ENERGY ANALYSIS PROCEDURES*

1. ANALYSIS OF SYSTEMS

Many questions of public policy concern important subsystems of an economy, such as agroecosystems, mining systems, manufacturing systems, tourist systems, etc. Energy analysis overviews can be prepared for these in the same way as described already for the whole nation. Diagrams are drawn, pathways evaluated in actual energy units, and then converted to embodied solar joules. The final summary diagrams can be used to calculate energy transformation ratios for the product of that system.

When the diagram has been completed with embodied energy flows calculated for the main flows, several useful ratios may be calculated to help interpretations to evaluate economic viability, net energy, future trends, etc. The evaluations may also be used for computer simulation.

A generic diagram for a production subsystem is given in Figure 1. Usually there are the inputs from the environment and sectors of environmental work. Connecting with these on the right are human economic activities that transform, process, and transport the products. Shown as a countercurrent of dashed lines are the flows of money where human services are involved. Included also are money flows to repay investments, interest, etc. Where flows have a common source and are byproducts, such as winds, waves, and rain generated by the global weather system, only the largest is used, usually the rain energy.

2. CALCULATING ACTUAL ENERGY FLOWS AND STORAGES

After an overview energy diagram has been drawn (Fig. 1), the main energy flows and long term storages may be calculated using various data on geography, climate, oceanography, and economics. Earlier a manual was developed for environmental energy evaluations (Odum et al. 1983). In this present effort, the principal formulae were modified and assembled as Tables 1 and 2. Units were arranged to yield results in joules whereas the earlier manual had results as kilocalories. For each formula the various data are identified first as words and then with their units, leaving an underlined blank where a data item characteristic of a particular country was substituted.

After these rough overview calculations were made the results constitute a "first law analysis" and if placed on an energy diagram it would be a "first law diagram." All inflowing energy must be accounted for in outflows or increases of storages.

However, ability to do work is not proportional to actual energy where energies of different quality are being compared. The actual energy flows and storages were multiplied by energy transformation ratios so as to express all values in solar equivalent units. After this is done, it is possible to see which ones were major and which ones were minor. Thereafter, more care and detail is used to evaluate the flows that turned out to be the major ones.

In general the higher the quality of energy, the less is the actual energy and the higher the solar energy embodied.

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* Extracts from Energy Analysis Overview of Nations. Ed. by H.T. Odum and E.C. Odum. 1983. Working paper, #WP-83-82 International Institute for Applied Systems Analysis.

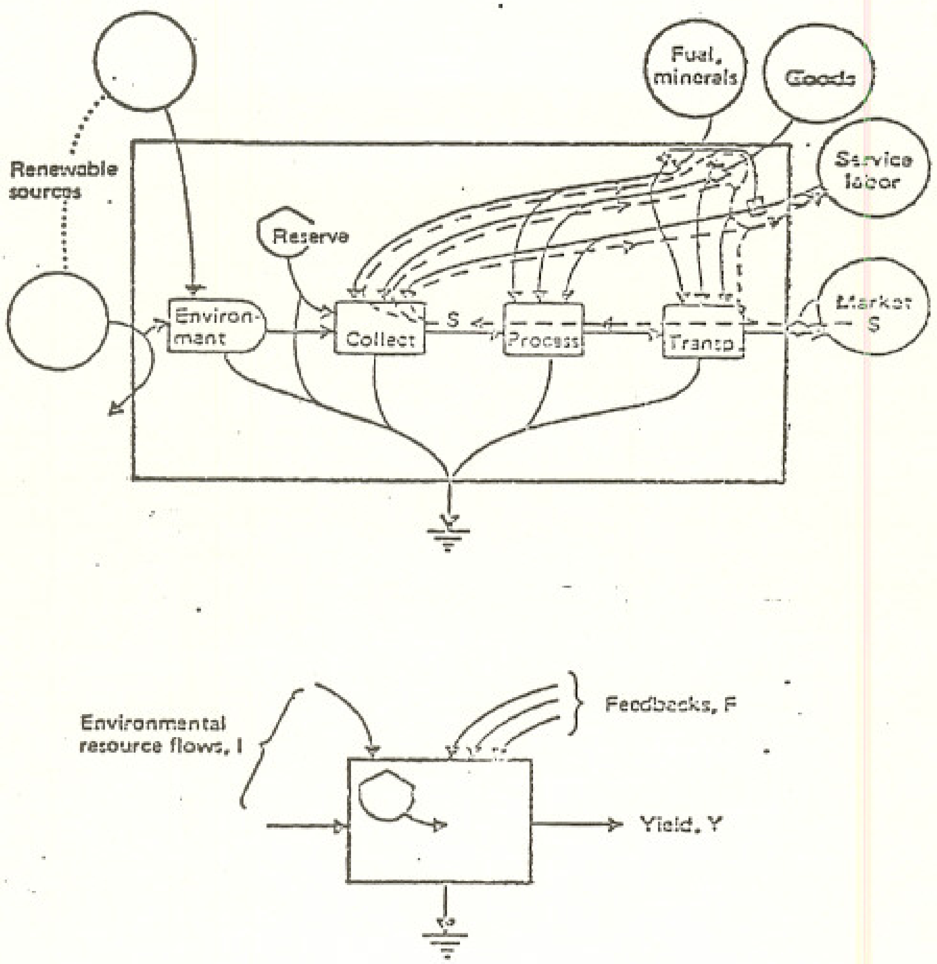


Figure 1. Generic diagram for a production subsystem. (a) typical components; (b) aggregated three arm diagram.

Table 1. Formulae used for calculating actual energy flows - joules per year.

DIRECT SUNLIGHT

Area of country is that of land plus continental shelf.

(Area of country)(Average of insolation) =

$$(\_\_\_\_\_\_\,\mathrm{m}^2)(\_\_\_\_\_\_\,\mathrm{J/m^2/yr}) =$$

KINETIC ENERGY OF WIND USED AT SURFACE

Kinetic energy of wind at 100 m is multiplied by its height, density eddy diffusion coefficient, the wind gradient, and area of country.

