367

EMBODIED ENERGY, FOREIGN TRADE, AND WELFARE OF NATIONS

by

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Abstract

A theory of embodied energy and energy quality is considered in relation to logarithmic and semi-logarithmic expressions of systems hierarchies. Energy transformation ratios are thus related to data on energy spectra. The embodied energy of commodities in foreign trade provide a measure of trade contribution to the economic vitality of nations.

Imbalance of embodied energy provides a measure of the feedback service, which constitutes a balance of service and position in an international hierarchy of nations.

Future patterns are considered in relation to the frenzied consumption model of the world human economy. Peace may be fostered by balancing embodied energy flows.

I. Introduction

Understanding and predicting the vitality of national economies and the international relationships of these economies is a major objective of traditional economics. More recently, energy analysis approaches purport to provide more fundamental understanding by recognizing the existence of deterministic principles in economic systems where most practitioners deny principles other than free human preference. This is an exposition of alternative theory of the environmental role in economic vitality, welfare of nations and role of international trade. Some critics may object to a reinvention of economics, but it may be necessary if it supplies missing ingredients. A summary of traditional economic models for evaluating foreign trade and its effect on a nation's welfare is given by Dixit and Norman (1).

Theory for understanding, predicting, and improving the welfare of nations often uses institutional structure, capital availability, labor, balance of payments, and other properties of national economies, and international monetary relationships as determinants. From time to time in the past, welfare and relationships of nations have also been related to resources of energy and environment, sometimes called externalities. Difficulties in evaluating impact of these resources beyond empirical prices and individual evaluations have not made it easy to show how economic vitalities, gross national products, and welfare are resource dependent. The money paid in trade is often regarded as a measure of raw resource value to the economies involved in that trade, but those measuring the real work of these resources regard this as faulty. Many sectors of economic opinion regard the external resources as unimportant in determining national economies.

However, there is a set of alternative theories for the role of resources in the vitality of national economies being generated from outside traditional economics using energy

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as a metric to measure the relative contribution of resources to real value generating work. Whereas early efforts to do this in the great depression were not very successful because of lumping of energy of different qualities (i.e., coal, electrical, human service, solar, etc.) (2). the concept of embodied energy and energy quality (3), now allows the utility of various resources to be predicted in terms of the work required to generate the economic input to the economy.

II. Concepts and Methods

Useful work

Work may be defined in a generalized way as the energy transformed from one state to another. For example, there are energy transformations of sunlight to organic matter, coal to electricity, food to human service, etc. Those transformations which are useful are those that feed back in the economy in which they are used, acting with multiplier actions so that their effect at point of use may be as great as the energy originally transformed in their making. Generally, energy transformation that do not feed back (i.e., are not useful) are not retained by systems except in small degree as part of variation, education, or investigation. A typical web is given as Fig. 1.

In the definition of useful there is opportunity for argument. Here usefuel means contributing to processing of more total resource through feedback. Many economists would define useful as human preference. However, if social institutions prefer in the aggregate what produces more, then the long range outcome is the same.

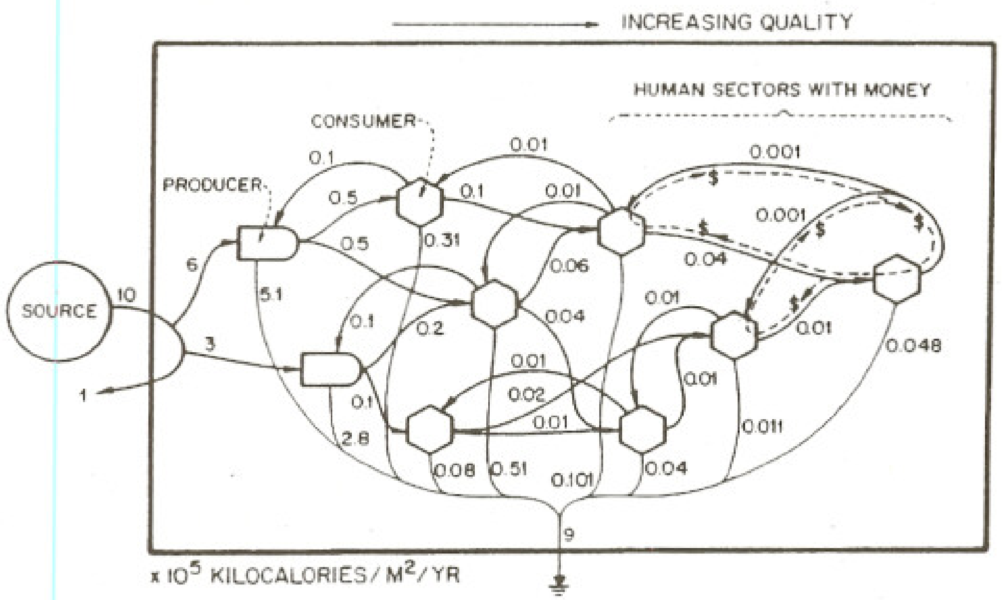


Figure 1. Diagram of the way energy is successively transformed, decreasing in actual value but increasing in quality from left to right. Dollars circulate more in the human part to the right. A source is a circle; other symbols are: producers on the left and hexagonal consumers on the right. Dollar flows are dashed.

