EMERGY* EVALUATION

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ABSTRACT

The procedure for making an EMERGY evaluation of a system is explained using a Monterrey Pine Plantation in New Zealand as an example. Included is an energy systems diagram, EMERGY evaluation table, and table of EMERGY indices for interpretation. The net EMERGY yield ratio of plantation wood was 2.0, much less than for fossil fuels now available. The EMERGY investment ratios were less than one, indicating that the system was economical. Exchange ratio on the market was 3.6 times more EMERGY to the buyer than the seller.

INTRODUCTION

EMERGY evaluation is a technique for evaluating on a common basis various flows of a system, including those free from environment and those purchased from the economy. At the ecological economics symposium at the meeting of the Ecological Society of America at San Antonio, EMERGY evaluation was explained, and areas of new application now under research were discussed such as the Valdez oil spill, the Persian Gulf war, equity in foreign trade, and biodiversity in rain forests. This paper presents the method of making an evaluation using a forestry example.

In a nutshell, EMERGY evaluation of a systems is done by making an EMERGY Analysis table that includes the inputs to the system, the products, and those items within the system which may be of special interest. Solar EMERGY of each item in the table is calculated. Then various sums, quotients and indices are calculated that give insight on the role of the system in the environment and the economy. By calculating what is required to make a product in units of the same common source, a common measure of work and wealth is found that includes both the work of nature and that of human services in the economy.

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*spelled with an "M"; capitalized to avoid confusion with energy.

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DEFINITIONS

EMERGY, spelled with an "M" is defined as all the available energy that was used in the work of making a product expressed in units of one type of energy. The unit of EMERGY is the emjoule. If the type of EMERGY is solar, then the unit of solar EMERGY is the solar emjoule. The concept was used in 1967b and renamed in 1983 (Scienceman, 1987).

Transformity is defined as the EMERGY of one type required to make a unit of energy of another type. It is the quotient of EMERGY divided by the energy. The unit of transformity is emjoule per joule. If the type of EMERGY is solar, then the unit of solar transformity is solar emjoule per joule, abbreviated sej/J. See example in Figure 1. The concept was defined in 1971 and renamed in 1983 (Odum,1971, 1988).

PROCEDURE FOR MAKING AN EMERGY EVALUATION OF A SYSTEM

EMERGY evaluation includes the following six steps, each of which is explained further in paragraphs that follow:

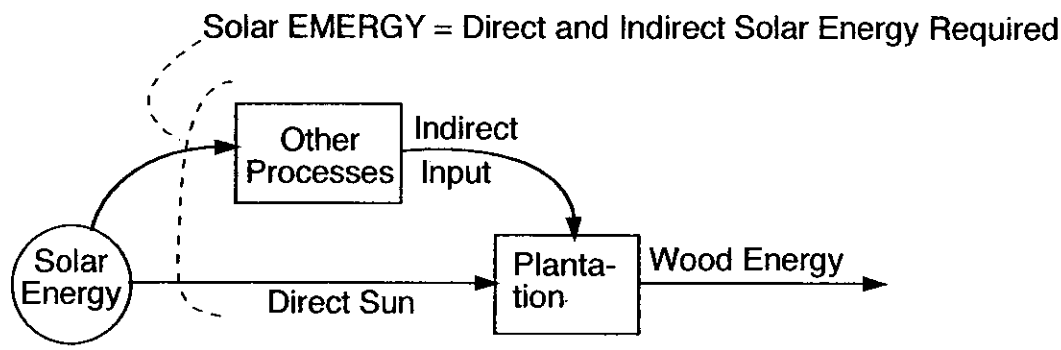
(A) First a detailed energy systems diagram was drawn as a way to gain an initial network overview, combine information of participants, and organize data-gathering efforts. Symbols of the energy systems language are given as Figure 2.

(B) Next, an aggregated diagram was generated from the detailed one by grouping components into those believed important to system trends, those of particular interest to current public policy questions, and those to be evaluated as line items.

(C) An EMERGY analysis table was set up to facilitate calculations of main sources and contributions of the system. Raw data on flows and storage reserves were evaluated in EMERGY units and macroeconomic dollars to facilitate comparisons and public policy inferences. See example in Table 1.