(height)(density)(diffusion coefficient)(wind gradient)(area)

$$(1000\mathrm{m})(1.23\mathrm{kg/m^3})(\_\_\_\_\_\_\,\mathrm{m^3/m/sec})(3.154\ \mathrm{E7\ sec/y})(\_\_\_\_\_\_\,\mathrm{m/sec/m})^2(\_\_\_\_\_\_\,\mathrm{m}^2)$$

Typical values of eddy diffusion and vertical gradient coefficients are:

	Eddy diffusion $m^3/m^2/sec$		Vertical gradient m/sec/m	
	January	July	January	July
Flint, Michigan	40.2	8.3	8.0 E-3	3.8 E-3
Oakland, Calif.	8.4	1.0	4.3 E-3	1.6 E-3
Tampa, Fla.	2.8	1.7	2.3 E-3	1.5 E-3

For other data see NRC Manual (Odum et al. 1983).

CHEMICAL POTENTIAL ENERGY IN RAIN

(Area including shelf)(Rainfall)(G) =

Where G is Gibbs free energy of rainwater relative to salt water within evapotranspiring plants or in seas receiving rain.

G is 4.94 J/g. See footnote .

$$(\_\_\_\_\_\ \mathrm{m}^2)(\_\_\_\_\_\_\,\mathrm{m/yr})(4.94\ \mathrm{J/g})(1\ \mathrm{E6\ g/m^3}) =$$

CHEMICAL POTENTIAL ENERGY IN RIVER

(Volume flow)(Dentisy)(G) =

where G is Gibbs free energy of river water relative to sea water

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

4

Table 1 (continued)

where S is dissolved solids in parts per million.

$$G = (138.8\ \mathrm{J/g})[\log_e \frac{(1E6 - S)}{(965{,}000)}]$$

$(\_\_\_\ \mathrm{m^3/yr})(1E6\ \mathrm{g/m^3})(\_\ G\ \_\ \mathrm{J/g}) =$

CHEMICAL POTENTIAL ENERGY WITH WATERS USED WITHIN A COUNTRY

Combine chemical potential energies calculated for rain and rivers:

(Rain) + (Inflowing rivers) - (Outflowing rivers)

If rivers reach the sea within the national boundary, combine:

(Rain) + (Inflowing rivers)

Alternative approach, combine:

(water evapotranspired) + (waters reaching sea within boundaries)

EARTH CYCLE

(Land area)(heat flow per area)

$(\_\_\_\ \mathrm{m^2})(\_\_\_\_\ \mathrm{J/m^2/y})$

Heat flow: old, stable, 1 E6 $\mathrm{J/m^2/y}$; rapid orogony, 3-10 E6 $\mathrm{J/m^2/y}$

NET UPLIFT

(Area)(uplift rate)(density)(0.5)(uplift)(gravity)

$(\_\_\_\_\ \mathrm{m^2})(\_\_\_\_\_\ \mathrm{m/y})(\_\_\_\_\ \mathrm{E3\ kg/m^3})(0.5)(\_\_\_\_\ \mathrm{m})(9.8\ \mathrm{m/sec^2}) = \_\_\_\_\_\ \mathrm{J/y}$

NET LOSS OF EARTH

Loss of clays from the area in river discharge or wind that is in excess of formation rate. See Appendix A18. Typical formation rate, 31.2 $\mathrm{g/m^2/y}$

(Earth cycle rate)(density)

$(\_\_\_\_\ \mathrm{E{-}6\ m/y})(\_\_\_\_\ \mathrm{E6\ g/m^3}) = \_\_\_\_\_\ \mathrm{g/m^2/y}$ formation

(ersion outflow) - (formation rate)(area of country)

$(\_\_\_\_\_\_\ \mathrm{g/y}) - (\_\_\_\_\_\ \mathrm{g/m^2/y})(\_\_\_\_\_\ \mathrm{m^2}) = \_\_\_\_\_\_\_\ \mathrm{g/y}$

Then multiply by ETR/g to get embodied solar energy.

CHEMICAL POTENTIAL ENERGY IN IMPORTED AND EXPORTED COMMODITIES WHOSE VALUE IS USED IN REACTIONS WITH OXYGEN (FOOD, FIBER, WOOD ETC.)

(Weight per year)(G) =

where G is the Gibbs free energy of oxidation with atmosphere. For organic substances with high free energies and small entropy changes of state in oxidation, G is practically equal to the bomb calorimetry values of heat of combustion (enthalpy changes). See tables of calorie value in nutrition tables and handbooks. For carbohydrates, starch, wood, etc., about 4 kcal/g; for proteins, wool,.etc., about 5 kcal/g dry; for fats and oils about 7-9 kcal/g. Multiply by 4186 to represent as joules.

Where G (Gibbs free energy) is small, calculate its value from the chemistry of the reaction

$(\underline{\qquad}\ \mathrm{T/yr})(\underline{\ G\ }\ \mathrm{J/g})(1\ \mathrm{E6\ g/T}) =$

For chemical potential energy in fuels see formula below.

NET LOSS OF TOPSOIL

Topsoil erosion rates in excess of profile formation rates are evaluated. See Appendix A18. Areas with mature vegetation are assumed to have little net gain or loss of topsoil.
Typical formation rate, 1260 $g/m^2/y$ or 8.54 E5 $J/m^2/y$ in areas in natural vegetation succession.