Energy Transformation Ratio Measuring Energy Quality

The energy transformation ratio between the one type of energy and another (Fig. 2) measures the amount of the second type of energy relative to the first. This ratio becomes a property interesting to open system thermodynamics if the transformation is being at that optimum speed for maximum power transformation. (That there is an optimum loading, speed, and efficiency for maximum power is now well established (4, 5)). The energy transformation ratio in this idealized case is the maximum useful power through that process if the work transformation has the amplifying feedback indicated above.

In the world of real food chains in ecology, or commodity webs in economics, the successive transformations of work, each feeding forward and back, become less and less in actual energy, but with higher and higher quality in the sense of their amplifier feedback role per unit energy (see Fig. 1). The ratio of information to actual energy decreases as transformations are added (6). Therefore, the energy quality is measured by the energy transformation ratios at maximum power loading. The transformation ratios are not easily measured because almost all transformations that are part of a real web receive a feedback amplifier in addition to low quality input and medium quality output (see Figs. 1 and 2). Often these control actions are left out of energy analysis diagrams. If, however, the feedback is a byproduct of the same energy transformation then it is a consequence of the same energy output rather than an independent input and can be omitted in calculating the ratio. Thus, it is possible to estimate the energy transformation ratios between one energy flow and another in a web with single dominant source of energy such as the world web running on sunlight (7). Calculations of energy transformation ratio between sun, wind, rain, rivers, etc., can be calculated (8). Whereas energy units are in joules or Calories (9), the energy transformation ratio is between two kinds of energy.

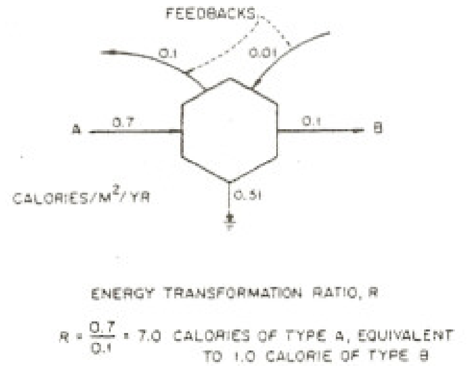


Figure 2. Role of work process within an ecologic, geologic or economic web showing energy transformations and including the usual feedback control amplifier loop. Energy transformation ratio R is the ratio of inputs to output, omitting those feedbacks that are byproducts of the same inputs. Numbers are actual Calories.

Energy Transformation Ratio and Spectral Graphs

The energy transformation ratio R may be related to many graphs of data on hierarchical relationships as given in Fig. 3. Examples are age classes in trees, food chains in estuaries, Horton stream hierarchies in hydrology, and possibly income distribution graphs in people during agrarian periods. The energy transformation ratio is logarithmically related to the number of successive steps in a semi-logarithmic plot where energy on the left is processed to generate energy to the right. In other words, there is a means of converting data from many fields to energy transformation ratios.

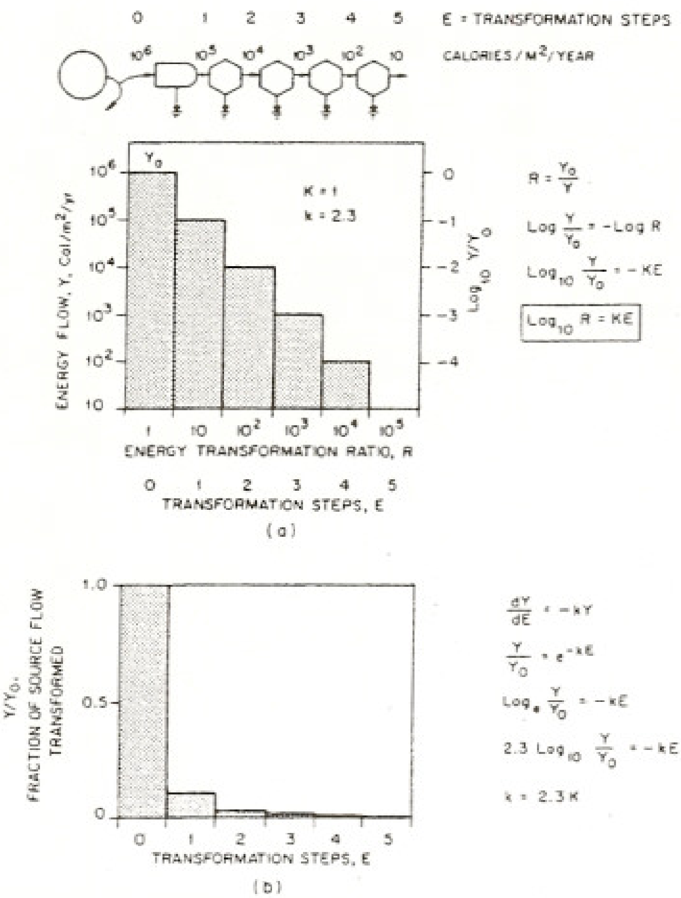


Figure 3. Spectrum of successive energy transformations where energy source is a dominant single source on the left. (a) Log of energy flows as a function of transformation steps, E (energy transformation ratio on log scale); with definition of energy transformation ratio R in terms of parameters of observed spectral distributións; (b) normalized energy flow for each transformation stage, E.