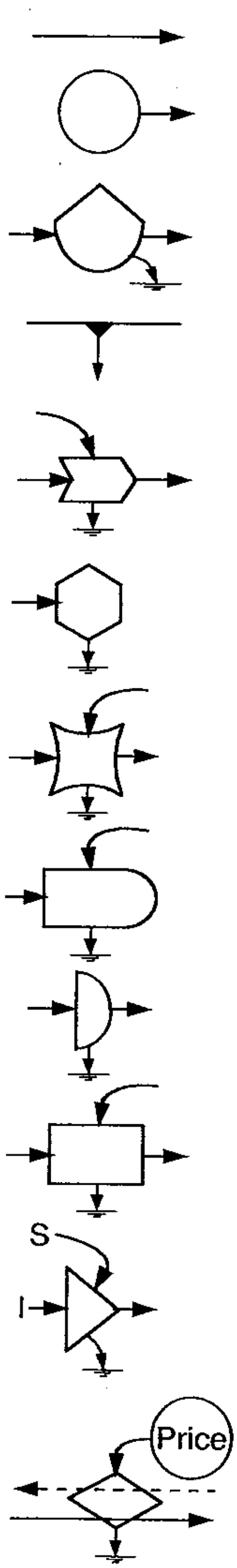
(D) From the EMERGY analysis table EMERGY indices were calculated to compare systems, predict trends, to suggest which alternatives will deliver more EMERGY, which will be more efficient, and which will be successful. See examples in Table 2.

(E) For some systems a microcomputer simulation program was written to study the temporal properties of an aggregated model. The program is



$$\text{Solar Transformitiy of Wood} = \frac{\text{Solar EMERGY Required}}{\text{Wood Energy}} = \frac{\text{1011 E12 sej/yr}}{\text{1.506 E11 J wood/yr}} = \text{6720 sej/j}$$

Figure 1. Definition of solar transformity with pine plantation example (Table 2).



Energy circuit. A pathway whose flow is porportional to the quantity in the storage or source upstream.

Source. Outside source of energy delivering forces according to a program controlled from outside; a forcing function.

Tank. A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable.

Heat sink. Dispersion of potential energy into heat that accompanies all real transformation processes and storages; loss of potential energy from further use by the system.

Interaction. Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both; control action of one flow on another; limiting factor action; work gate.

Consumer. Unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow.

Switching action. A symbol that indicates one or more switching actions.

Producer. Unit that collects and transforms low-quality energy under control interactions of high-quality flows.

Self-limiting energy receiver. A unit that has a self-limiting output when input drives are high because there is a limiting constant quality of material reacting on a circular pathway within.

Box. Miscellaneous symbol to use for whatever unit or function is labeled.

Constant-gain amplifier. A unit that delivers an output in proportion to the input but changed by a constant factor as long as the energy source S is sufficient.

Transaction. A unit that indicates a sale of goods or services (solid line) in exchange for payment of money (dashed line). Price is shown as an external source.

Figure 2. Symbols of the energy language used to represent systems (Odum, 1967, 1983).

Table 1
EMERGY Analysis of Pinus Radiata Plantations in New Zealand

Note	Item	Raw Units	Transformity sej/unit	Solar Emergy E12 sej	Macroeconomic Value* 1983 US $
A	Sunlight	5.14 E13 J	1	51.4	23.0
B	Rain transpired	3.16 E10	1.6 E4/J	506.0	230.0
C	Soil used	2.1 E7	6.3 E4/J	1.3	0.6
D	Phosphate added	4.84 E6	4.4 E7/J	213..0	97.0
E	Fuel used	1.79 E8	6.6 E4/J	12.0	5.0
F	Services	57 1978 $	4.6 E12/$	262.0	119.0
G	Annual Yield	1.507 E11	6.7 E3/J	1012.0	460.0

* EMERGY flow in column 3 divided by 2.2 solar emjoules/$ for U.S. in 1983; analysis from IIASA report (Odum and Odum, 1983). Harvest after 24 years growth.

A Costs for 1978 from D.J. Mead; mean insolation 333.65 Langleys per day (Lisle, 1960)
$(5.1 \text{ E9 J/m}^2\text{/y})(1\text{E4 m}^2\text{/ha}) = 5.14 \text{ E13 J/ha/y}$

B Rain used per year: 2.06 rain - 1.42 m runoff = 0.64 m^2 (Toebes, 1972))
$(0.64 \text{ m}^3/\text{m}^2)(1 \text{ E4 m}^2/\text{ha})(1 \text{ E6 g/m}^3)(4.9 \text{ J/g}) = 3.16 \text{ E10 J/ha/y}$

C Phosphate used, 2 T/ha/24 y.
(0.083 T/ha/y)(1 E6 G/T)(58.3 J/g) = 4.84 E6 J/y

D Liquid fuels used per cubic meter of wood from New Zealand Ministry of Forestry for 1981: logging, 52 E6 J/m^3; transport 130 E6 J/m^3; loading, 33 E6 J/m^3; and total 215 E6 J/m^3.
$(215 \text{ E6 J/m}^3)(20 \text{ m}^3\text{/ha/24 y}) = 1.79 \text{ E8 J/ha/y}$