Typical erosion rates of topsoils from farmed areas from Larson et al (1983) from U.S. are:

	$g/m^2/y$		$g/m^2/y$
Pacific states	250	Cornbelt, delta area	1000
Mountain states	260	Southeastern states	850
Plains	500	Appalachian states	1250
		Northeastern states	700

Actual energy of net loss:

(farmed area)(erosion rate) - (successional)(area)(formation rate)

$(\underline{\qquad}\ \mathrm{m}^2)(\underline{\qquad}\ \mathrm{g/m^2/y})(- (\underline{\qquad}\ \mathrm{m}^2)(\underline{\qquad}\ \mathrm{g/m^2/y}) = \underline{\qquad}\ \mathrm{g/y}$

$(\underline{\qquad}\ \mathrm{g/y})(0.03\ \mathrm{organic})(5.4\ \mathrm{kcal/g})(4186\ \mathrm{J/kcal}) = \underline{\qquad}\ \mathrm{J/y}$

or

$(\underline{\quad}\ \mathrm{T/m^2})(\underline{\quad}\ \mathrm{m})(\underline{\quad}\ \frac{\mathrm{organic}}{\mathrm{fraction}})(5.4\ \mathrm{kcal/T})(4186\ \mathrm{j/kcal}) =$

GEOPOTENTIAL IN INFLOWING RIVERS

(flow volume)(density)(height of river entry - river egress)(gravity)

(_____m^2)(_____m)(_____m /y)(1 E3 kg/m^3)(9.8 m/sec^2) =

GEOPOTENTIAL IN RAIN USED

(Area)(mean elevation**)(runoff)(density)(gravity) =

(_____m^2)(_____m)(_____m/y)(1 E3 kg/m^3)(9.8 m/sec^2) =

OCEAN WAVES ABSORBED AT THE SHORE

(shore length)(1/8)(density)(gravity)(height squared)(velocity) =

(_____m)(1/8)(1.025 E3 kg/m^3)(9.8 m/sec^2)(_____m^2)(_____m/sec)(3.154 E7 sec/y) =

where velocity is square root of gd = $[(9.8\ m/sec^2)(\_\_\_\_\_\ m\ deep)]^{1/2}$

TIDE ABSORBED IN ESTUARIES

(area elevated)(0.5)(tides/yr)(height squared)(density)(gravity) =

(_____m^2)(0.5)(706/yr)$(\_\_\_\_\_m)^2$(1.0253 E3 kg/m^3)(9.8 m/sec^2) =

0.5 x height is center of gravity

TIDE ABSORBED ON CONTINENTAL SHELVES

Same as above multiplied by 0.1 to 0.5.

CHEMICAL POTENTIAL ENERGY IN IMPORTED AND EXPORTED COMMODITIES WHOSE VALUE IS IN ITS CONCENTRATION**

(Weight per year)(G) =

where G is the Gibbs free energy per unit weight relative to concentration of the commodity in the environment. For example G for iron ore is 14.2, Gilliland et al. (1981).

(_____T/yr)(___G___ J/g)(1 E6 g/T) =

COAL FLOWS OR OUTFLOWS

(Weight per year)(energy per unit weight) =

(____T/yr)(3.18 E10 J/T) =

OIL INFLOWS OR OUTFLOWS

(Barrels per year)(energy per barrel)

(_____bbl/yr)(6.28 E9 J/bbl) =

Table 1 (continued)

NATURAL GAS INFLOWS OR OUTFLOWS

(Volume of gas/yr)(energy per unit volume) =

(____thsd cubic ft/yr)(1.1 E9 J/thsd cubic ft) =

or

(_____therms/yr)(1.055 E5 J/therm) =

FLOW OF ELECTRIC POWER

(Power units for a time)(Energy per unit power for a time)

(______KWH/yr)(3.60 E6 J/KWH)

or

(capacity of power plant)(% of capacity)(hours per year)(energy/unit)

(______kilowatt)(_%__/100)(1.40 E9 J/kw/yr) =

GEOPOTENTICAL IN NET ROCK UPLIFT

(height of elevated rock)(area)(rock density)(half of elevation rate)

(gravity) =

(______mm/yr)^2(1 E-6 m^2/mm^2)(____m^2)(______E3 kg/m^3)(0.5)(height)

(9.8 m/sec^2) =

ELECTRICAL OUTPUT OF NUCLEAR PLANTS

Evaluate electricity delivered

(______KWH)(3.6 E6 J/KWH)

HEAT PRODUCTION OF FISSION

(Weight of uranium used per time)(fraction U 235)(Energy per unit U 235)

(_____T/yr U_3O_8)(0.007)(1 E6 g/T)(7.95 E10 J/g U235)

EMBODIED ENERGY IN IMPORTED OR EXPORTED SERVICE

($ paid for imports)(ratio of SEJ/$ for that year) ≠

Footnotes for Table 1.

* Where data are in kilocalories (kcal), multiply by 4186 J/kcal.

\+ Conventions for exponents, 2 x 10^7 is 2 E7, 5 x 10^{-3} is 5 E-3.

** Elevation measured relative to low point on the nation's border where rivers leave the country.

Footnotes to Table 1 (continued)

\# Gibbs free energy for 10 ppm rain relative to sea water salinity in evapotranspiring plants or to estuaries receiving freshwaters.

$$G = \frac{RT}{w} \log_e C_2/C_1 = \frac{(8.33\ \mathrm{J/mole/deg})(300°\mathrm{C})}{(18\ \mathrm{g/mole})} \left[\log_e \frac{(999{,}990)}{(965{,}000)}\right]$$

$$2.3 \log_{10} \frac{999{,}990}{965{,}000} = .0355$$

$$= 4.94\ \mathrm{J/g} = 4.94\ \mathrm{E6\ J/m^3}\ \text{rainwater.}$$

++ Effective concentration is that solution concentration in equilibrium with solid. For solids it is the solution concentration in which they are used. Environmental concentration is the solution concentration of waters in the soils and surface waters of the nation. Molecular weight is the mean molecular weight of the effective components of the commodity.

$$G = \frac{(8.33\ \mathrm{j/mole/deg})(300°\mathrm{C})}{(\text{effective molecular weight})}$$

$$\left[\log_e \frac{(\text{Effective concentration})}{(\text{Environmental concentration}}\right]\ \mathrm{J/g}$$

" Gibbs free energy of a chemical reaction is that of its standard states (gas at 1 atmosphere, solutions at 1 molar, and solids with assumed activity = 1) plus a term for the concentration differences from standard state that includes products in numerator and reactants in demonimator of logarithmic term

$$\Delta G = \frac{\Delta G_o}{w} + \frac{RT \log_e \frac{(c)(d)}{(a)(b)}}{w}\ \mathrm{J/g}$$

where G_o is obtained using standard free energy tables, W is molecular weight of commodity, (c) and (d) are concentrations of products, (a) is concentration of commodity, (b) is pressure of oxygen (0.21), R is 8.33 J/mole/deg, and T is Kelvin temperature.