Embodied Energy

If the various energy flows are all converted to equivalents of the same type that generate them, under conditions believed to be operating at optimum efficiency for maximum useful power delivery, then all of the pathways are comparable in the sense of the energy of one type required to generate them. This concept of embodied energy puts resources outside and inside the economy on a similar basis in terms of what is actually required to do the work (8).

Alternative Concepts of Embodied Energy

There is more than one type of embodied energy. The one most familiar to readers of Science is one in which the energy outside a web is allocated within the branching pathways of the web so that they add up to the total embodied energy coming into the web from outside (9, 10, 11). This is shown in Fig. 4c and is a different concept from that used in this paper. The concept here retains the meaning that the embodied energy is what is required to do the work (at maximum power). Byproducts of a work transformation have the same embodied energy because they could not be generated with less. As shown in Fig. 4b, the undivided values of embodied energy (7, 12, 13) are the same within closed loops where every byproduct is used to improve the efficiency and power of the whole web. Needless to say, with this definition one does not add together the byproduct branches when they converge again. The reason for using this concept of embodied energy by input-output calculations or other means, is that partition is arbitrary, leads to values smaller than necessary to do the work, and is often done in proportion to something like dollars or actual energy, neither of which are proportional to the work actually

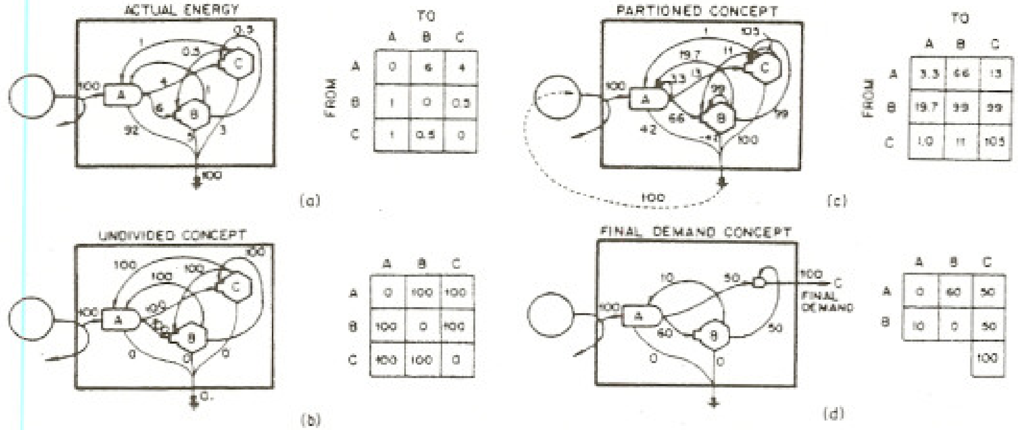


Figure 4. Alternative concepts of embodied energy. Solar Calories driving the web are allocated differently to pathways in the web. (a) Actual energy; (b) concept of undivided embodied energy assigns the same embodied energy to branching pathways where the flows are byproducts (8); (c) concept of partitioned embodied energy used by input-output energy analysis assigning only part of the necessary energy for a process to a pathway within the web (9, 10, 11); (d) concept of partitioned embodied energy used by input-output analysts orienting only to final demand omitting labor entirely.

required. There may be uses for the partioned embodied energy, but not for assigning the actual energy of the initial type required. Much of the confusion in the energy analysis field is because of the different concepts of embodied energy.

Relation of Embodied Energy to Economic Process

As shown in Fig. 1, the externalities driving the economy can be expressed in embodied energy of one type as a common denominator metric using energy transformation ratios. Although sometimes questioned by economists, no one with scientific training would question that if all the energy was turned off the economy would stop as soon as its storages had run out. In other words, the amount of economic process is a function of the embodied energy where embodied energy was defined as above (energy of one type required to do useful work).

Embodied Energy to Evaluate Externalities

In order to evaluate externalities, first in energy metric and then in dollar flow of the using economy, a proportion can be given shown in Fig. 5 (8). The percent that a particular resource contributes to the total embodied energy use of a nation is the proportion of the gross national product due to the work of that externality. Thus, inputs to an economy, such as agricultural products, forest products, minerals, fuels from within the country, or those brought in with trade, which includes human manufactured goods and services, may all be given in the dollars proportional to the work contribution of these externalities estimated from embodied energy.

Embodied Energy in Environmental Products

The embodied energy in environmental products such as agricultural products, forestry products, fishery products, and mining, are the result of work transformations, first of environmental processes and then of human and technological operations. Microenergy analyses of these production systems are done so as to determine the embodied energy per unit of product (all in units of the same type of energy, such as sunlight). Although progress has been made in reducing the confidence limits, there are still many practical difficulties getting accurate numbers:

1. Is the energy transformation ratio between sunlight and fossil fuels correct? It has been determined by several indirect ways with a large range of values (Lavine, 1983)(8).
2. Is a microanalysis of some typical production system such as a sheep paddock representative enough of the sheep production of a whole country to estimate embodied energy in such products as mutton and wool?

Embodied Energy Allocation in Dividing a Flow

Whereas the undivided concept of embodied energy does not divide the embodied energy among byproduct flows of different quality, it does allow dividing up the embodied energy among branches of the same quality. In Fig. 6, for example, compare the allocation of embodied energy (and way of diagramming) a byproduct branching and a branching of a flow of one product.