E Data on services in 1978 New Zealand $ supplied by D.J. Mead: Fertilizer, $205; roads, $73; land preparation, $60; planting, $60; stock, $33; restock, $20; first thinning, $60; second thinning, $45; administration, $480; cutting and roads, $334; total $1364/ha/24 yrs; $57/ha/y.
($57/ha/y)(4.6 E12 sej/$) = 262 E12 sej/y
For planting and fertilizing only
($1036/24 y)(4.6 E12 sej/$) = 199 E12 sej/y

F Yield is 10 T dry/ha/y when averaged over one 24 year cutting cycle.
(10 T/ha/y)(1 E6 g/T)(3.6 kcal/g)(4186 J/kcal)
= 1.507 E11 J/y in wood harvest.

used as a controlled experiment to study the effects of varying one factor at a time. Insights on sensitivities and trends are suggested from the computer graphs. Algorithms may be included that calculate stored EMERGY and solar transformities, given those of the input sources.

(F) Models, evaluations, and simulations may be used to consider which alternatives generate more real contributions to the unified economy of humanity and nature.

(A) Detailed Energy Systems Diagram

For understanding, for evaluating, and for simulating, our procedures start with diagramming the system of interest, or a subsystem in which a problem exists. This initial diagramming is done in detail with anything put on the paper that can be identified as a relevant influence, even though it is thought to be minor. The first complex diagram is like an inventory. Since the diagram usually includes environment and the economy, it is an organized impact statement.

The following are the steps in the initial diagramming of a system to be evaluated:

1. The boundary of the system is defined.

2. A list of important sources (external causes, external factors, forcing functions) is made.

3. A list of principal component parts believed important considering the scale of the defined system is made.

4. A list of processes (flows, relationships, interactions, production and consumption processes, etc.) is made. Included in these are flows and transactions of money believed to be important.

5. With these lists agreed on as the important aspects of the system and the problem under consideration, the diagram is drawn on the blackboard and on large sheets of paper.

<u>Symbols:</u> The symbols each have rigorous energetic and mathematical meanings (Figure 2) that are given elsewhere (Odum, 1983). An example of a system diagram involving both nature and the human economy is given in Figure 3.