≠ See Fig. 4.2.

Table 2. Formulae used for calculating actual energy in storages.

GEOTHERMAL HEAT STORAGE POTENTIAL

(reservoir volume)(density)(specific heat)$(\Delta T)^2$(1/T)(0.5)

(____m^3)(1 E6 cm^3/m^3)(____g/cm^3)(____gcal/g/deg)(____°)^2(1/____°K)

(4.186 J/gcal) =

POTENTIAL ENERGY IN STORED ORGANIC MATTER (FUELS, SOIL, PEAT, WOOD, ETC.)

(volume of material)(density)(organic fraction)(G)

where G = (_____kcal/g)(4186 j/kcal)

(______m^3)(1 E6 cm^3/m^3)(_____g/cm^3)(______organic)(__G__) =

Typical soil: 5.4 kcal/g; fraction organic; 0.03 g/g; density, 1.47 g/m^3

(1 E6 cm^3/m^3)(1.47 g/cm^3)(0.03)(5.4 kcal/g)(4186 J/kcal) = 10.0 E8 J/m^3

or

(weight)(chemical potential energy per unit weight)

(_____T)(1 E6 g/T)(____kcal/g)(4186 J/kcal)

or for fuel gas

(volume)(chemical potential energy per volume)

(______thsd cubic feet)(1.05 E9 J/thsd cubic feet)

GEOPOTENTIAL OF ELEVATED MATERIALS (WATER, MOUNTAINS, ROCK, ETC.)

(volume)(density)(gravity)(height of center of gravity of mass)

(____m^3)(1 E6 cm^3/m^3)(____g/cm^3)(1 E-3 kg/g)(9.8 m/sec^2)(____m)

NUCLEAR ENERGY

Heat equivalents from Schipper (1975)

(Weight of Uranium ore)(Fraction R235 in ore)(heat per weight)

(_____T)(0.007)(1 E6 g/T)(7.95 E10 J/g U235)

CHEMICAL POTENTIAL ENERGY OF WATER AND GROUNDWATER STORAGES

(Water volume)(density)(G)

where G is Gibbs free energy of water relative to salt water

$$G = \frac{(8.33\ \mathrm{J/mole/deg})(300^\circ\mathrm{C})}{(19\ \mathrm{g/mole})}\ [\log_e \frac{(1\ \mathrm{E6} = \mathrm{S})}{(965{,}000)}\ \mathrm{J/g}$$

where S is ppm solutes.

To estimate volume of ground waters:

(Volume of land mass)(porosity fraction)

(______m^3)(______)(= (______m^3)

Typical porosities:		
	Shale	.10
	Granite	.05
	Limestone	.10
	Basalt	.10
	Sands	.25
	Gravels	.40

(_____m^3)(1 E6 g/m^3)(__G__) =

CHEMICAL POTENTIAL ENERGY OF MINERAL DEPOSITS

(Volume)(density)(G)

where G is Gibbs free energy of the mineral relative to the surrounding environment in which it is used, dispersed or destroyed in chemical reactions.

For common minerals typical values for G are:

	J/g	Appendix
Phosphate deposits	58.3	6, note 4
Copper ore	1.65	
Bauxite (Al ore)	65.3	12
Iron ore	14.2	13
Potassium (KCl)	702.	15, note 8
Nitrogen (NH_3)	2170.	16, note 3

CHEMICAL POTENTIAL ENERGY OF BEDROCK READILY AVAILABLE (UPPER 10 m)

(Volume)(density)(G) =

where G is the Gibbs free energy of the bedrock relative to states after weathering.

Typical values of G are:

	Density, g/m^3	G, J/g
Shale	2.40	100
Sand, sandstone	3.17	611
Limestone	1.95	50
Granite	2.61	50
Basalt	2.79	172

(____m^3)(1 E6 cm^3/m^3)(______g/cm^3)(__G__) =

3. Transformities (ENERGY TRANSFORMATION RATIOS) AND CALCULATION OF EMBODIED ENERGY

The transformity (energy transformation ratio) measures the joules of one type of energy that must be transformed to generate a joule of another type of energy (or kilocalories of one type to generate a kilocalorie of another type). The ratio measures the factor by which one type of energy must be utilized to generate an energy of higher quality. Figure 2 is an example where the transformity (energy transformation ratio), in terms of energy of the type A on the left, is 20 joules of type A per joule of type B.

Examination of the transformities (transformation ratios) in real systems that have been operating for long periods under competitive circumstances, provides ratios that may approach the maximum that can be transformed at competitive, full power conditions.

If all kinds of energy are expressed in terms of solar energy reaching earth, the ratio becomes a numerical scale of the amount of work involved in generating various types of energy. Since flexibility, scarcity and ability to amplify increase as the energy transformation ratios from sunlight increases, the ratios constitute a scale for measuring energy quality.

The transformities (energy transformation ratios) provide an easy shorthand for calculating embodied energies in units of one type, simply by multiplying the actual energy flow or storage of one type by its solar energy transformation ratio. To obtain transformities (energy transformation ratios) from real world measurements, one constructs a systems diagram in which all of the inputs are known. Then these are all converted to embodied energies of solar quality using available energy transformation ratios. Then the ratio for the commodity is calculated by dividing the sum of inputs expressed in solar equivalent joules by actual output energy in the commodity produced. An example of this procedure is given in Fig. 3.

A table of transformities (energy transformation ratios) is given in Table 3.