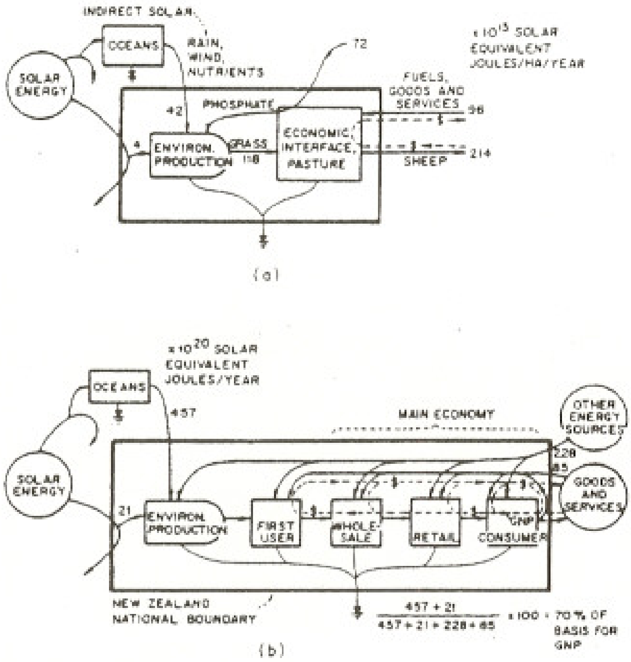


Figure 5. Embodied energy flow of externalities for evaluating environmental work and its use to estimate dollar part of the GNP. (a) Sheep pasture system of New Zealand with embodied energy evaluation of environmental work; (b) proportion of total work used to determine proportion of GNP due to environmental resources.

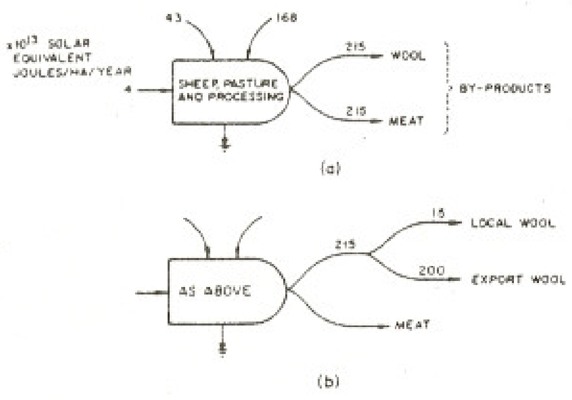


Figure 6. Comparison of embodied energy flow of byproduct branching and branching of a flow of one quality. (a) Wool and meat have same embodied energy; (b) dividing wool flow divides embodied energy (25).

Human Service as an Aggregated Flow of One Quality

In macroeconomic models the total human service may be regarded (in first approximation) as a feedback of the same quality and of sufficient flexibility that it may be treated in branching as a dividing up of the total embodied energy. In this approximation, embodied energy is directed in proportion to the dollars paid for this service.

Dollar to Energy Relationships

Actual dollars tend to be concentrated in their circulation at the terminal end of a web (final demand sectors, urban sectors, etc.) (Fig. 1). In fact, there are no dollars circulating in the environmental sectors. Actual energies (without regard to quality) tend to be concentrated at the low quality solar energy of the system. Thus, the ratio of actual energy to dollars varies throughout the web.

However, in as much as there is an overall energy budget expressable in embodied calories of one type and an overall dollar circulation expressed as gross national product, there is an overall ratio of dollar flow to energy flow. This ratio may be used to allocate the feedback of embodied energy in human service based on the dollar flow paid (14). For New Zealand, dividing the gross national product by the embodied energy used within the country, produces a ratio of 3.0×10^{12} solar equivalent joules per dollar in 1980 (25).

Balance of Payments Using Money

Exchange of money tends to be balanced in foreign trade as is well known. When an imbalance of one or two percent develops in foreign trade so that one country gets more money than the other, the relative values of the currencies change as buyers and sellers of currencies transact until the balance is again achieved.

III. Energy and Public Policy in New Zealand

New Zealand and its public policies regarding foreign trade may be used to illustrate the concepts of embodied energy evaluation and the making of recommendations for increased economic vitality (15, 16).

It is a strong dogma in national planning of many countries to try to maximize the balance of foreign trade as measured by relative balance of payments (in monetary units). For example, stated public policies of New Zealand in recent years advocate various measures for sending out more products so as to generate more foreign income with which to buy fuels and capital goods for growth, etc. (15).

Balance of Payments Using Embodied Energy of One Quality

A balance of payments may also be computed for the imports and exports in units of embodied energy of one quality. This is done in Fig. 7 for New Zealand in 1978. Although the imbalance of payments in dollars is small, there is a larger imbalance in trade as expressed in embodied energy of one type. In other words, the means for useful work to augment an economy is much larger going out as that coming in (17).

