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Energy Quality Interactions of Sunlight, Water, Fossil Fuel, and Land

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In times of changing basis of energy for man, many alternative ideas are proposed for new energy, and out of these the real world selects and reinforces the unified system that delivers maximum power. In Florida and Arizona, sometimes called sunshine states, large flows of solar energy can interact in various ways with land, water, and fossil fuels. What kind of energy system maximizes work by man and by nature? What kinds of energy interactions generate a vital economy? What is the carrying capacity of these energy systems for man? For an understanding of potentials consider some principals of energy systems and the concept of energy quality.

Energy Quality Principles

Principles are illustrated with systems energy diagrams using energy language symbols (Odum, 1971).

1. To maximize power, energy flows generate energy of higher quality capable of amplifer actions. These are stored and either fed back to increase the upstream energy effectiveness, used to pump in secondary sources or exchanged with other systems for energy advantage. See Fig. 1.

2. A chain of energy quality transformations develops (Fig. 2) with total calories of energy decreasing at each step but with increasing quality and concentration of that transformed. A graph of energy distribution describes the system's high and low quality energy flows.

3. The increase in energy quality of some of the energy is paid for by the use of low quality potential energy in work in which most of the energy is

degraded into heat. Increase in energy quality in a transformation is measured by the heat dispersed in the upgrading process. Energy quality is evaluated by measuring energy cost in Calories. For example, the energy quality of electricity is 3.6 times that of coal because this is the ratio of Calories of coal required to generate a Calorie of electricity. See Fig. 3.

4. High Quality energy realizes its value only when it is used to amplify another energy flow of lower quality with as much stimulation of new energy flow as was used in its formation. A Calorie of high quality energy is poorly used that does not amplify a flow of energy of low quality. See Fig. 4. For example, fossil fuel yields less food when converted by yeast directly than when it acts on sunlight in industrialized agriculture.

5. If there are inflows of energy of several types and quality to a system, the system develops more power by organizing high quality flows as amplifiers on the lower quality energy flows (Fig. 5a) rather than using them separately (Fig. 5b). Thus systems that survive are those that interact their energies rather than using them separately. In the example in Fig. 5, plants use water, wind, land energy, and chemical raw material energies to interact with sun in photosynthetic production. Productivity measurements can be used to determine the resulting values. Environmental systems spread water for interaction with sun in floodplains, deltas, and other land forms.

6. If there is an excess of low quality energy, it develops a chain of transformations to develop some high quality energy that is fed back to help maximize power (Fig. 2). If there is an excess of high quality energy and a shortage of matching low quality energy to be amplified, the high quality energies compete for the low quality, are underutilized for high quality purposes, and some of their energy goes for low quality uses (Fig. 4a). For example, high quality electricity in the absence of sunlight is used poorly to develop greenhouse plants.

7. An energy source can be a major contributor if it supplies net energy in excess of all energy that went into processing and transformation. For example, see Fig. 6a. In calculating the energy contributions, one traces the flows back to work done on it in the main economy outside the system used to concentrate it. Both energy yield (50) and energy feedback cost (10) are expressed in fossil fuel equivalents. The return is five for one.

8. High quality energy may be brought in from an outside system by exchanging with an export. Energy from outside can be attracted up to that amount that is

competitive. An export is competitive in attracting energy when it offers more than the average offered by competitors. The average system attracting fossil fuel energy in the U.S. augments its exports with 1 Calorie of fossil fuel equivalent of local energy for every 2.5 Calories of fossil fuel quality imported. See Fig. 9. One may decide whether an expenditure is more a cost or a benefit by the investment ratio (purchased energy divided by matching local energy). If proposed plans require more than 2.5 purchased to 1 matched local free energy, the system will not compete and can be regarded as a waste.

9. An energy source can be a secondary contributor even if it yields no net energy by being subsidized by a rich primary source. (Fig. 6b)

10. Energy models (Fig. 7) show the way money circles as a counter current to work of humans only so that there is a relationship of the total money circulating to the total energy flowing overall. However, money does not recognize the external inflow of values at the point of entry. Thus price does not measure energy values of sun, water, fuels, environmental values, or wastes impacts. This ratio is 25,000 Calories per dollar. Fig. 8 shows U.S. economy. By dividing the total Calories of fossil fuel equivalent work of the U.S. (including the sales contributions) by the Gross National Product in dollars, the average proportion of the energy involved per dollar is found.

11. High quality energy can generate a net energy effect by amplifying and interacting with matching low quality energy, exporting the product of this work for fossil fuel with a favorable ratio of exchange. See Fig. 10.

12. Natural systems of vegetation and landform develop water storages and processes that maximize the energy effect of water in some of the same ways needed by systems that include man; maximum energy flows may be achieved by fitting man into these preformed systems rather than setting up competing systems that may be less energy effective.

13. The several kinds of energy flow to environmental systems of man and nature may have different ratios of Calories in different geographical locations. The outside energy sources are also called forcing functions since the forces these flows deliver are causal actions from outside the system. One example is Fig. 5. Each situation may be characterized by the relative ratios of the energy flows expressed first in Calories of heat equivalence and then expressed in Calories of fossil fuel equivalence. The description of a location by its energy inflows can be called an energy signature. For each different energy signature, unique structures may develop to organize the energy interactions to maximize power and thus reinforce continuation of that system. Learning more about which environmental systems go with which energy systems is a research opportunity in ecology and geomorphology, allowing predictions from a knowledge of energy sources.

Energy Quality of Sunlight, Water, and Fossil Fuel

The energy qualities of a Calorie of sunlight, fossil fuel, and water estimated from the energy used in transformations are summarized in Table 1. A chain of plant production with adequate water develops about 1% of sunlight as gross productions, 0.1% as net production in form of organic matter collected, and as 0.05% when concentrated as fossil fuel. See Fig. 11. In other words, 2000 Calories of sunlight are equivalent to one Calorie of fossil fuel. Conversely one Calorie of fossil fuel needs to be matched by 2000 Calories of low quality sunlight for the high quality energy to yield its full potential.

Water has Calories of its elevated potential against gravity, Calories of its chemical potential energy relative to salt water of the sea into which it ultimately runs, potential energy in its heat content if there is a temperature gradient, and chemical potential energy in its content of scarce nutrient. When estimates are made of the energy used in developing these energies, the energy in water is found to be higher quality than fossil fuels. Calculations used for estimating energy quality are diagramed in the figures cited in Table 1.

As shown in Fig. 12a, the sun generates the world water cycle and in the process develops high quality. Water falling as rain carries Calories of much higher quality than the sunlight that generated the rain through its weather cycles. Expression of water's potential as work is fully realized when the water is used to amplify and match the sunlight in the ratio of about 2,000 Calories of sunlight to 3 Calories of water used in the transformation.

Arid regions have potential energy in the drying power of their winds with large saturation deficits. This energy source reduces air conditioning costs if there is water, may attract some industries, some income bearing people, pull water through long roots, etc. Depreciation rates may also be lower.

Energy Quality of Earth Cycles and Man

Energy quality is shown to increase as sunlight drives the earth cycles including the atmosphere, the oceans, and mountain building (see Fig. 11 and 12a). Water is high quality and the land forms built by the hydrological cycle and by chemical energy deposited in the sediments is even higher quality (Table 1). Water cycling in the biosphere may be like the biochemical substance ATP, which serves as a flexible, controlling, and high quality energy in living protoplasm. The uplifted land is one of the highest energy values on earth.

Man, his civilization, and his complex information are also high quality energy flows that used much energy in their development and to adequately regard and protect their sources must feed back large amplifier actions as custodians of the biosphere's environmental systems.

Draining Storages Faster than Renewals

When man uses storages of water and fossil fuel faster than they are being renewed by normal earth cycles, he may build his economy to a higher level than can be sustained later. Use of these high quality energies without as much low quality matching as possible generates less work than is their potential. In the long run the system that uses high quality energy with less than maximum possible yield attracts less outside energy and competes poorly.

There is a temporary competitive advantage in rapid inefficient use of rich energy, when there is a situation wtih competitive growth and the system which is ahead can draw more new energy by acceleration than by matching, but this is temporary. Later power is maximized by emphasis on efficient matching.

Water as an Amplifier on Solar Energy for Attracting Fossil Fuel Investment

When it is proposed to divert water from solar interactions of nature, agriculture, and other environmental systems to fossil fuel activity of industries and towns, one may inadvertently reduce the economic vitality by taking water from its high amplifier situation to a lower quality use. Water interacting with solar energy is a main matching attraction for purchasing fossil fuels as shown in Fig. 13a. In Fig. 13b without the water the basis for attracting the purchased energy disappears and economic development goes elsewhere. The water necessary for direct use by fossil fuel based activity is much less than for the resident solar-linked work to attract the fossil fuel activity. A city uses less water per person than the countryside must use to attract the economic activity upon which the city's demand is based.

When natural adapted vegetation develops, the theoretical principles suggest that it maximizes energy flow by using water well, transpiring in miminal ways in dry periods and doing its growth when waters are more available, developing water conserving water percolation systems, improving water quality, and using the dark absorbing vegetation surfaces to absorb and utilize more solar energy that would otherwise be reflected back from light desert surfaces. Removal of vegetation to save water may be an example of the diversion of water from one of its major free inputs upon which economic attractions are based but not recognized. Attractions of tourists, retirees, federal payrolls, etc. may be based in part on a stable landscape and panoramas.

Desalination

The energy relations of desalination shown in Fig. 12b are helpful in comparing the utilization of fossil fuel in salt water desalination with the theoretical 2.5 to 1 by which one may estimate economic feasibility. The fossil fuel-based inputs required to desalinate the water are the energy costs of upgrading quality transformation. These indicate an energy quality factor for saltwater-freshwater conversion of about 0.2. The figure shows the solar interaction of the desalinated water in plant production. The ratio of fossil fuel purchased (5 Cal FFE) to resident free energy amplified (1 Cal FFE) greater than the average ratio (2.5) used as a competitive standard even before any economic activity has been started. According to this theory the desalination will not compete.

Solar Energy Conversion to Electricity

Energy cost of developing Calories of electricity from solar energy may be estimated using the energy transformation chain of a power plant operating on wood, using the electricity produced by an algal mat coupled to platinum electrodes, and by solar cells (See Fig. 11). These conversions were used to estimate a solar energy quality factor in Table 1. Examining the purchased energy part to resident solar energy part shows high ratios, not a good investment of purchased energy.