Goods and Services from Energy/$ Ratio

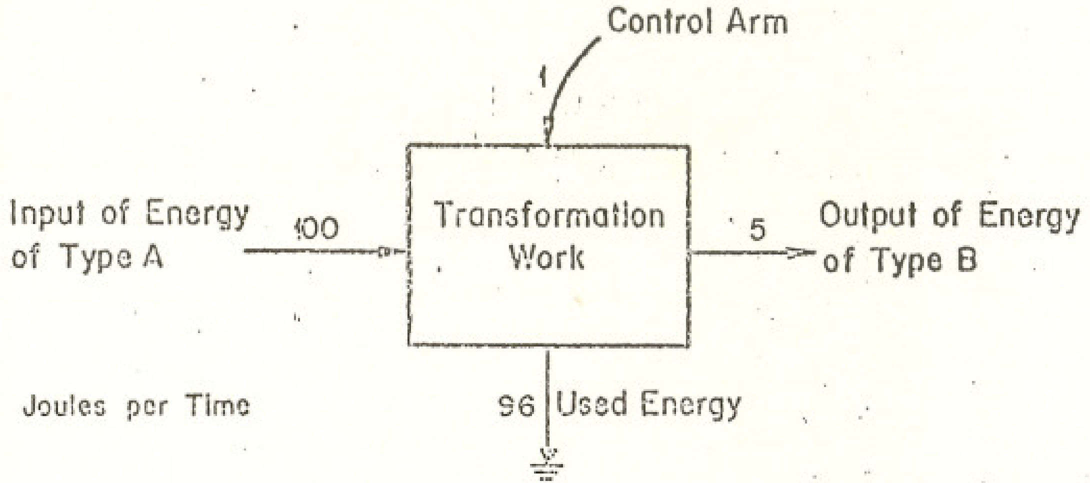
To evaluate the embodied energy in goods and services, multiply the dollars spent for them ~~by the~~ solar emergy ~~embodied energy~~/$ ratio of the economy.

Avoiding Double Counting

A subsystem such as corn production (Fig. 3) receives services, but also contributes the emergy ~~embodied energy~~ of its direct energy sources to the general economy and to the emergy ~~energy~~-dollar ratio. When evaluating service with emergy ~~energy~~/$ ratio, to avoid double counting, the contribution of the corn system's energy (s) to the economy must be subtracted from the emergy ~~energy~~/dollar ratio (P) before that ratio is used to calculate services to the subsystem. The corrected emergy ~~energy~~/dollar ratio to use is:

$$P' = (P - \frac{s}{X}) \qquad \text{where X is GNP}$$

Where services are less than 10% of a subsystem and the category of subsystems is less than 10% of the national energy budget, the correction is less than 1% and may be ignored. In the corn example calculated in Fig. 3, the correction is 3%.



TRANSFORMITY

~~Energy Transformation Ratio~~ $= \frac{A}{B} = \frac{100}{5} = 20$

Figure 2. Definition of transformity (energy transformation ratio) when the control arm input is a feedback from B and can be ignored as it is not an energy source.

Table 3. Energy transformation ratios from solar energy used.

Footnote	Energy Type	Transformity (Energy Transformation Ratio) Solar emjoules [redacted] per Joule sej/j
1	Solar energy	1
2	Surface winds; vapor gradient	62
	kinetic energy	663
3	Tides	23564
4	Physical energy in elevated rain	8888
5	Physical energy in elevated river flow	23564
6	Chemical potential energy in rain:	
	over land	15423
	in rivers	41068
7	Waves absorbed at shore	25889
8	Earth cycle	2.90 E4
	Net uplift	5.5 E18
	Geothermal heat (Appendix 2)	6.1 E3
	Geothermal convection (Appendix 3)	1.8 E4
9	Iron, 9.13 E14 SEJ/T	10.1 E6
	Steel, 1.78 E15 SEJ/T	1.97 E7
	Machinery, 6.7 E15 SEJ/T	7.50 E7
	Aluminum ingots, 1.63 E10 SEJ/T	--
10	Phosphate rock, 1.41 E11 SEJ/g	4.14 E7
	Nitrogen fertilizer	1.69 E6
	Potassium fertilizer	2.62 E6
	Iron ore, 8.55 E8 SEJ/g	6.02 E7
	Bauxite, 8.5 E8 SEJ/g	1.32 E7
11	Fuels:	
	Rainforest wood harvested	3.49 E4
	Coal	3.98 E4
	Oil	5.3 E4
	Electricity	15.9 E4
	Natural gas	4.8 E4
	Liquid moterfuel	6.6 E4
	Ethanol	6.0 E4
	Corn stalks	3.0 E4
	Straw	4.3 E3
	Dung	2.7 E4

Table 3 (continued)

Footnote	Energy Type	Energy Transformation Ratio Solar Equivalent Joules per Joule SEJ/J
12	Primitive corn	2.7 E4
	Industrial corn	6.8 E4
	Sugar	8.4 E4
	Bananas	5.3 E5
	Coconuts	1.9 E4
	Coconut oil	1.2 E4
	Copra	6.9 E5
13	Rubber	2.1 E4
	Soap	7.2 E5
	Wool	3.8 E6
14	Primitive labor	8.1 EE
	Bullock work	1.23 E5
15	Sheep meat	1.71 E6
	Calves	4.0 E6
---	Milk	2.2 E5
	Butter	1.3 E6
16	Selected high quality logs	3.1 E5
	Plantation pine	6.7 E3
17	Top soil	6.3 E4
	Earth (clay), 1.7 E9 SEJ/g	--
18	Uranium	1.8 E3

Footnotes to Table 3

1. Solar energy input absorbed, 3.93 E24 J/yr. See Appendix 1. Energy transformation ratio is 1 by definition.

2. Wind used at surface of the earth estimated as 10% of total flux of wind energy, 2 E12 kw (Monin, 1972).

   (2 E12 kw)(1 J/sec/watt)(1 E3 w/kw)(3.154 E7 sec/yr)

   (0.10) = 6.31 E21 J/yr

   ETR as ratio of total biosphere input, 3.93 E24 SEJ/yr (Appendix 2) to surface wind energy:

   $$\frac{3.93\text{ E24 SEJ/yr}}{6.31\text{ E21 J/yr}} = 663\text{ SEJ/J surface wind}$$

Footnotes to Table 3 (continued)

Water vapor gradient in wind.