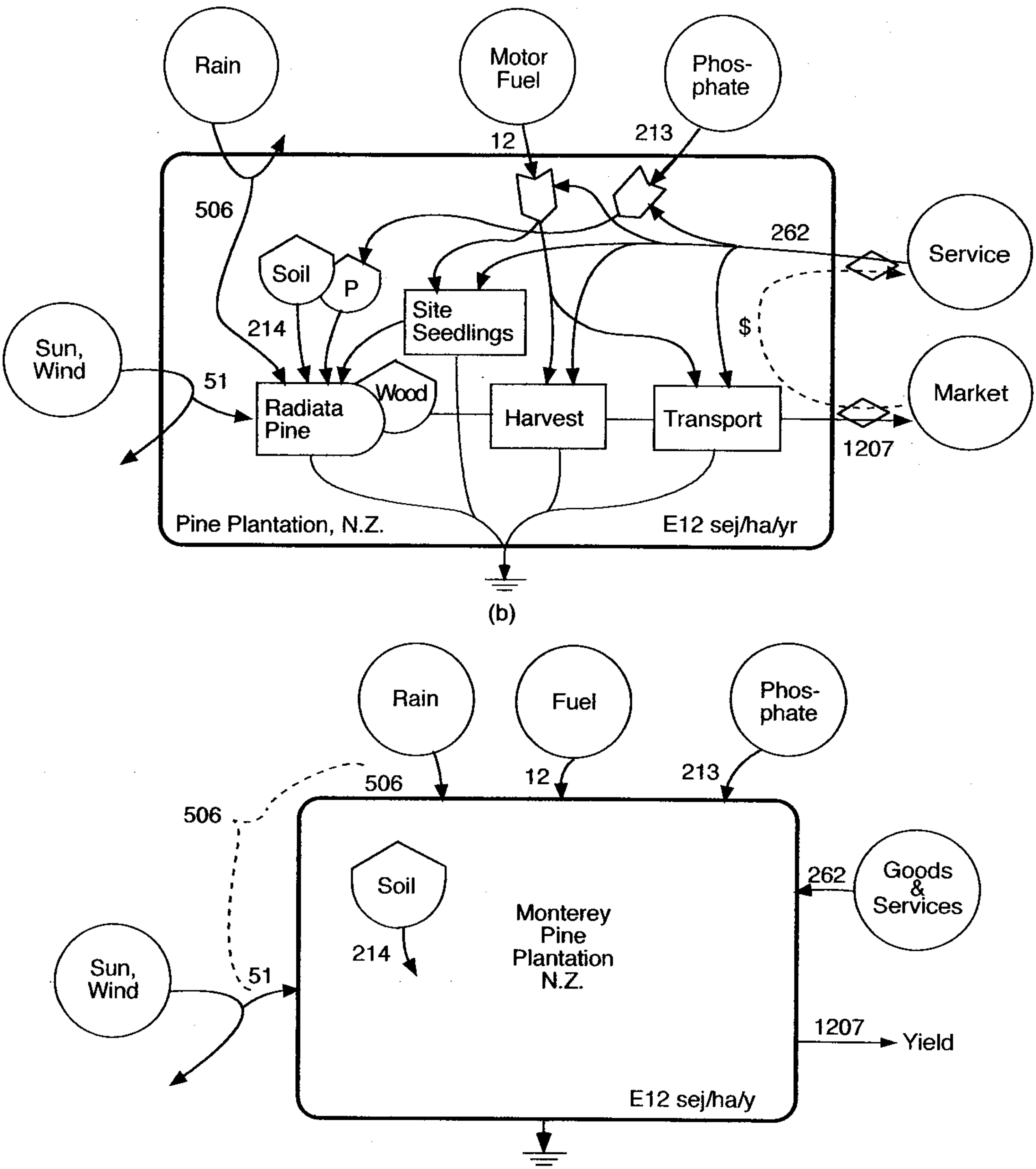


Figure 3. Energy systems diagrams of Monterrey Pine plantations in New Zealand evaluated in Table 1. For energy systems symbols see Figure 2. (a) Partly aggregated systems diagram; (b) summary diagram.

System Frame: A rectangular box is drawn to represent the boundaries that are selected.

Arrangement of Sources: Any input that crosses the boundary is an energy source, including pure energy flows, materials, information, the genes of living organisms, services, as well as inputs that are destructive. All of these inputs are given a circular symbol. Sources are arranged around the outside border from left to right in order of their energy quality, starting with sunlight on the left and information and human services on the right.

Pathway Line: Any flow is represented by a line including pure energy, materials, and information. Money is shown with dashed lines. Lines without barbs flow in proportion to the difference between two forces; they may flow in either direction.

Outflows: Any outflow which still has available potential, materials more concentrated than the environment, or usable information is shown as a pathway from either of the three upper system borders, but not out the bottom.

Adding Pathways: Pathways add their flows when they join or when they go into the same tank. Every flow in or out of a tank must be the same type of flow and measured in the same units.

Intersection: Two or more flows that are different, but are both required for a process are drawn to an intersection symbol. The flows to an intersection are connected from left to right in order of their transformity, the lowest quality one connecting to the notched left margin.

Counterclockwise Feedbacks: High-quality outputs from consumers such as information, controls, and scarce materials are fed back from right to left in the diagram. Feedbacks from right to left represent a loss of concentration because of divergence, the service usually being spread out to a larger area.

Material Balances: Since all inflowing materials either accumulate in system storages or flow out, each inflowing material such as water or money needs to have outflows drawn.

(B) Aggregated Diagrams

Aggregated diagrams are simplified from the detailed diagrams, not by leaving things out, but by combining them in aggregated categories. See example in Figure 3b.

Simplified diagrams have the source inputs (cross boundary flows) to be evaluated: environmental inflows (sun, wind, rain, rivers, and geological processes); the purchased resources (fuels, minerals, electricity, foods, fiber, wood); human labor and services; money exchanges; and information flows. Exports are also drawn. Initial evaluations may help in deciding what is important enough to retain as a separate unit in the diagram.

Inside components include the main land use areas; large storages of fuel, water, or soil; the main economic interfaces with environmental resources; and final consumers. Interior circulation of money is not drawn, but all the major flows of money in and out of the systems are shown.

(C) Emergy Analysis Table

An EMERGY analysis table is prepared with 6 columns with the following headings:

1 Note	2 Item	3 Raw Data	4 Transformity	5 Solar EMERGY	6 Macro- economic $

If the table is for flows, it represents flows per unit time (usually per year). If the table is for reserve storages, it includes those storages with a turnover time longer than a year.

Column number one is the line item number, which is also the number of the footnote in the table where raw data source is cited and calculations shown.

Column number two is the name of the item, which is also shown on the aggregated diagram.

Column number three is the raw data in joules, grams, or dollars derived from various sources.

Column number four is the transformity in solar emjoules per unit (sej/joule; sej/gram; or sej/dollar, see definition below). These are obtained from previous studies.