Solar Energy Use by Productivity Compared with Solar Technology

Whereas the solar based productivity is the principal basis by which resident local energy matches and attracts purchased energy for economic development, many propositions are considered for converting sunlight through technological devices rather than through well established vegetation and agricultural pathways already in use. In general, the solar technology uses a higher ratio of fossil fuel-based energy to solar energy, much higher than the 2.5 to 1 ratio believed competitive (both in fossil fuel equivalents). High grade energy is not used well and thus, the system does not compete well. Increasing costs of fossil fuel will make the situation worse. It may be that very high quality energies cannot process low quality energy effectively except through intermediate steps.

Solar Water Heater

One technological use of solar energy that has been in economic use for many years is the solar hot water heater. In Fig. 14 James Zucchetto and Sandra Brown (Zucchetto & Brown, 1975) evaluated the energy flows and associated money costs, the capital costs being prorated over a ten year estimated lifetime of the equipment. This is a model on the commercial market in Miami. They did similar analyses of gas and electric hot water heaters, finding less fossil fuel energy used by the solar heater than by the gas and much less than by the electric heater.

However, Fig. 15 shows why the solar hot water heater is not an effective energy transformer although less wasteful than other heaters. All the numbers are in fossil fuel equivalents. Ninety-nine percent of the energy is from fossil fuel spent in developing the equipment. The ratio of purchased energy to matching solar energy is too large to be a good use of high quality fossil fuel. The potential energy of the output of hot water in fossil fuel equivalents was estimated by multiplying the heat Calories in the hot water by the Carnot ratio of the heat one would get by simply burning the fossil fuel directly. In other words, all separated heaters are luxuries, energy ineffective devices except where their hot water has unusual multiplier actions on other energy flows. Hot water released as byproducts of more important energy uses such as essential house heating is more energy effective.

Energy Quality of Dispersed Solar Heat

The sun falling over the earth heats the surfaces over a wide area but only by a few degrees before the heat is borne away by the atmospheric system. What is the energy quality of this dispersed heat as related to fossil fuel equivalents? The solar hot water heater provides a way to estimate the conversion (See Fig. 15c). If the fossil fuel equivalents of the solar input are multiplied by 2000, one obtains the sun's energy required to provide all the inputs to the concentration. A ratio of about 10,000 to 1 is found. Whereas man has difficulty harvesting such dilute energies, he can derive some work from the atmosphere's climate that is generated from the dispersed heating.

Choices in Use of Energy and Water in Arid Regions

In Fig. 16 are some of the energy interactions discussed at the Arid Lands conference in important in Arizona. Many aspects may be omitted in this diagram that could be added in a more complete state-wide model, but the diagram suggests a way to start on an overall evaluation. The figure suggests that climate, lands and water amplify solar energy generating free, local productivities, agriculture, climate, soil control, etc., as the basis for the exported values that attract the income to pay for the fossil fuel base of the local urban economy.

The model also shows the present and proposed developments that draw water away from the basis of attraction to direct urban uses on the assumption that more income will be attracted. For example, water is diverted in hydroelectric plants, power plants on fossil and nuclear fuels, and urban ornamental vegetation. Does water attract more income in water-intensive agriculture? . . . in drier types of agriculture? . . . in keeping general environment green? . . . in coal mining or in industries?

The yield of coal per unit of fossil fuel work used may be lower than the ratio of foreign oil presently obtained per Calorie of fossil fuel-based work exported to maintain balance of payments. Coal may not compete until the richer foreign fuels have been used. If foreign oils are used first and local coals are mainly held until later, reserves will insure a stable independent period later when the richer foreign oils have been used. With less net yield, the energy per capita may be lower. Electric power generation may not be the best way to use the coal.

Incomes to Arizona from tourists, retirees, federal payrolls and welfare may decline as energy per capita nation-wide declines reducing buying power that is beyond necessities. Increasing energy costs of processing deeper waters may also decrease attractions of development money. There may not be a need for so much electrical capacity or other water project investments. Demand for electricity will drop. Using coal to generate the higher quality electricity may have been justified when incomes for urban growth were assured, but without them coal may need to go directly to industry plants located near the coal with only small amounts to electricity.

Although many still plan for a growth economy, it seems prudent that some should plan for transition to a steady state economy and population.

TABLE 1

Energy Quality Factors for Expressing Forms of Energy in Fossil Fuel Equivalents*

Name of Energy	Energy per unit of fossil fuel Equiv. Cal/Cal of coal		Diagram
Sun as dilute heating	10,000		Fig. 15
Sun (visible light) as photo-chemical action	2,000	[illegible]	Fig. 11
Gross plant production dispersed	20		Fig. 11
Net production (wood)	2		Fig. 11
Coal (at point of use)	1		Fig. 11
Electricity	0.28	10,000 .12/1,2000	Fig. 3
Water potential due to elevation	0.3		Fig. 12
Water potential due to lack of salt #	0.2	5 .2	Fig. 12
Elevated land with geological uplift	0.001		Fig. 12

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* Very tentative pending more detailed documentations; for discussion purposes

= Based on chemical potential energy; $\Delta F = RT \ln C_2/C_1$ where C_2/C_1 is the ratio of salinities (10 ppm and 35,000 ppm). See Odum (1970)

Legends for the Figures

Fig. 1. Three ways that upgraded energy may be used as amplifier to generate more energy inflow. (a) pump more from same source; (b) pump from a secondary source; (c) exchange with another system where exchange ratio is favorable.

Fig. 2. Energy flows develop chains of energy transformation that upgrade energy quality, using the feedbacks to help the system as a whole process more energy. (a) energy diagram; (b) total energy decreases through the chain; (c) energy quality per unit increases through the chain.

Fig. 3. Energy transformations in a power plant. Energy degraded in transforming energy (2.6 Calories) is a measure of the energy qualtiy increase. Energy quality factor is the ratio of inflow of one quality of energy (3.6 Calories) to outflow of upgraded energy. (1.0 Calories)

Fig. 4. Use of high quality energy with and without low quality energy with which it may amplify. (a) without low quality energy, high quality energy is used for low quality purposes and useful work is small. (b) with matching low quality energy, high quality energy is used only to amplify and much more useful work results.

Fig. 5. Diagram showing how surviving systems maximize their useful work by interacting energies. (a) plant production diagram showing definitions of gross and net production; (b) hypothetical systems of separate energy use in which high quality energies do not amplify low quality energy.

Fig. 6. Diagram used to analyze net energy values of an energy source. (a) a fuel which yields net energy; (b) a fuel which does not yield net energy.

Fig. 7. Diagram showing circle of money not recognizing the energy inflows of sun, water, environmental value, mined fuel.

Fig. 8. Energy flows and money circulation in a simplified model of the United States in 1970. 25,000 Calories per dollar is the fossil fuel equivalent of solar and fossil fuel potentials being used.

Fig. 9. Diagram illustrating the investment ratio for estimating relative economic feasibility (a) average ratio in the United States in 1973; (b) same as (a) except with flows of money shown and investment ratio expressed in another way.

Fig. 10. Diagram of the fuel return from using 2.5 FFE Calories with 2,000 Calories of solar energy (1 FFE) to develop a product sold to a fuel-rich country at $10/barrel of oil.

Fig. 11. Transformations of solar energy. (a) chain of conversions of light wood to power plant generating electricity; (b) blue-green algal mat in shallow estuary generating half volt electrical system (Armstrong and Odum, 1964); (c) electricity from solar cells.

Fig. 12. Energy relations in water elevation and desalination. (a) biosphere desalination and production followed by driving of earth cycles; (b) technological desalination followed by use of the water as amplifier on solar energy in production by plants and attraction for economic investment in local community;(c) hydroelectric power from 100 ft. elevated water.

Fig. 13. Diagram showing the use of water to amplify solar values to attract income for supporting urban economy. (a) water used as amplifer; (b) water diverted to city directly undermining the city's basic income-energy relationship.

Fig. 14. Energy and money relationships for a solar hot water heater in commercial use in Miami, Florida as calculated by James Zucchetto and Sandra Brown. (Zucchetto and Brown, 1975)

Fig. 15. Summary of data in Fig. 14. (a) data in dollars and Calories of different quality; (b) conversion of (a) to fossil fuel equivalents; (c) substitution cf solar pathway for fossil fuel subsidy to relate sun to potential energy in the hot water.

Fig. 16. Model of some main energy, water, and economic relationships that may be important in Arizona based on discussions at the Arid Lands conference.

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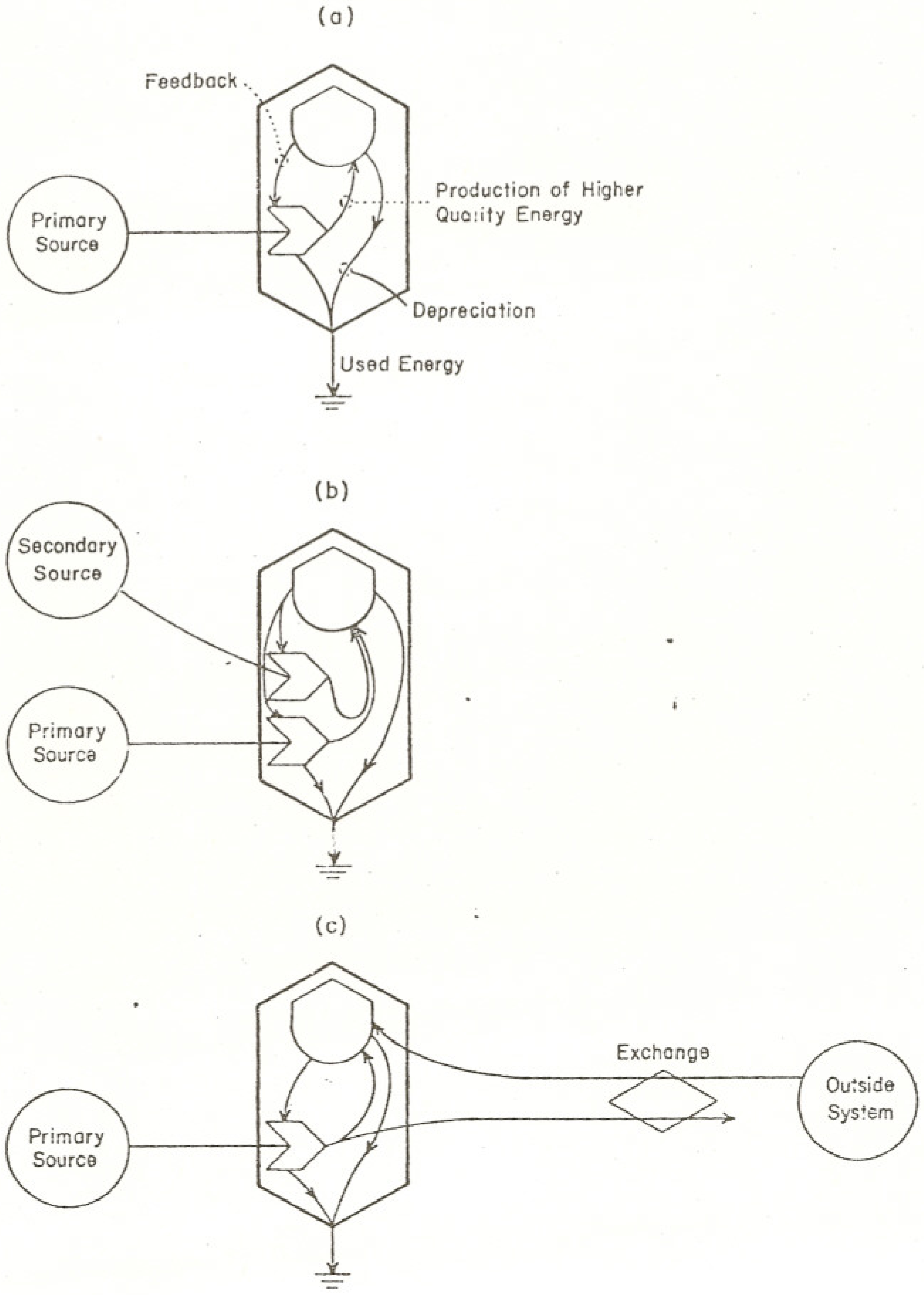