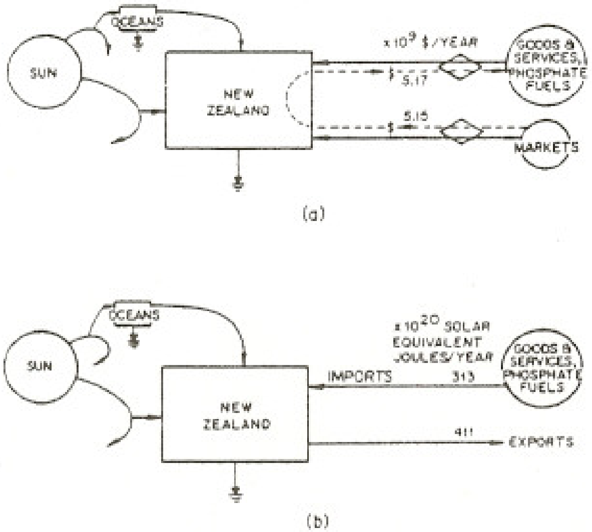


Figure 7. Balance of foreign trade of New Zealand, 1980. (a) Balance of dollar payments; (b) balance of embodied energy in solar equivalents. Energy/dollar ratio in N.Z. in 1980 was 30×10^{12} SEJ/$; in U.S., 2.6 10^{12} SEJ/$.

Embodied Energy Theory of Economic Welfare

Since economies depend on useful work done, the nations receiving more embodied energy than they deliver have more useful work done, more real GNP, a higher standard of living, and more products for which the population can exert their personal preferences and price controls. (This is not to say, this is the only factor).

Buying Power and Embodied Energy to Dollar Ratio

It is well known that the dollar, although exchanged according to marketplace between one country and the next, may have much different buying power in terms of basic commodities or even of all commodities (19). The embodied energy to dollar ratio measures this. New Zealand, for example, has a higher embodied energy per dollar than the United States. This is because its quota of environmental energy is larger in the form of rains, winds and mountain-climatic actions which promote very rapid growths of pasture products and forestry products.

Example of New Zealand Aluminum and Hydroelectric Power

The Bluff Aluminum plant in Invercargill, N.Z., uses hydroelectric power to form aluminum ingots sent to Japan. Great pride has been publicly expressed by government and economic advisors because 52 million dollars of import dollars are incoming to help balance of payments (20, 21).

In Fig. 8 is shown an estimation of the embodied energy exported in the aluminum ingots (embodied electrical energy which in turn is embodied solar energy). The loss of potential economy given to Japan instead of to New Zealand is 0.83 billion dollars.

Looking at this situation in a microeconomic way generates similar understanding: If this export was shut down, the price of aluminum in New Zealand and the price of electricity in New Zealand would both tend to collapse. Eventually, investments from all over the world would rush in to use the cheap resources generating finished products from electricity and/or aluminum within New Zealand making jobs, increasing exports of cheap finished goods with much greater total effect on the local economy.

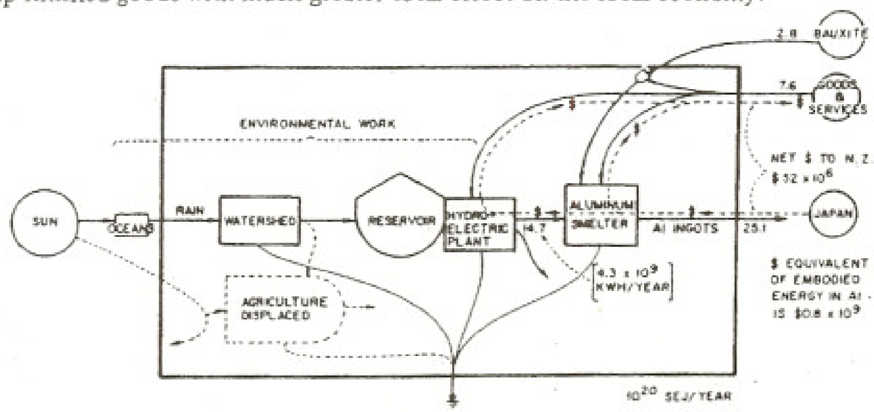


Figure 8. Dollar and energy exchange in aluminum export from New Zealand in 1977. Data from N.Z. Yearbook (22). Calculations (25). Ingots: $(25.1 \times 10^{20}\ \mathrm{SEJ/y})/(3.0 \times 10^{12}\ \mathrm{SEJ/\$}) = 0.83 \times 10^{9}$ $/y.

Maximizing Economy of New Zealand

Using embodied energy measurements, it is quite clear why the export of wool, mutton, wood, and other products between 1910 and 1973 caused a net balance of economic welfare, prosperity, and rapid growth. In those days, although the embodied energy in the agricultural products was much higher than in the money received back, they could buy from oil suppliers an even better bargain of embodied energy, paying as little as 1/40th of the real work equivalents in money for the oil. It was only when the OPEC price jumps came in 1973 that the embodied energy balance went negative. The real GNP declined. Being locked into the old policy of fostering more exports because it worked earlier, they drove themselves further and further down, helping Japan and other raw importers more and more.

The remedy from the point of view of generating prosperity in New Zealand is to reestablish a net balance of embodied energy in foreign trade. This means reducing the shipments out of high embodied energy products, let the prices of these fall at home, let the investments come in to use the raw products for finished goods, and let the diversification of land use progress away from export cash crops that export too much embodied energy. In this way, New Zealand's subsidy of other countries (England, U.S., Japan, etc.) will be replaced with a more equal trade.