Column number five is the solar EMERGY. It is the product of columns three and four.

Column number six is the macroeconomic value in macroeconomic dollars for a selected year. This is obtained by dividing the EMERGY in column number five by the EMERGY/dollar ratio for the selected year. The EMERGY/dollar ratio is obtained by dividing the gross national product by the total contributing EMERGY use by the combined economy of man and nature in that country that year. These are obtained from EMERGY analysis of national systems as summarized in Figure 4. See published examples (Odum, Odum, and Blissett, 1987; Pillet and Odum, 1984; Huang and Odum, 1991). As the diagram shows, EMERGY used includes renewable environmental resources such as rain, non-renewable resources used such as fuel reserves and soil, imported resources, and imported goods and services. Rural countries have a higher EMERGY/dollar ratio because more of their economy involves more direct use of environmental resources without exchange of money.

(D) Emergy Indices

The following are EMERGY indices used to draw inferences from EMERGY analyses.

The <u>solar transformity</u> of an object or resource is the equivalent solar energy that would be required to generate (create) a unit of that object or resource efficiently and rapidly. Figure 1 shows the solar transformity defined as the solar EMERGY required for one joule of another form of energy, which is wood energy in the example (Table 2). Solar transformities for main inputs from global climate were obtained from world energy budgets. Solar transformities of one or more products are obtained from each analysis. From many previous analyses, tables of solar transformity are now available to make future analyses easier.

The <u>net EMERGY ratio</u> is the EMERGY of an output divided by the EMERGY of those inputs to the process that are fed back from the economy (see Figure 5). This ratio indicates whether the process can compete in supplying a primary energy source for an economy. In recent years the ratio for typical competitive sources of fuels has been about 6 to 1.