(a)
Feedback
Production of Higher Quality Energy
Primary Source
Depreciation
Used Energy
(b)
Secondary Source
Primary Source
(c)
Exchange
Primary Source
Outside System

Figure 1.

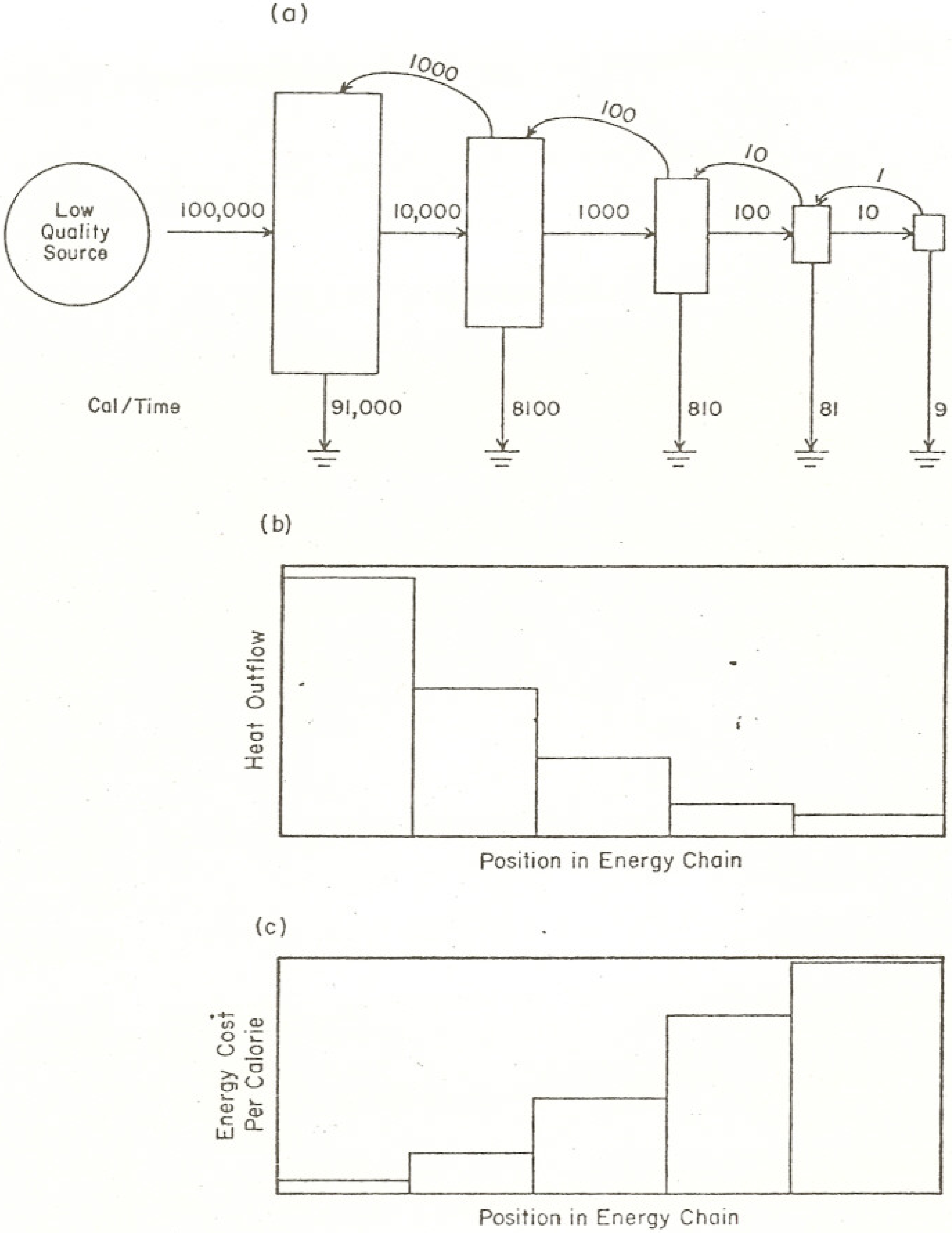
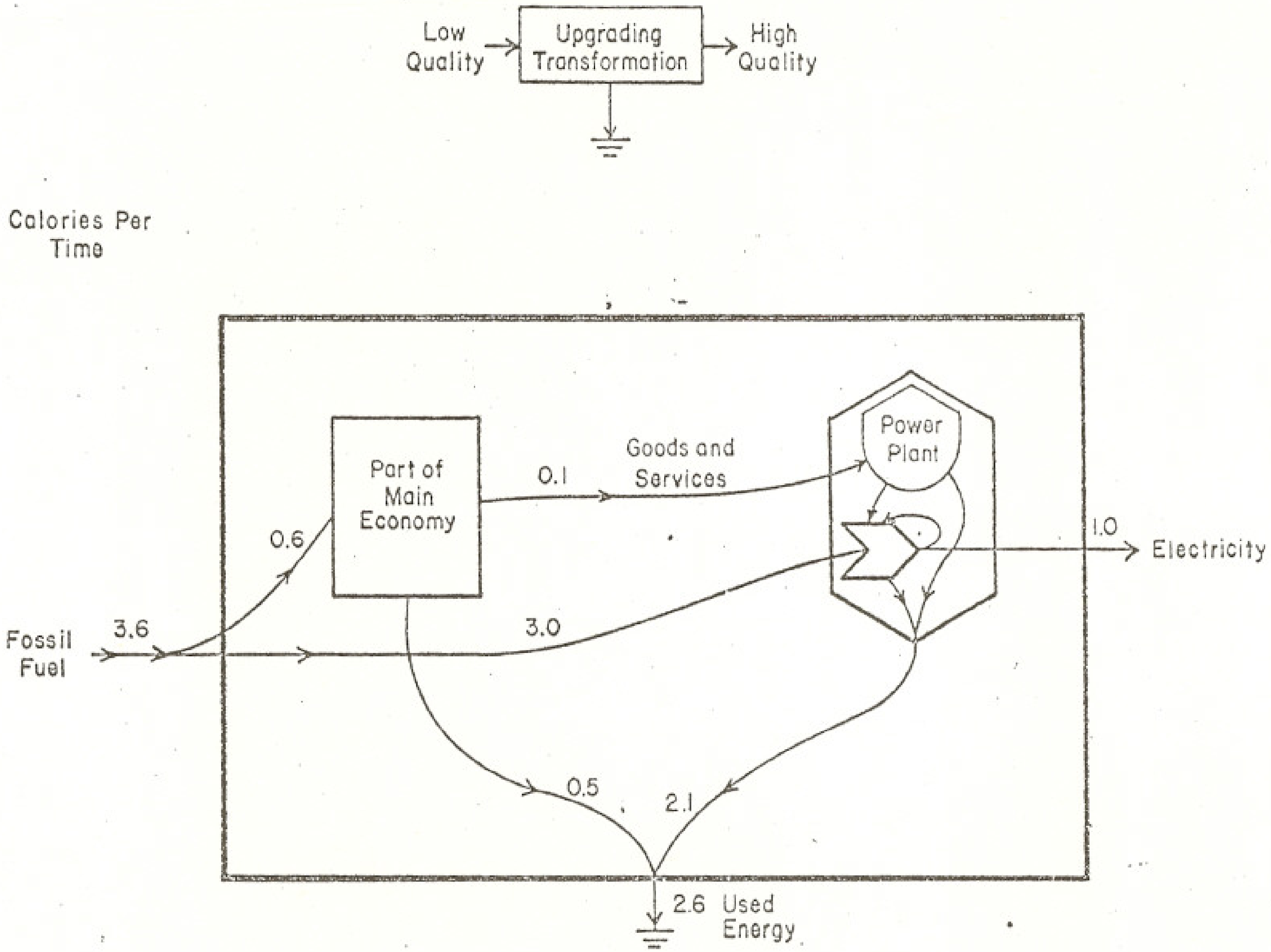

(a)
Low Quality Source
100,000
10,000
1000
100
10
1000
100
10
1
Cal/Time
91,000
8100
810
81
9
(b)
Heat Outflow
Position in Energy Chain
(c)
Energy Cost Per Calorie
Position in Energy Chain

Figure 2.



$$\text{Energy Quality Factor} = \frac{\text{Inflow of Lower Quality}}{\text{Upgraded Flow}} = \frac{3.6}{1.0} = 3.6$$

Figure 3.