Relationship of Foreign Trade Networks to Hierarchical Energy Webs

In Fig. 9 one nation (on the left) is shown in the role of a rural supplier of raw products that converge to a nation with urban centers, industrial manufacture and human concentration (on the right). Figure 9a shows an energy pathway diagram of the exchanges and Fig. 9b a spatial representation of the converging and diverging aspect of the system.

From studies of similar configurations in smaller systems we may regard the relationship as a symbiosis if the work done by the rural county for the urban center is equivalent to the work of the center for the rural county. With our present world trade policies, the prices and flows of money are relied on to make the feed forward and feedback symmetrical as to real useful work done and welfare of both subsystems.

According to the theory of this paper, however, money evaluation is erroneous, since the money is paid to people for their services and not to the environmental processes and storages that supply the work. Therefore, the money paid to the rural county is a fraction of the work contribution of the rural county, whereas the money paid to the city is the full representation of the fraction of the work culminated there. In other words, where externalities are being processed, as in a rural country trading with a more urban industrial center, balance of payments does not represent appropriate payments to the rural area from the center. The outrage at the results of such a system eventually produced the anti-colonialist movement which still has not run its course. That the difficulty was not understood caused enormous ill feeling. The difficulties with monetary-based trade have been analyzed by many using economic measures and more traditional evaluations of the causes and consequences (23, 24).

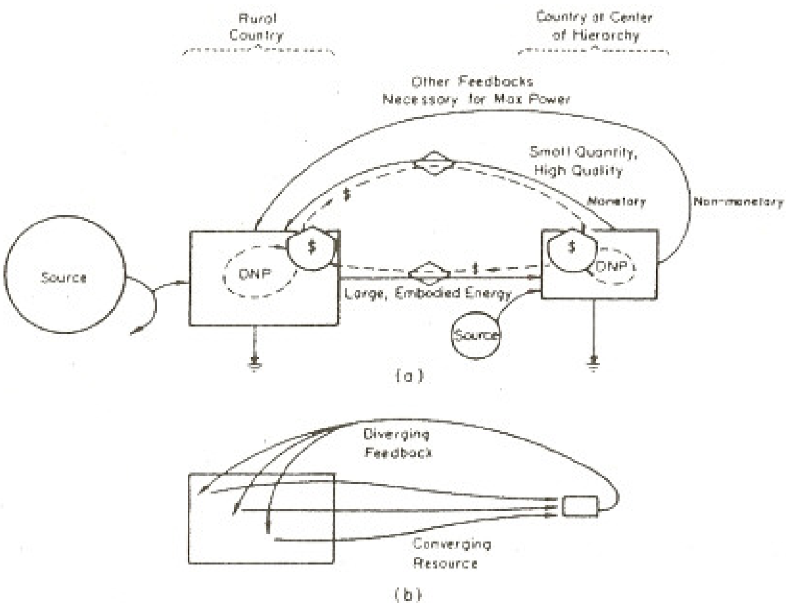
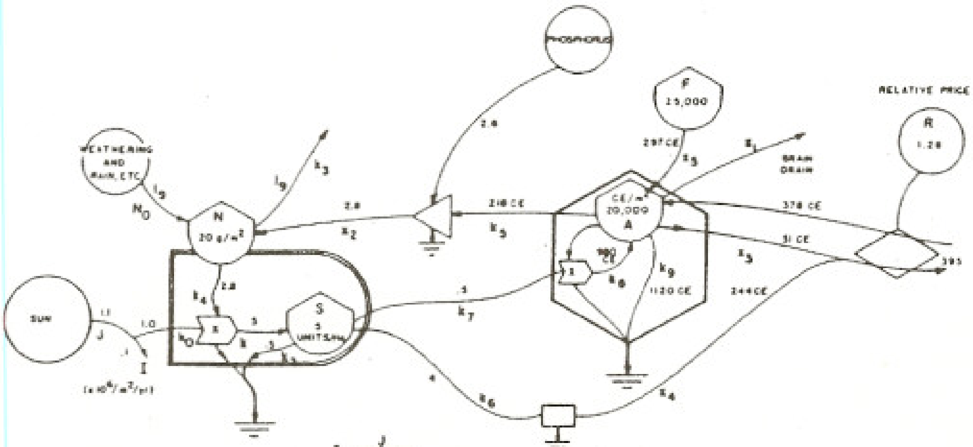


Figure 9. Relationships of country supplying raw, rural products to one receiving raw goods and supplying manufactured products and services.

Symbiosis of Nations

If balance of currency payments does not balance exchange, what does? As shown by the upper pathway in Fig. 9, the rural contributor may receive back enough high quality goods and services so that the ultimate balance of embodied energy is equal. These may be in form of military protection, education, ideas, cultural inputs, inventions, etc. If these come back to the rural area without monetary payment, they help to balance the



$$I = \frac{J}{1 + k_0 N}$$

$$N = N_0 - k_3 N - k_4 IN + k_2 A$$

$$A = C + R(k_4 S + k_5 A) + k_8 SA - k_9 A - k_5 A - k_1 A - k_3 A$$

$$S = kIN - k_2 S - k_6 S - k_7 SA$$

$$C = k_5 F$$

Figure 11. Simulations of the model of New Zealand in Figure 10. (a) A historical simulation; (b) continuation into the future; (c) elimination of foreign trade policy. N, soil phosphorus, g/m^2, as an index of farm assets; A, urban assets, coal equivalents embodied per square meter; S, sheep per ha as index of agricultural product storage; F, fuel reserves in New Zealand, coal equivalent joules per square meter; R, embodied coal equivalents received per unit embodied energy export.