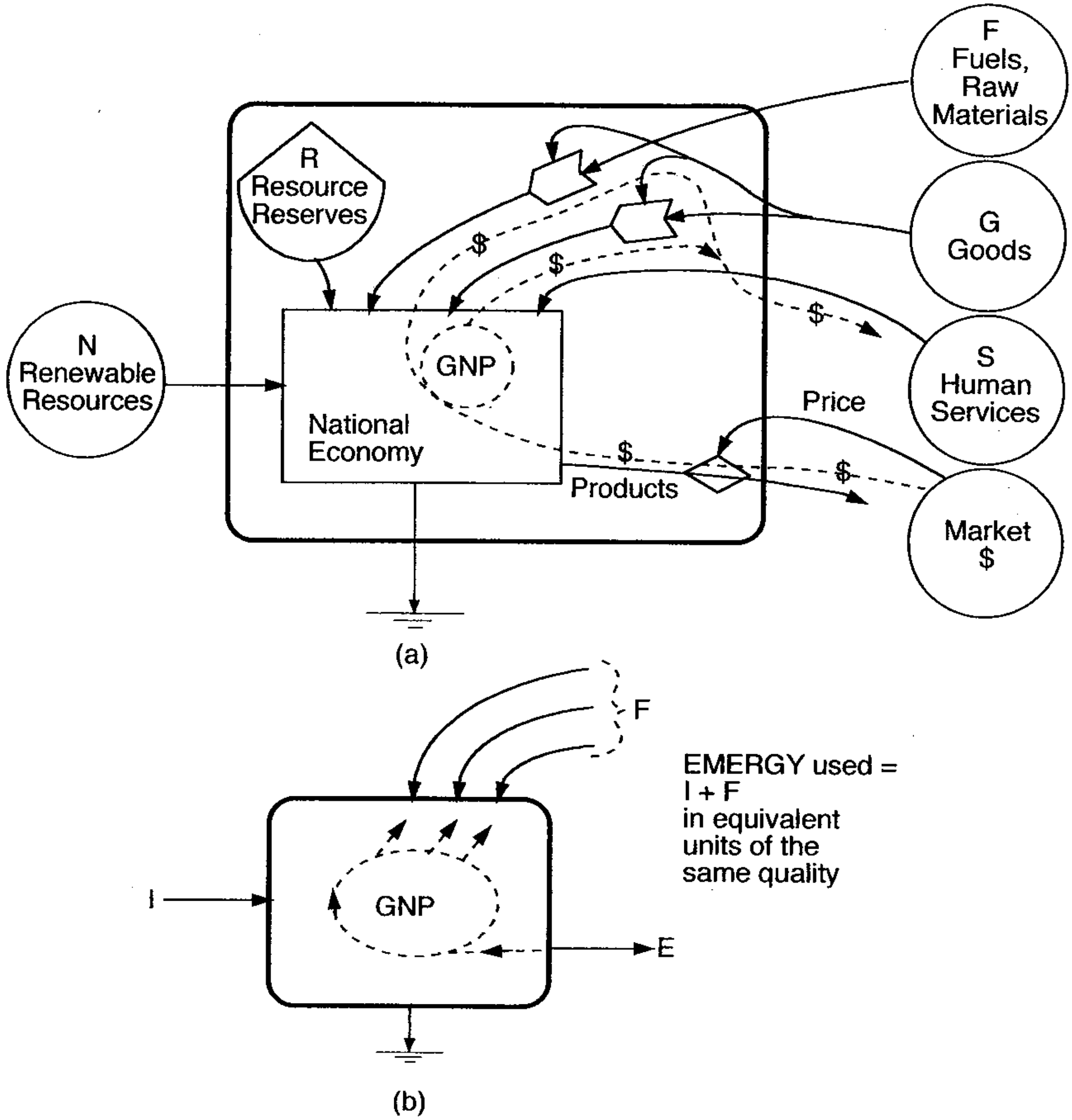
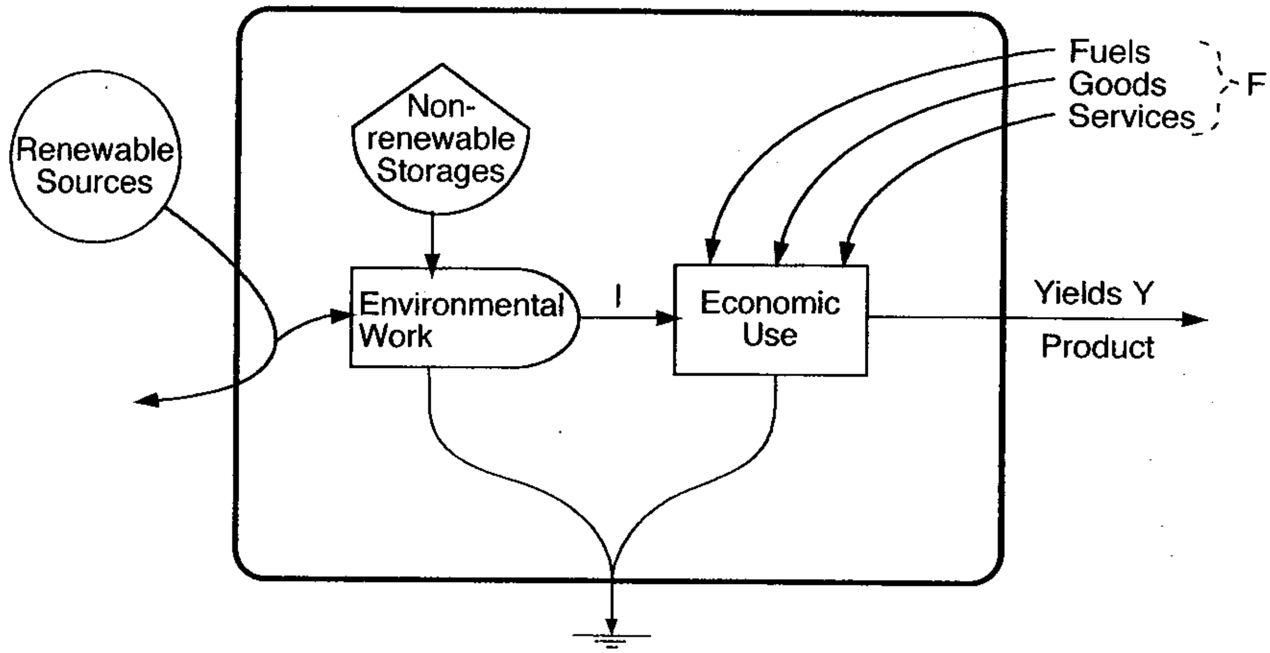


Figure 4. Overview diagram of a national economy. (a) Main flows of dollars and energy; (b) summary of input EMERGY flows.



EMERGY Investment Ratio = $\frac{F}{I}$ = R

Net EMERGY Yield Ratio = $\frac{Y}{F}$

Figure 5. Net EMERGY yield ratio for evaluating primary sources and investment ratio for evaluating whether matching of investments with environmental contributions is competitive. I and F are in EMERGY units.

Processes yielding less than this are not economical as primary EMERGY sources. The net EMERGY yield ratio of the wood from the radiata plantations was 2, not now competitive with fossil fuels.