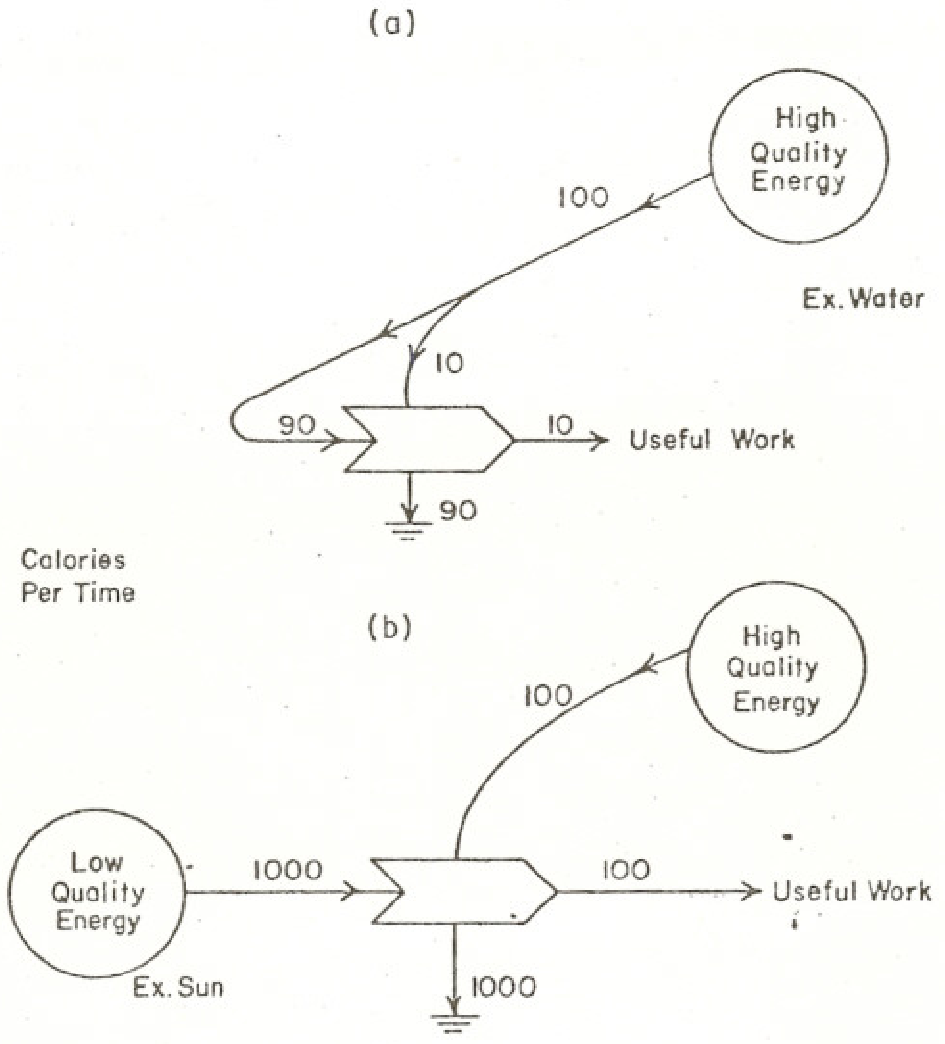

(a)
High Quality Energy
100
Ex. Water
10
90
10
Useful Work
90
Calories Per Time
(b)
High Quality Energy
100
Low Quality Energy
1000
100
Useful Work
Ex. Sun
1000

Figure 4.

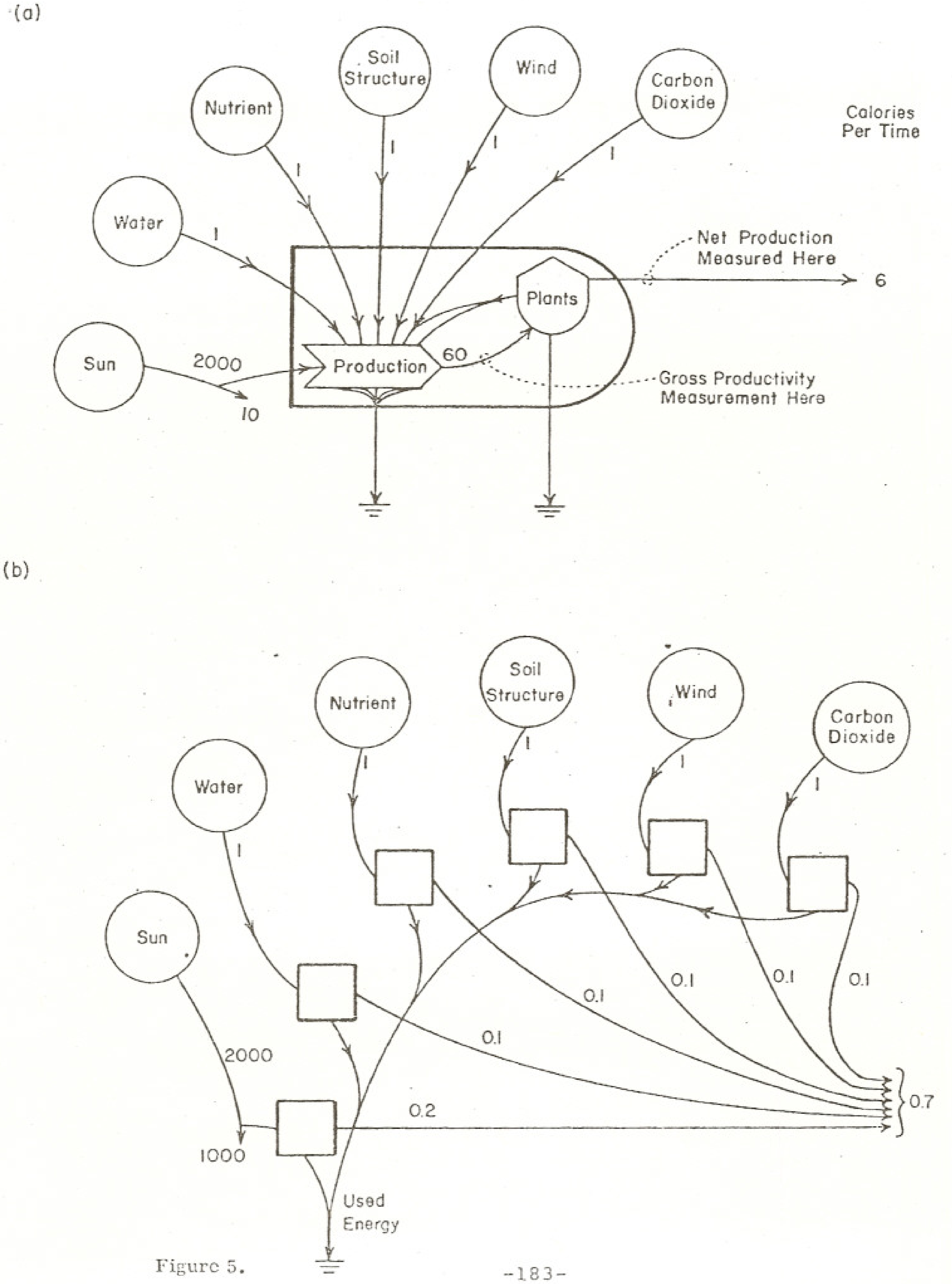

(a)
Soil Structure
Wind
Carbon Dioxide
Nutrient
Calories Per Time
Water
1
1
1
1
1
Net Production Measured Here
6
Plants
Sun
2000
60
Production
10
Gross Productivity Measurement Here
(b)
Soil Structure
Wind
Nutrient
Carbon Dioxide
Water
1
1
1
1
1
Sun
0.1
0.1
0.1
0.1
0.1
2000
0.2
0.7
1000
Used Energy

Figure 5.

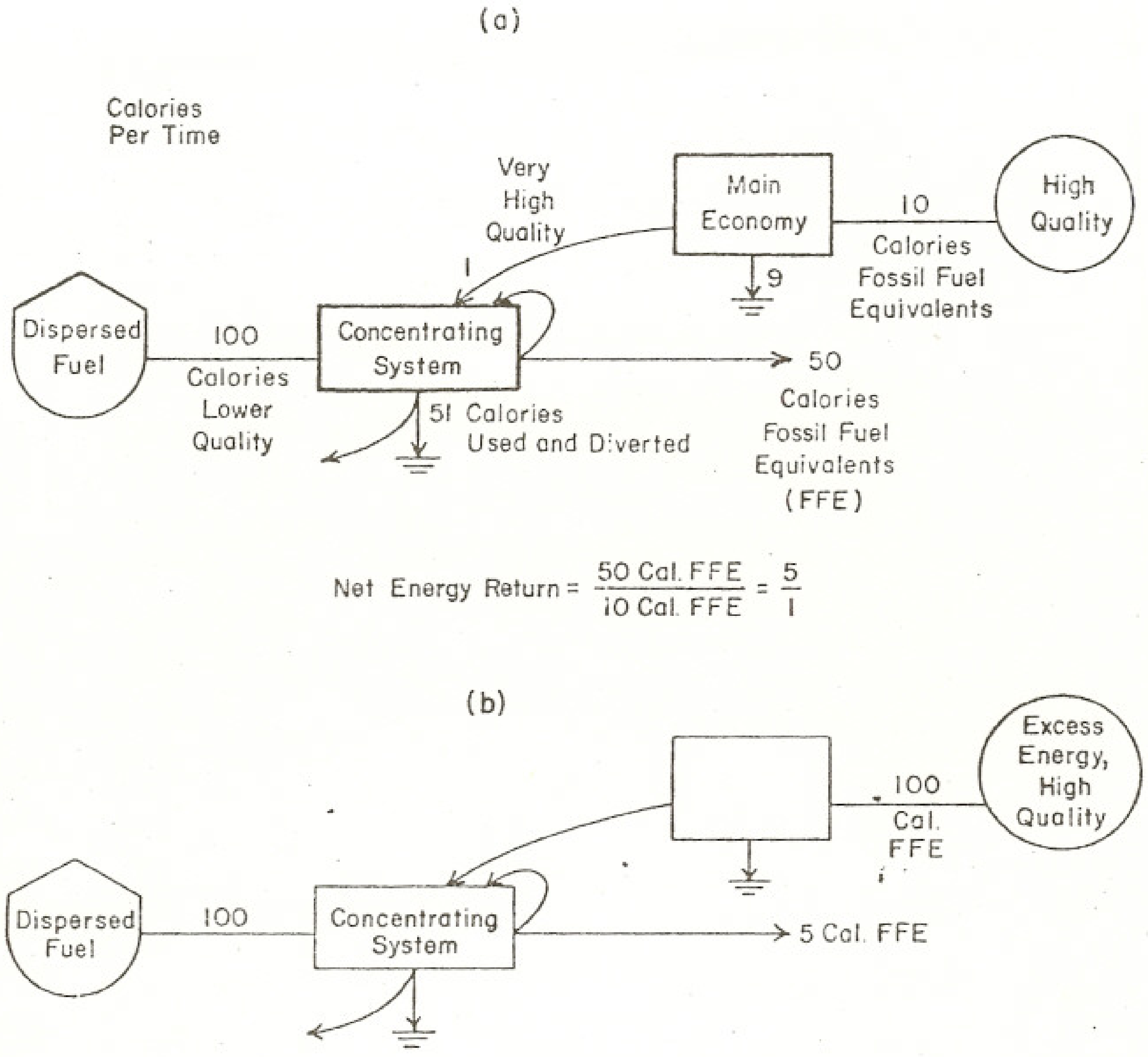

(a)
Calories
Per Time
Very
High
Quality
Main
Economy
10
High
Quality
Calories
Fossil Fuel
Equivalents
1
9
Dispersed
Fuel
100
Calories
Lower
Quality
Concentrating
System
50
Calories
Fossil Fuel
Equivalents
(FFE)
51 Calories
Used and Diverted
Net Energy Return = 50 Cal. FFE / 10 Cal. FFE = 5 / 1
(b)
Excess
Energy,
High
Quality
100
Cal.
FFE
Dispersed
Fuel
100
Concentrating
System
5 Cal. FFE

Figure 6.