Total mass of water in atmosphere = 1.24 E19 g; turnover time for water in the atmosphere = 11.23 d (Monin 1972); mean flux of vapor, 1.24 E19 g/11.23 d = 1.104 E18 g/d.

$$\text{Gibbs free energy per gram} = \frac{(8.33\ \text{J/mole/deg})(275\ \text{deg})\ \log_e\ (7\text{mb}/2\text{mb})}{(18\ \text{g/mole})}$$

$$= 159\ \text{J/g vapor}$$

World vapor gradient flux:

(1.104 E18 g/d)(365 d/y)(159 J/g) = 6.41 E22 J/y

$$\text{ETR:}\quad \frac{(3.94\ \text{E24 SEJ/y})}{(641\ \text{E22 J/y})} = 61.5$$

3. Tidal physical energy absorbed in estuaries and on shelves. Energy transformation ratio the same as that for elevated stream waters.

4. Physical energy in rain on elevated land.

World's rain on land, 105,000 km^3/yr; average elevation of land, 875 m (Ryabchikov 1975).

$(1.05\ \text{E5 km}^3)(1\ \text{E12 kg}\cdot\text{km}^3)(9.8\ \text{m/sec}^2)(8.75\ \text{E2 m})$

= 9.0 E20 J/yr

$$\text{ETR:}\quad \frac{8.0\ \text{E24 SEJ/yr}}{9.0\ \text{E20 J/yr}} = 8888\ \text{SEJ/J}$$

5. Physical energy in stream flow.

Global runoff, 39.6 E3 km^3/yr (Todd 1970); average elevation, 875 m

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

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

6. Chemical potential energy in rain.

Continental rain 105,000 km^3/yr, 10 ppm rain compared to 35,000 ppm.

$$\text{Gibbs free energy/g} = \frac{(8.33\ \text{J/mole/deg})(300°\text{C})}{(18\ \text{g/mole})}$$

$$\log_e \frac{(999{,}990)}{(965{,}000)} = 4.94\ \text{J/g}$$

$(1.05\ \text{E5 km}^3/\text{yr})(1\ \text{E15 g/km}^2)(4.94\ \text{J/g Gibbs free energy})$

= 5.187 E20 J/yr

Footnotes to Table 3 (continued)

6A. Chemical potential energy in rivers.

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

Gibbs free energy per gram water:

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

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

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

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

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

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

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

8. Earth cycle

Work of earth uplift replacing erosion without net change in elevation indicated by heat flow. From Sclater et al. (1980); continental heat flow is 2.746 E20 J/y; solar equivalents from Appendix A3.

$$ETR: \frac{(8.0\ E24\ SEJ/y)}{(2.746\ E20\ S/y)} = 2.90\ E4\ SEJ/J\ continent\ heat\ flow$$

Net uplift and land elevation, 875 m over 1 billion years; density 2.6 T/m^3;

$$(area)(uplift\ per\ time)(density)(0.5)(uplift\ per\ time)(9.8\ m/sec^2)$$

$$(1.5\ E14\ m^2)(875\ m/1\ E9\ y)(2.62\ E3\ kg/m^3)(0.5)(875\ m/1\ E9\ y)(9.8\ m/sec^2)$$

$$= 1.47\ E6\ J/g;$$ See Appendix A8

$$ETR: \frac{(8.0\ E24\ J/y)}{(1.47\ E6\ J/y)} = 5.44\ E18\ SEJ/J$$

9. Iron, steel, machinery, see Appendix A13; aluminum ingots, see Appendix A12.

10. Phosphate, see Appendix A6, note 4.
Potassium, see Appendix A15
Iron ore, see Appendix A7.
Bauxite, see Appendix A7.
Nitrogen, see Appendix A16.

Footnotes to Table 3 (continued)

11. Fuels, see Appendix A5, Parts 1-3; ethanol, Appendix A17; corn stalks, Appendix A9; straw and dung, Appendix A19.

12. Corn, Appendix A9; sugar, Appendix A17; bananas, Fig. 9.4; coconuts, Fig. 9.5.

13. Rubber, see Fig. 7.5; soap, Fig. 9.5; wool, Appendix A11.

14. Human Labor.

    Hand labor as in primitive agriculture, the energy per area of support; Gibbs free energy in rain, 4.94 J/g from footnote 6, Table 3.1.

    $(4.94 \text{ J/g})(1 \text{ E6 g/m}^3)(1 \text{ A/person})(0.405 \text{ ha/A})(1 \text{ M}^3/\text{m}^2)$
    $(1 \text{ m}^3 \text{ rain/m}^2)(1 \text{ E4 m}^2/\text{ha}) = 2.00 \text{ E10 J/person}$

    Embodied energy per person:

    (2.0 E10 water J/person)(1.54 E4 SEJ/J water)

    = 3.09 E14 SEJ/person/y

    $$\text{ETR:} \quad \frac{3.09 \text{ E14 SEJ/person}}{(2500 \text{ kcal/person/day})(4186 \text{ J/kcal})(365 \text{ d/y})}$$