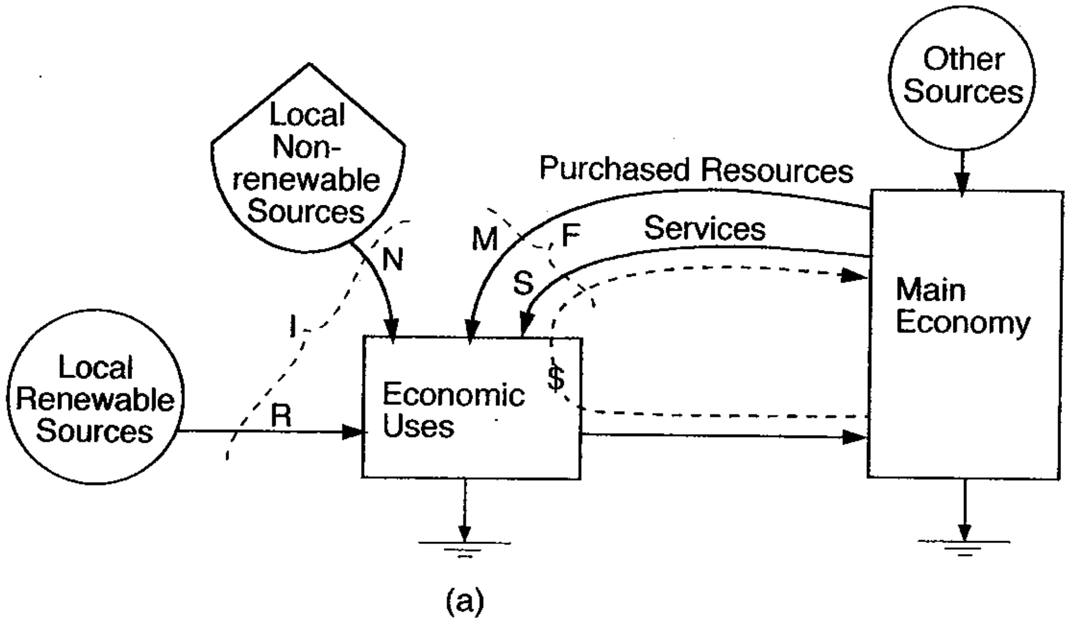
The EMERGY investment ratios relate the EMERGY fed back from the economy to the EMERGY inputs from the free environment (see Figure 6). There are several related ratios defined in Table 2 referring to Figure 6a. These ratios indicate if a process is economical as utilizer of the economy's investments in comparison to alternatives. To be economical, the process should have a similar or lower ratio to its competitors. If the ratio is less, it buys less from the economy, and its prices are less so that it will tend to compete in the market. Its prices are less when it is receiving a higher percentage of its useful work free from the environment than its competitors.

However, operation at a low investment ratio uses less attracted investment than is possible. The tendency will be to expand, increasing the purchased inputs so as to process more output and more money. The tendency is towards maximum resource use. If the ratio is higher than alternatives, prices will be too high to be competitive. Thus, operations above or below the regional investment ratio will tend to change towards the investment ratio.

For the plantation example in Figure 6, ratios are less than one (Table 2), but so is the average of this ratio for all of New Zealand, a rural nation. Investment ratios are higher in the United States, Japan, and Europe, which means that the plantation wood can compete in world markets, as observed.

Often in the development of environmental resources, early success is followed by over-development which puts too much purchased EMERGY for the matching environmental input. This wastes economic potential and overloads the environmental resource. The EMERGY investment ratios (Table 2) show the development intensity and the environmental loading. The ratio should not exceed the regional investment ratio if the development is to be part of that economy.

The EMERGY exchange ratio is the ratio of EMERGY received for EMERGY delivered in a trade or sales transaction (see Figure 7). For example, a trade of wood for oil can be expressed in EMERGY units. The area receiving the larger EMERGY receives the larger value and has its economy stimulated more. Raw products such as minerals, rural products from agriculture, fisheries, and forestry, all tend to have high EMERGY exchange