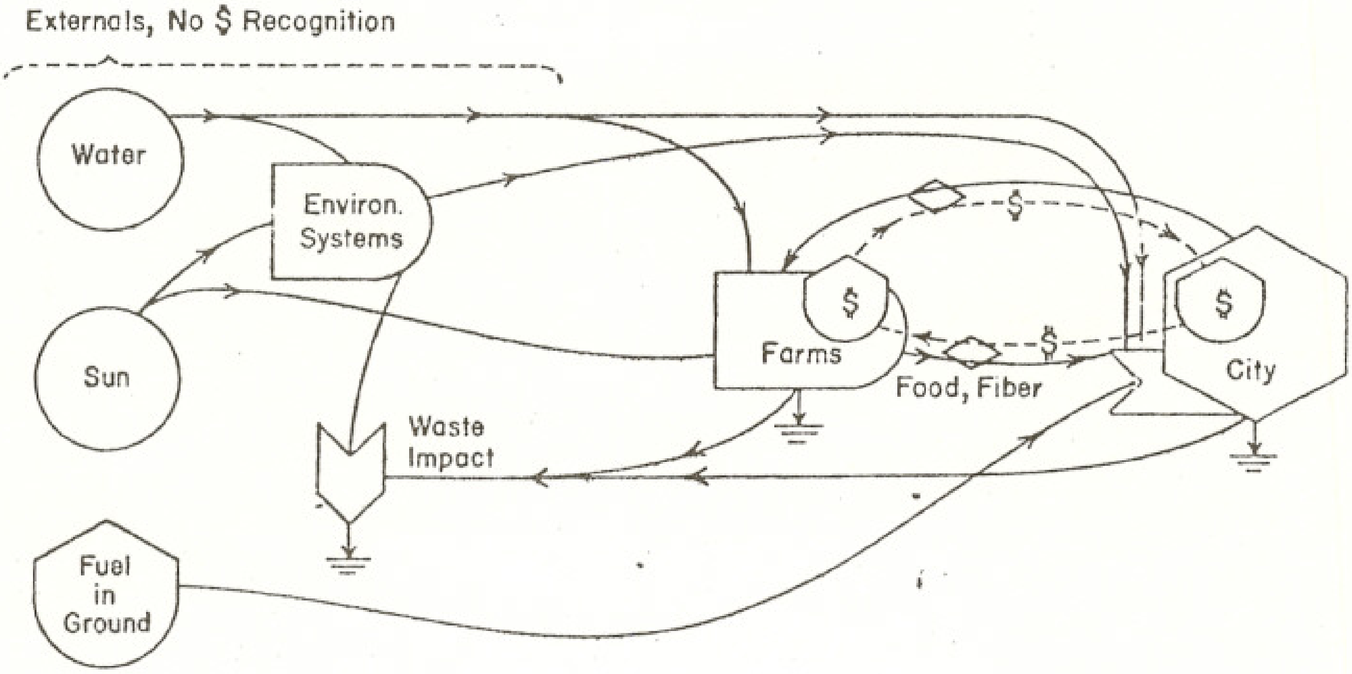

Externals, No $ Recognition
Water
Environ. Systems
Sun
Fuel in Ground
Waste Impact
Farms
$
$
Food, Fiber
$
$
City

Figure 7.

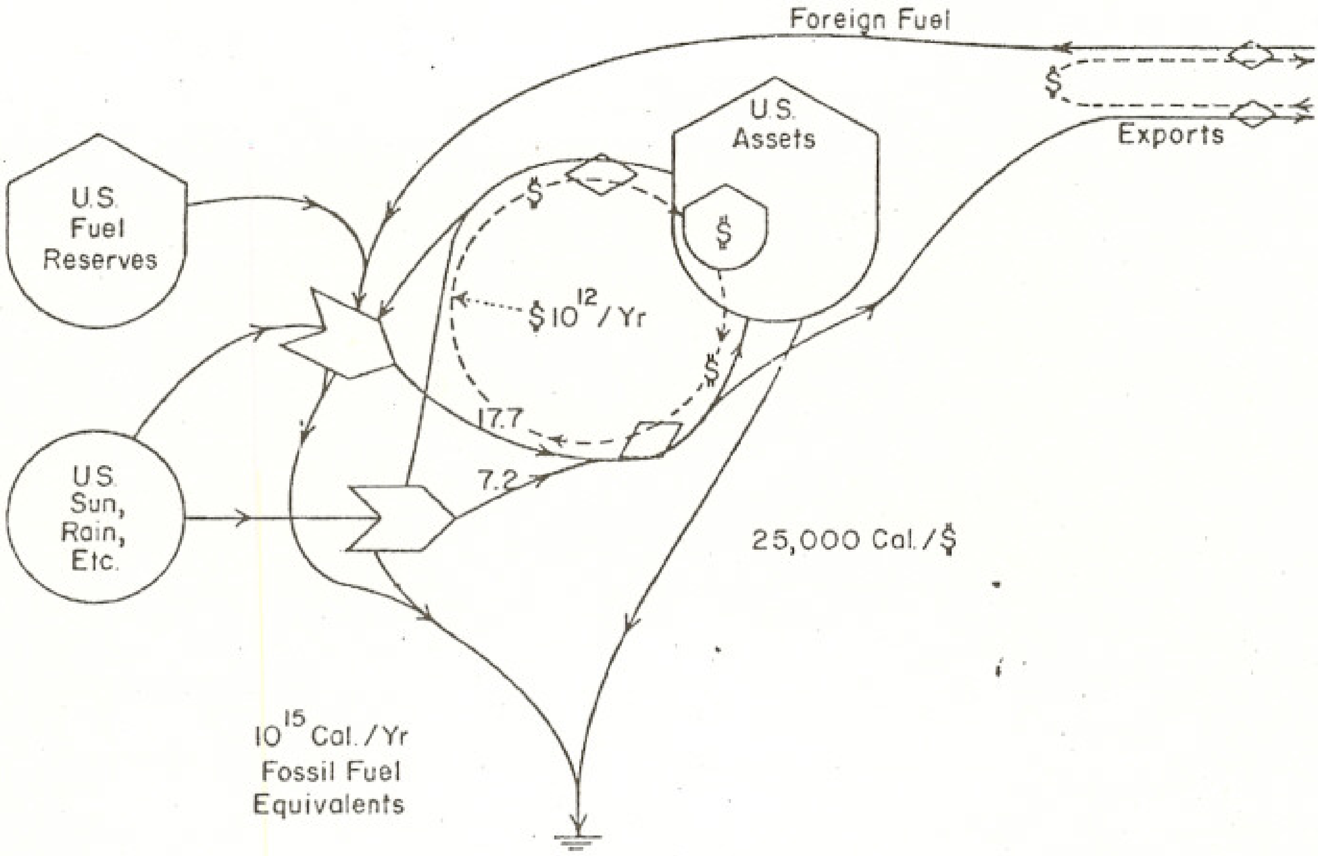
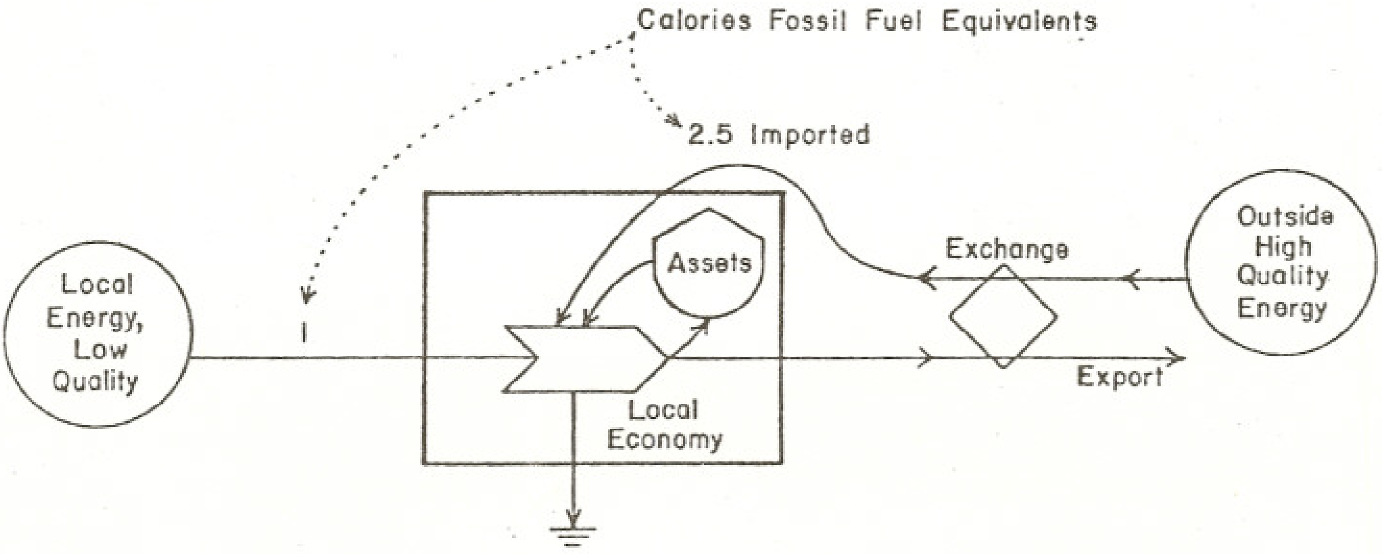