    = 8.09 E4 SEJ/J

15. See also Appendix A9a. Sheep meat, Appendix A11; calves, butter, milk, Appendix A19.

16. Selected high quality rain forest timbers shipped. See Fig. 7.6; plantation pine, see Appendix A10.

17. Top soil, see Appendix A18.

18. Uranium in fission reactor

    109 E13 kcal U235 generated 4.9 E13 kcal net

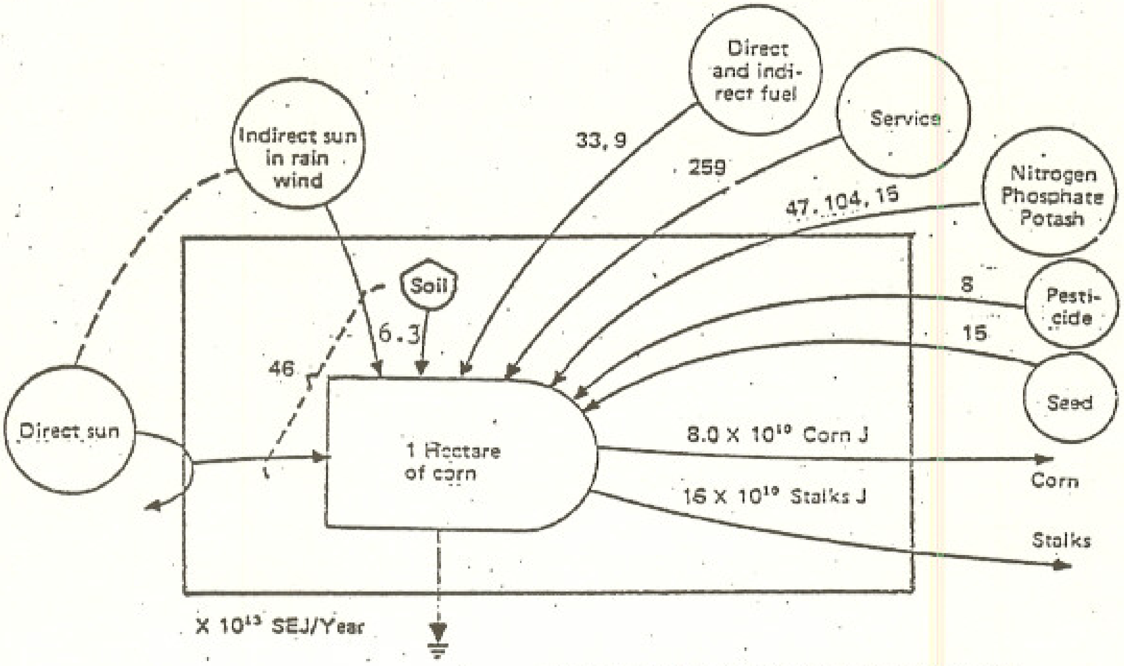
    Coal equivalents of electricity (Kylstra and Ki Han 1975)

    $$\frac{109 \text{ E13 kcal U235}}{4.9 \text{ E13 coal kcal}} = 22.2 \text{ uran J/coal J}$$

    $$\frac{3.98 \text{ E4 SEJ/coal J}}{22.2 \text{ uran J/coal J}} = 1793 \text{ SEJ/uran J}$$

4. AN EXAMPLE, INDUSTRIAL CORN

Using data supplied by Pimentel (1979) and adding environmental and service inflows, a more complete energy analysis was given. See Table 4 and Fig. 3.



$$\mathrm{ETR} = \frac{(46 + 6.3 + 42 + 259 + 166 + 8 + 15) \times 10^{13}}{8.0 \times 10^{10}} = 6.3 \times 10^{4}$$

Fig. 3. Energy analysis of industrial corn. See Table 4.

Table 4. Energy flows in one ha of industrial corn.

Footnote	Type of Energy	Actual Energy J/y	ETR SEJ/J	Embodied Solar Energy Energy E13 SEJ/y
1.	Direct Sun	1.05 E13	1	1.05
2.	Indirect Sun, rain	3.0 E10	1.54 E4	46.0
3.	Soil used up	9.92 E8	6.3 E4	6.3
4.	Direct fuel	5.02 E9	6.6 E4	33.0
5.	Indirect fuel in machinery in coal equivalents	2.39 E9	4.0 E4	9.4
6.	Service, $782/y	–	3.45 E12/$	270.0
7.	Pesticide, oil equivalent	1.2 E9	6.6 E4	8.0
8.	Phosphate	2.51 E7	4.14 E7	104.0
9.	Nitrogen	2.78 E8	1.69 E6	47.0
10.	Potassium	5.62 E7	2.62 E6	14.7
11.	Seed (fuel equivalents)	2.20 E9	6.6 E4	14.5
12.	Corn yield	8.02 E4	6.8 E4	548.9
13.	Corn stalks	16.0 E4	3.4 E4	548.9

Footnotes for Table 4.

* Many data from Pimentel (1979, p. 69)

1. Direct Sun

$(1\ E6\ kcal/m^2/y)(1\ E4\ m^2/ha)(0.25y)(4186\ J/kcal)$

$= 1.05\ E13\ J/y$

2. Indirect sun in rain
5 J/g (Table 3.1, footnote 6)
rain transpired by crop, $0.6\ m^3/m^2/y$

$(1\ E4\ m^2/ha)(0.6\ m^3/m^2/y)(1\ E6\ g/m^3\ density)(5\ J/g)$

$= 3\ E10\ J/y$

Footnotes to Table 4 continued

3. Soil used up

Organic matter in cornland soil, 12 T/acre in 45 cm.

$$\frac{(12\ \mathrm{T/acre})\quad(1\ \mathrm{E6\ g/T})}{(4.05\ \mathrm{E3\ m^2/acre})(0.45\ \mathrm{m^3/m^2})} = 6.58\ \mathrm{E3\ gorg./m^3}$$

Top soil loss in corn land, 10 T/ha/y
(Larson, Pierce and Dowdy, 1983)

$$\frac{(10\ \mathrm{T/ha/y})(1\ \mathrm{E6\ g/T})(6.58\ \mathrm{E3\ gorg./m^3}}{(1.5\ \mathrm{E6\ g/m^3\ density})} = 431\ \mathrm{E4\ g/ha/y}$$

(4.39 E4 g/ha/y)(5.4 kcal/g)(4186 J/kcal) = 9.92 E8 J/y

4. Direct fuel

(1.2 E6 kcal/ha/y)(4186 J/kcal) = 5.02 E9 J/y

5. Indirect fuel in machinery

5.58 E5 kcal coal equiv./ha/y based on 10 y depreciation (Pimentel, 1979); (5.58 E5 kcal/y)(4186 J/kcal) = 2.34 E9 J/y

6. Service

To avoid double counting of the service that the fuel embodied in goods (machinery) generated, the dollar equivalent of that fuel was subtracted; 1975 US Energy-dollar ratio from Appendix A4 is

3.45 E12 SEJ/$.

Correction: $\dfrac{(2.34\ \mathrm{E9\ J/y\ coal\ equiv.\ in\ machinery})(4\ \mathrm{E4\ SEJ/J})}{3.45\ \mathrm{E12\ SEJ/\$}}$

= $27.1

($150/T)(5.39 T) - ($27.1) = $782

To elimnate double counting in evaluating service due to corn contributing to US energy-dollar ratio, US corn energy(S) contributing to the total energy-dollar artio(P_1) is subtr subtracted. The corrected energy-dollar ratio for service is:

5. INDICES

The following are useful indices for the system analyses.