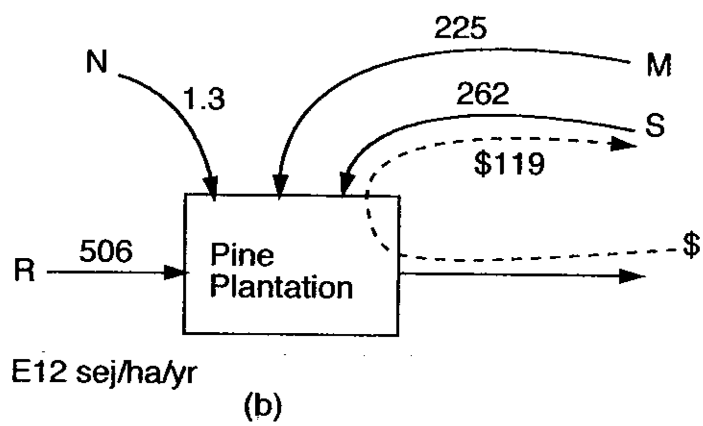
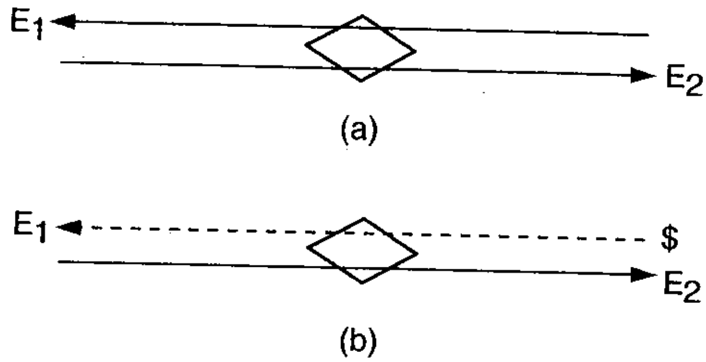


Figure 6. Diagrams illustrating EMERGY ratios in Table 2 for evaluating investment in a local resource. (a) Main pathway categories; (b) example of data used for calculating investment ratios, Monterrey Pine plantations in New Zealand (Table 2).

Table 2
EMERGY Indices for Radiata Pine Evaluation in Table 1
See Figures 3 and 6.

Name of index	Calculation	Result
<u>Solar Transformities (Figure 1):</u>		
Wood standing in forest	$\dfrac{(525 + 213 + 199)\ \text{E12 sej/y}}{1.506\ \text{E11 J wood}}$	= 6221 sej/j wood
Harvested wood	$\dfrac{(525 + 213 + 262 + 12)\ \text{E12 sej/y}}{1.506\ \text{E11 J wood /y}}$	= 6720 sej/j wood
<u>Net Emergy Yield Ratio (Figure 5):</u>		
	$\dfrac{(506 + 1.3 + 225 + 262)}{(225 + 262)}$	= 2.0
<u>Investment Ratios:</u>	Letters from Figure 6	
Purchased / free (Figure 5)	(M + S) / (R + N)	487/507 = 0.96
Non-renewable / renewable	(N + M) / R	226/506 = 0.45
Service / free	S / (N + R)	262/507 = 0.52
Service / resource	S / (R + N + M)	262/732 = 0.36
Developed/environmental	(N + M + S)/R	488/506 = 0.96
<u>Exchange Ratio:</u>	$\dfrac{\text{EMERGY of product}}{\text{EMERGY given for product}} = \dfrac{994}{262}$	= 3.7



$$\text{EMERGY Exchange Ratio} = \frac{E_2}{E_1}$$

Figure 7. EMERGY exchange ratio of a transaction. (a) Trade of two commodities; (b) sale of a commodity.

ratios when sold at market price. This is a result of money being paid for human services and not for the extensive work of nature that went into these products. For the sale of radiata plantation wood, the buyer gets 3.6 times more EMERGY than he pays in buying power (Table 2).

When products are exchanged or sold, the relative benefit is determined from the exchange ratio (Figure 7). A local economy is hurt when the new development takes more EMERGY than it returns in buying power. Keeping the product for home use raises the standard of living at home. Or, the product may have additional value added until its sale price is high enough to make the EMERGY exchange ratio unity.

The term macroeconomic value refers to the total amount of dollar flow generated in the entire economy by a given amount of EMERGY input. It is calculated by dividing the EMERGY input by the EMERGY/dollar ratio.

(E) Microcomputer Simulation Programs

Details on microcomputer simulation of ecologic-economic models are given in our teaching workbook (Odum and Odum, 1991). This includes instructions for continuous evaluation of EMERGY within the program as it runs. For each state variable there is a corresponding EMERGY state variable that receives EMERGY as the product of solar transformity and energy inflow. Unlike the energy storage, the corresponding EMERGY storage has no depreciation. The program continuously calculates transformities of internal storages as the quotient of EMERGY and energy. Outflow EMERGY is the outflux of energy times the inside solar transformity.

(F) Public Policy Questions

In addition to interpreting the EMERGY indices, various policy questions can be examined by comparing EMERGY contributions of alternatives. The alternatives with higher EMERGY flows represent solutions that will tend to prevail because their contributions to real wealth are greater. Through trial and error as well as through rational argument, alternatives are tried so that their utility can be observed by the public decision process. The hypothesis is that people will eventually come to accept the high EMERGY alternatives because these succeed and survive. By doing the EMERGY analysis in advance, one should be able to predict what will eventually be accepted policy.

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LEGENDS FOR THE FIGURES

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