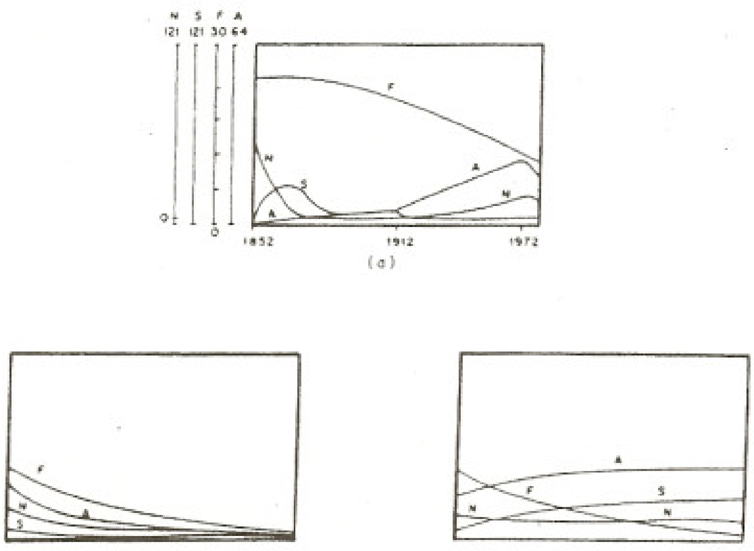


Figure 10. Simulation model of New Zealand with differential equations and values of the storages and pathways used to calibrate coefficients.

embodied energy flow. These products of urban centers have very high embodied energy value and have great amplifier action when they are received.

Over the years New Zealand, like the Falkland Islands, as a supplier to England did receive back from England commensurate non-economic services and military protection, more so because of cultural compatibility than did other British colonies that went independent. Perhaps the degree of imbalance in embodied energy in trading relationships now judged by their balance of payments can be corrected by governments in their trade agreements, hereafter requiring balance of embodied energy. This may introduce more world social justice, more work distribution, and more security from wars because no center can develop excessive power from buying more resources.

A Simulation Model of New Zealand

A small model and simulation helps to show these relationships in another dimension. In Fig. 10 is a model of the essence of New Zealand's economy expressed in embodied energy terms. Phosphorus in soils is a representative of agricultural assets. Flow of embodied energy in sheep production represents agricultural production, its use within New Zealand and its export outside. Urban growth is shown receiving local fuels, goods, services and fuels from exchange of sheep products, and use of urban assets to distribute phosphate fertilizer to all rural areas (New Zealand's geology is very low in phosphorus naturally).

The simulation in Fig. 11 shows a colonization period that plateau's with degradation of soils. Then there is the period of rapid prosperity and growth due to exports with a good balance of embodied energy (sheep products for oil), (the model turns foreign trade on at that time when shipping and refrigeration technology allowed more foreign trade). After 1973 there is a declining economy.

This model was presented to the Ministry of Energy in New Zealand in 1978 (16). When this run is extended beyond 1978 the economy keeps going down.

When exports are terminated in the model and the rural resources allocated to the New Zealand's own urban developments (instantaneously in the model – requiring time for change in land use and diversification in the real world), the economy grows again, leveling some time in the middle of the next century. (This run holds the real price of foreign fuel constant.)

If, however, the price of phosphate goes up sharply, the economy again comes down – a warning as to the effect of another OPEC situation to be expected in a few years. Phosphate has a very high embodied energy per gram.

Validity of Agricultural and Environmental Subsidy

A corollary of this theory is that any use of environmental sectors by human economy requires a feedback to reinforce the rural sector's process and storages. Otherwise these systems are drained and displaced by competing ecosystems of less use to humans. The collapse of various world fisheries and the areas of exotic gorse thorn scrub displacing grazing land over much of New Zealand are examples of pulling a product from a natural work sector without payment so that the resources flow to competing food chains. An environmental sector cannot accept money since it is not a person.

Thus, the conclusion is that there must be a subsidy to the environment in useful work from a using economy in order to maintain a continuing relationship. The amount is calculable from the embodied energy balance. By agricultural subsidy we don't mean payments of cash to farmers to spend on human needs. The return must be directed to rebuilding soils, helping fish food chains, or augmenting natural processes concentrating mineral storages.

In classwork on energy analysis at the University of Florida we have done very preliminary energy balances for thirty countries, each person taking a country. The results are fascinating, in most cases suggesting some kinds of reversal in public policy like that discussed here for New Zealand. Recently embodied energy balances for twelve countries were calculated (25).

The success of embodied energy in predicting and helping to understand economies of nations suggests some general revision in the indeterminancy of economics that comes from a too athropocentric view that humans have absolute free choice. It is a new challenge to sociologists and political scientists to elaborate just how do the energy constraints control the group preferences of human social behavior so that they eventually do what the energy system requires of them for survival.