Foreign Fuel
$
Exports
U.S. Assets
$
U.S. Fuel Reserves
$
$ 10^12 / Yr
$
17.7
7.2
U.S. Sun, Rain, Etc.
25,000 Cal./$
10^15 Cal./Yr Fossil Fuel Equivalents

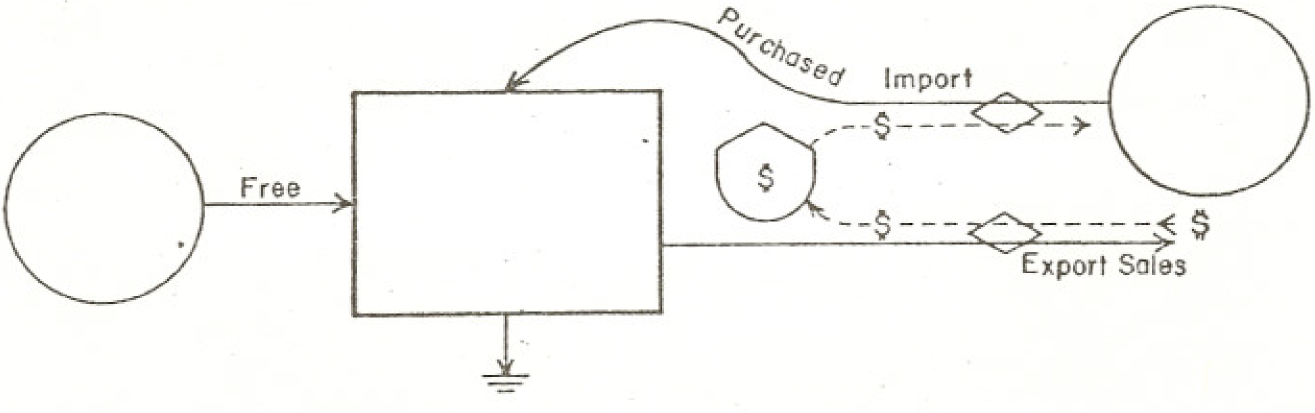
Figure 8.

(a)



$$\text{Investment Ratio} = \frac{\left(\begin{array}{c}\text{High Quality}\\ \text{Imported in FFE}\end{array}\right)}{\left(\begin{array}{c}\text{Local Contribution}\\ \text{in FFE}\\ \text{Low Quality}\end{array}\right)} = \frac{2.5}{1}$$

(b)



$$\text{Investment Ratio} = \frac{\left(\begin{array}{c}\text{Purchased FFE}\\ \text{High Quality}\end{array}\right)}{\left(\begin{array}{c}\text{Free, Low Quality}\\ \text{FFE}\end{array}\right)}$$

Figure 9.

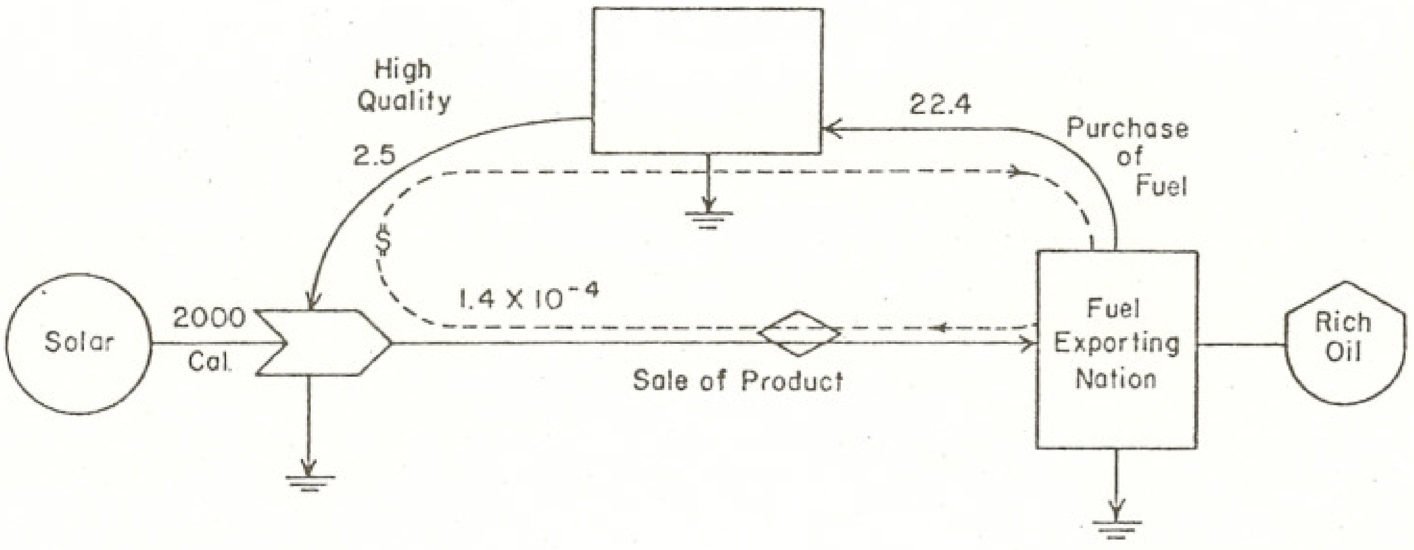

High Quality
2.5
22.4
Purchase of Fuel
$
Solar
2000 Cal.
1.4 X 10^-4
Fuel Exporting Nation
Rich Oil
Sale of Product

Figure 10.

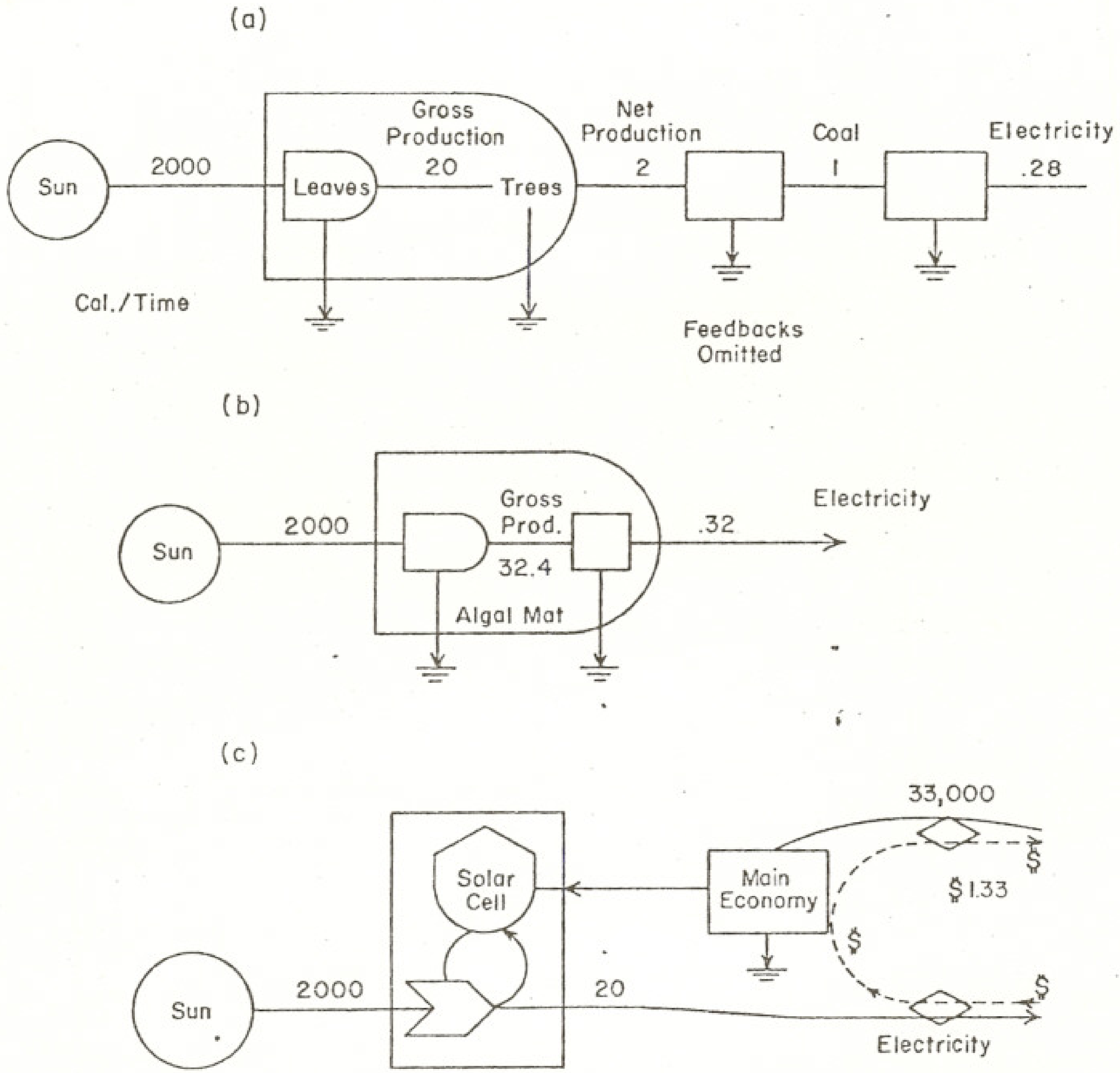

(a)
Sun
2000
Gross
Production
Leaves
20
Trees
Net
Production
2
Coal
1
Electricity
.28
Cal./Time
Feedbacks
Omitted
(b)
Sun
2000
Gross
Prod.
32.4
.32
Electricity
Algal Mat
(c)
Solar
Cell
Main
Economy
33,000
$
$1.33
$
$
Sun
2000
20
Electricity

Figure 11.

