each of the subsystems being studied. It is necessary to include all storages and flows of energy identified on the diagram in this table. It is also necessary to document the calculations and relevant references for each of the flows and storages.

Step 9: Translating Energy Circuit Diagrams to Differential Equations

The energy circuit model shown in Fig. 4 is actually a complex set of differential equations in diagrammatical form. The storage symbol in the diagram represents a state variable where each flow into the storage is a positive term in the equation and each flow out of the storage is a negative. After the equations have been written for each of the subsystems, the next step in the process can occur, which is the simulation of the model.

Step 10: Simulating the Energy Circuit Language Model

Simulation of the dynamic behavior of the model of the system has several uses. Possibly the most important use is to provide a clearer understanding of the system being studied. Model simulation can also be used to generate various alternatives resulting from some changes in an external energy source, such as a decrease in the availability of fossil fuels. Such future scenarios provide a wide range of possibilities, which are of considerable importance to decision makers who must plan for an uncertain future.

Several methods of continuous system simulation have been successfully used to study the dynamic properties of energy circuit language models. The two most popular are: 1. development of analogous electrical circuits through the use of an analog computer; and 2. numerical approximation using the digital computer. Each simulation methodology has significant advantages and disadvantages, but because of the almost universal availability of digital computers, numerical approximation is the most preferable.

Step 11: Validation of the Model

The results of the simulation model provide a useful tool for validation. The simulation of the behavior of the system makes possible the comparison of the response of the model to observed changes in the system under study. Unfortunately no specific test for the validity of large-scale simulation models is known. Some researchers have attempted to use statistical methods such as correlation analysis to statistically compare the model behavior to the behavior of the system under study, however, the results of such test appear inconclusive.

Possibly the most useful validation method is thoroughly testing the model by introducing parameter changes and observing the response of the system. In many cases similar parameters changes may be observed in the system under study such that the results of the two may be compared.

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