References

1. A.K. Dixit and V. Norman, 1980. Theory of International Trade. Nisbet, Cambridge, University Press, Cambridge, U.K., 399 pp.
2. A movement in the 1930's attempted to use an energy theory of value, but it had no energy quality concept, and fell into the interesting activist movement called technocracy, advocating elimination of money. Rather instead, theories here suggests that free markets using money are among the means by which economies maximize their utilization of resources, but they are only part of the system and cannot be understood alone.

   At least qualitative theory on energy determinancy of all processes including economic systems has a long history among distinguished scientists and engineers such as L. Boltzmann, W. Ostwald, F. Soddy, A.J. Lotka, K. Hubbert, F. Cottrell, and many others. Review of some of these are included in a book (5).
3. Odum, H.T., 1976. Energy quality and carrying capacity of the earth. (Response at Prize Ceremony, Institute La Vie, Paris.) Trop. Ecol. 16(1), 1–8.
4. A full discussion is given by the author in a new book (5). See also: Odum, H.T., Maximum Power and Efficiency – A Rebuttal. 1983. Ecological Modelling, 20:71–82.
5. H.T. Odum, 1983. Systems Ecology, an Introduction. Wiley, New York, 644 pp.
6. M. Tribus and E.C. McIrvine, 1971. Energy and information. Scientific American. 225:179–188.
7. H.T. Odum, 1978. Energy analysis, energy quality and environment. In: Energy Analysis, A New Public Policy Tool. AAAS Selected Symposium Vol. 9. Ed. by M. Gilliland. Westview Press, Boulder, Colo. pp. 55–87.
8. In this paper embodied energy used is the solar Calories and the energy transformation ratios are between solar Calories and other forms of energy content of various fuels, raw products, minerals, services, etc. Many in energy analysis and thermodynamics refer everything to mechanical work equivalents, now often called exergy. Mechanical work is a moderately high quality work. It is just as feasible to express everything in embodied exergy to indicate the exergy required for every other kind of flow. Solar equivalents are used here since discussions are more on environmental processes. Coal equivalents are often used as a common unit of embodied energy. Uncertainties in value of numerical equivalents between solar and coal energies makes calculations approximate that involve them both. See paper at this symposium by M.J. Lavine. Also see New Transformation ratios including earth heat energies (25).
9. B. Hannon, 1973. Marginal Product pricing in the ecosystem. J. Theoret. Biol. 41:252–267.

10. R.A. Herendeen, 1981. Energy interstates in ecological and economic systems. J. Theoret. Biol. 91:607–620.
11. R. Costanza, 1980. Embodied energy and economic evaluation. Science 210:1219–1224.
12. H.T. Odum, 1971. Environment, Power and Society. Wiley, New York. 331 pp.
13. H.T. Odum and E.C. Odum, (1976) 1980. Energy Basis for Man and Nature, 2nd Ed. McGraw Hill, N.Y., 336 pp.
14. Whereas other embodied energy approaches use dollar energy ratios throughout the web, this procedure uses it only for human service, since only humans are paid money, not machines and externalities.

In recent years the United States has begun to behave more like a rural supplier of raw materials than an urban supplier of technology goods and services. Examples are the outflows of phosphorus, grains, and even coal, which have very high energy advantages to the receivers.
15. W. Duncan, 1981. Energy Planning '81. Ministry of Energy, Wellington, N.Z., 37 pp.
16. H.T. Odum and E.C. Odum, 1979. Energy system of New Zealand and the use of embodied energy for evaluating benefits of international trade in Proceedings of Energy Modeling Symposium, Technical Publication No. 7, New Zealand Ministry of Energy, Wellington, N.Z., pp. 106–167. A revised version with complete calculations and tables was given in 1983 (25) using 1980 data.

E.C. Odum, G.C. Scott and H.T. Odum, 1981. Energy and environment in New Zealand. Joint Centre for Environmental Science, Christchurch, N.Z., 180 pp.
17. An effort to evaluate embodied energy of N.Z. foreign trade with the alternative concept of Fig. 4e (input-output partition was made by Baines *et al.* (18)).
18. J.T. Baines, N.J. Peet, and A.E. Currier, 1981. Indirect energy of New Zealand's foreign trade, 1969–1978. Dept. of Chemical Engineering, Univ. of Canterbury, Christchurch, N.Z. 77 pp.
19. I.B. Kramer, Z. Kennessey, A. Heston, and R. Summer, 1975. A System of International Comparisons of Gross Product and Purchasing Power. John Hopkins U. Press, 289 pp.
20. T.K. MacDonald, 1980. The contribution of Bluff Aluminum smelter to New Zealand's foreign exchange position. N.Z. Institute of Economic Research, pp. 1–4, Wellington, N.Z.
21. P. Van Moeseke, 1981. Aluminum and power: the second smelter report. Economics Discussion Papers. Univ. of Otago, Denedin, N.Z., 45 pp.
22. New Zealand Official Yearbook, 1981. Dept. of Statistics, Wellington, 1040 pp.
23. A. Emmanuel, 1972. Unequal Exchange, a Study of the Imperialism of Trade. Monthly Review Press, New York, 453 pp.
24. G. Corea, 1975. The instability of an Export Economy. Marga Institute, Colombo, Sri Lanka, 374 pp.
25. H.T. Odum and E.C. Odum, ed., 1983. Energy analysis overview of nations. Working Paper, International Institute for Applied Systems Analysis, WP–83–82, Laxenburg, Austria, 469 pp.