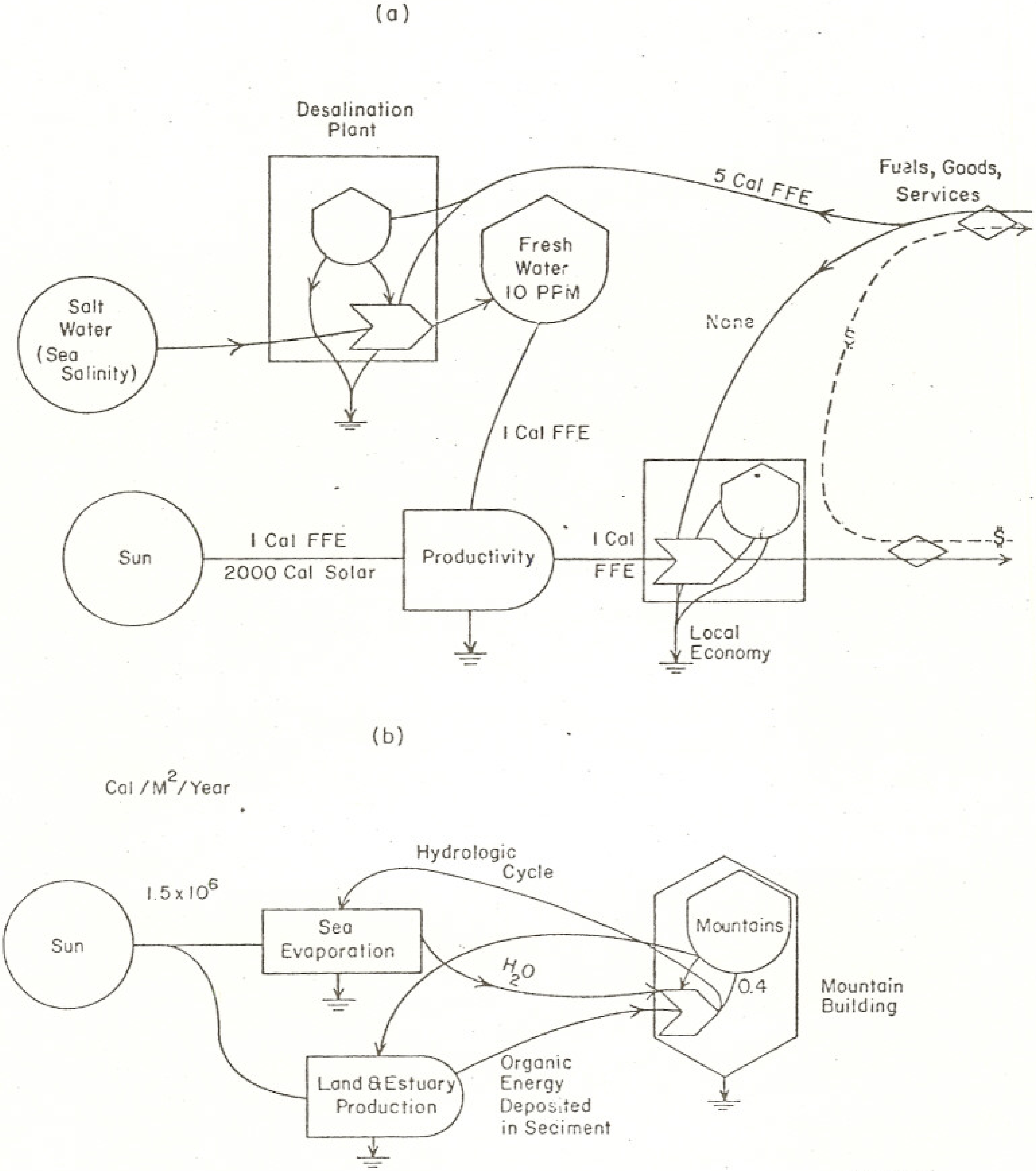

(a)
Desalination Plant
5 Cal FFE
Fuels, Goods, Services
Fresh Water 10 PPM
Salt Water (Sea Salinity)
None
1 Cal FFE
Sun
1 Cal FFE
2000 Cal Solar
Productivity
1 Cal FFE
$
Local Economy
(b)
Cal / M² / Year
Hydrologic Cycle
Sun
1.5 x 10⁶
Sea Evaporation
H₂O
Mountains
0.4
Mountain Building
Land & Estuary Production
Organic Energy Deposited in Sediment

Figure 12.

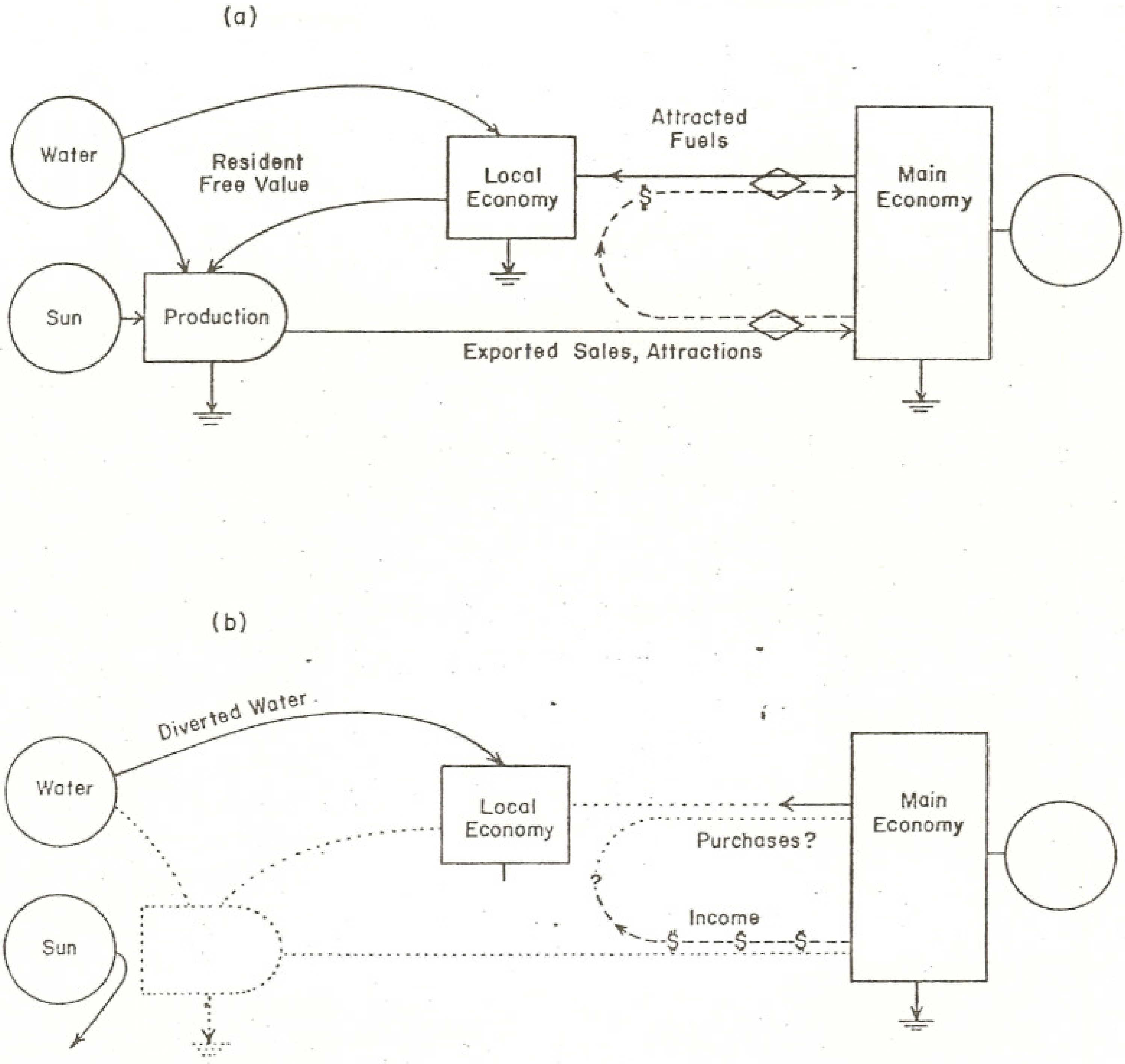
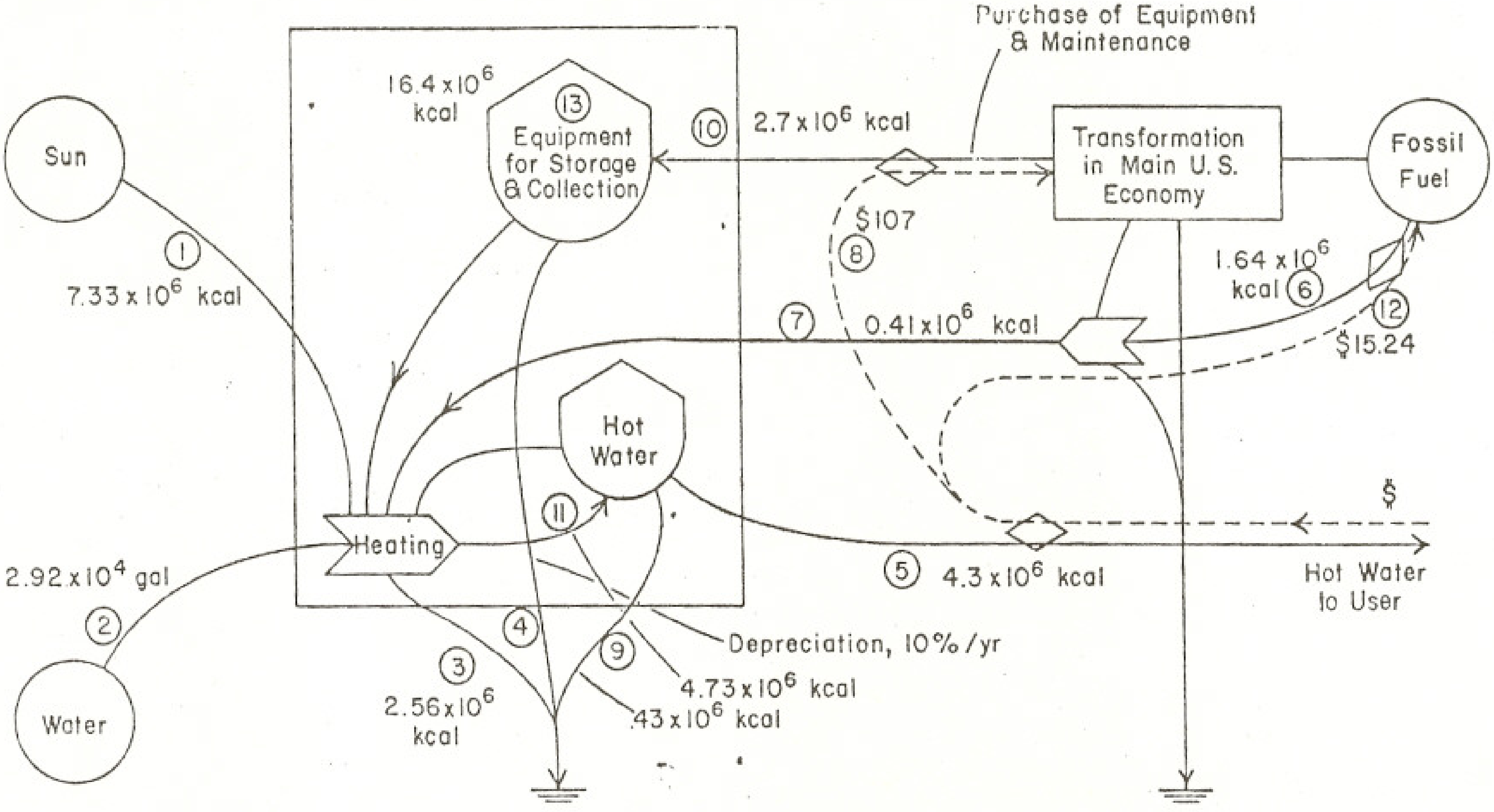

(a)
Water
Resident
Free Value
Local
Economy
Attracted
Fuels
$
Main
Economy
Sun
Production
Exported Sales, Attractions
(b)
Diverted Water
Water
Local
Economy
Main
Economy
Purchases?
?
Income
$
$
$
Sun

Figure 13.



All Flows Are Per Year

Figure 14.

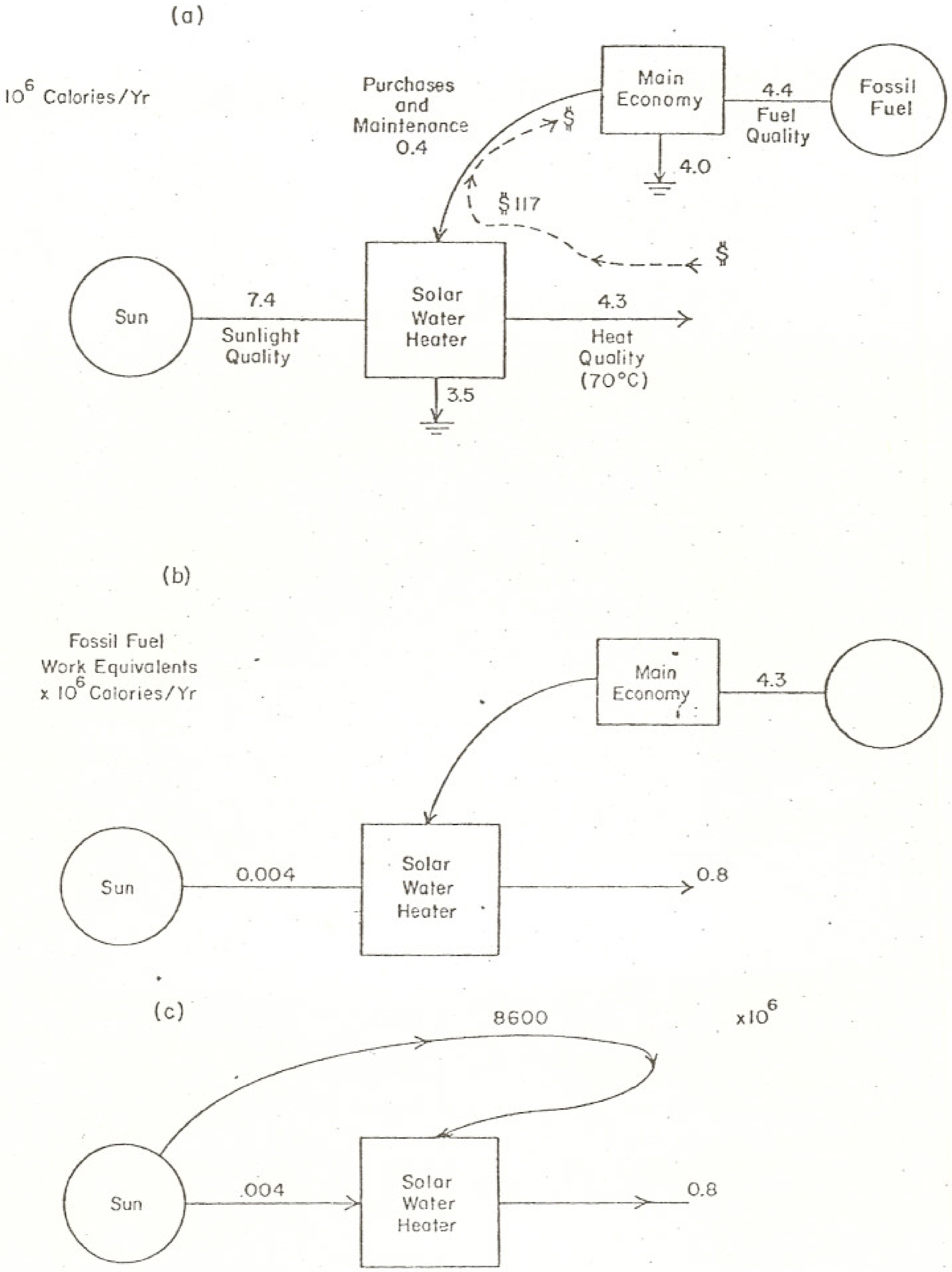


Figure 15

$\frac{\text{Calories Invested}}{\text{Calories Netted}} \quad \frac{8600}{0.8} = \frac{10750}{1}$

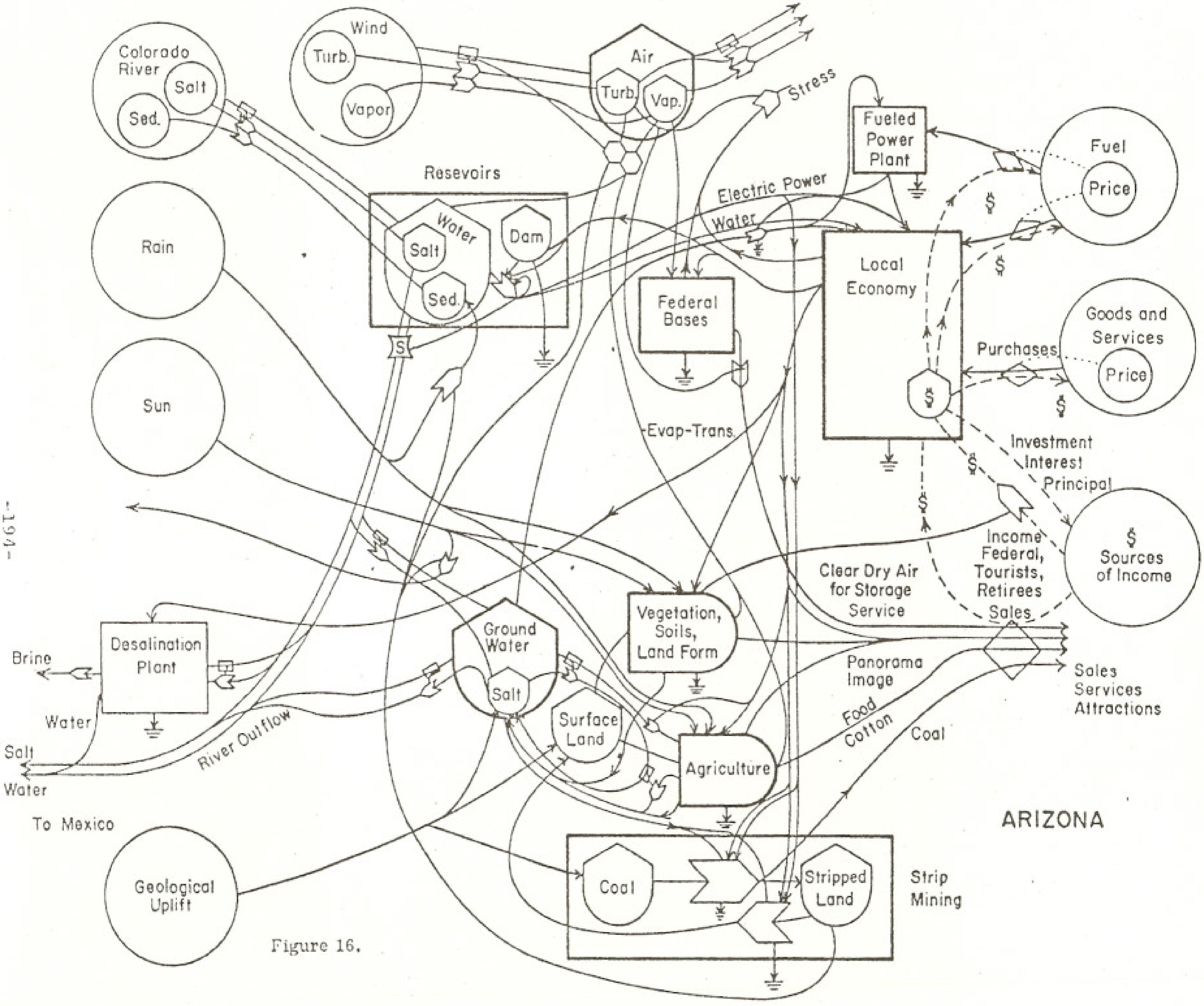

Colorado River
Salt
Sed.
Wind
Turb.
Vapor
Air
Turb.
Vap.
Stress
Fueled Power Plant
Fuel
Price
Resevoirs
Water
Salt
Sed.
Dam
S
Rain
Electric Power
Water
Local Economy
$
$
Federal Bases
Goods and Services
Price
Purchases
$
$
Sun
Evap-Trans.
Investment
Interest
Principal
$
$
Income
Federal,
Tourists,
Retirees
$
Sources of Income
Clear Dry Air for Storage Service
Sales
Desalination Plant
Brine
Water
Salt
Water
To Mexico
River Outflow
Ground Water
Salt
Vegetation, Soils, Land Form
Panorama Image
Sales
Services
Attractions
Surface Land
Agriculture
Food
Cotton
Coal
ARIZONA
Geological Uplift
Coal
Stripped Land
Strip Mining

Figure 16.