The net energy ratio is the embodied energy of the output divided by the embodied energy of the inputs to the process fed back from the economy. See Figure 4. This ratio indicates whether the process can compete in supplying a primary energy source for the economy. In the recent past the ratio for buying foreign oil was about 6 to 1. Processes yielding less than this are not economic as primary energy sources.

The energy investment ratio is the ratio of the embodied energy fed back from the economy to the embodied energy inputs from the free environment. See Fig. 5. This ratio indicates if the process is economic as a utilizer of the economy's investments in comparison with alternatives. To be economic the process should have a smaller ratio than competitors so that its prices are less and it can 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. The world ratio in 1980 was 1.4 but the energy voracious United States was about 8 (Appendix A.4).

Some systems may be useful without being a good primary source (having high net energy yield ratio) or being good secondary source (having a competitive energy investment ratio). If the system is a consumer system such as a household or hospital, it may draw some environmental energies into its processes thus making the consumption more efficient. The appropriate index to evaluate measures for improving consumer efficiency in units of embodied energy is service increase (ΔY) for increase in energy invested (ΔF). See Fig. 6.

The energy analysis of subsystems may be useful for evaluating the degree of industrialization, contributions of environment and associated environmental loading, for anticipating success of subsystems being considered for development, etc.

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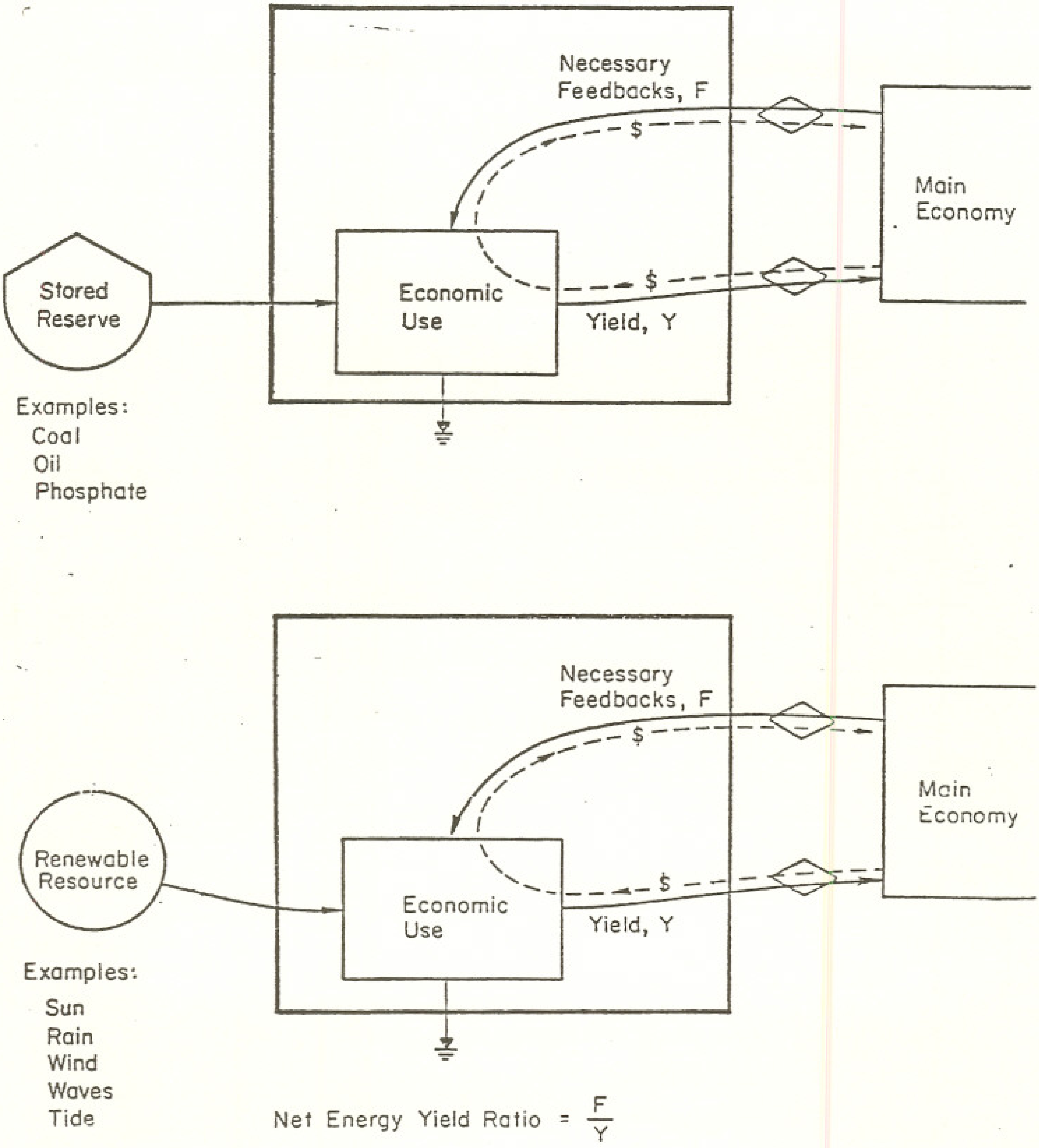
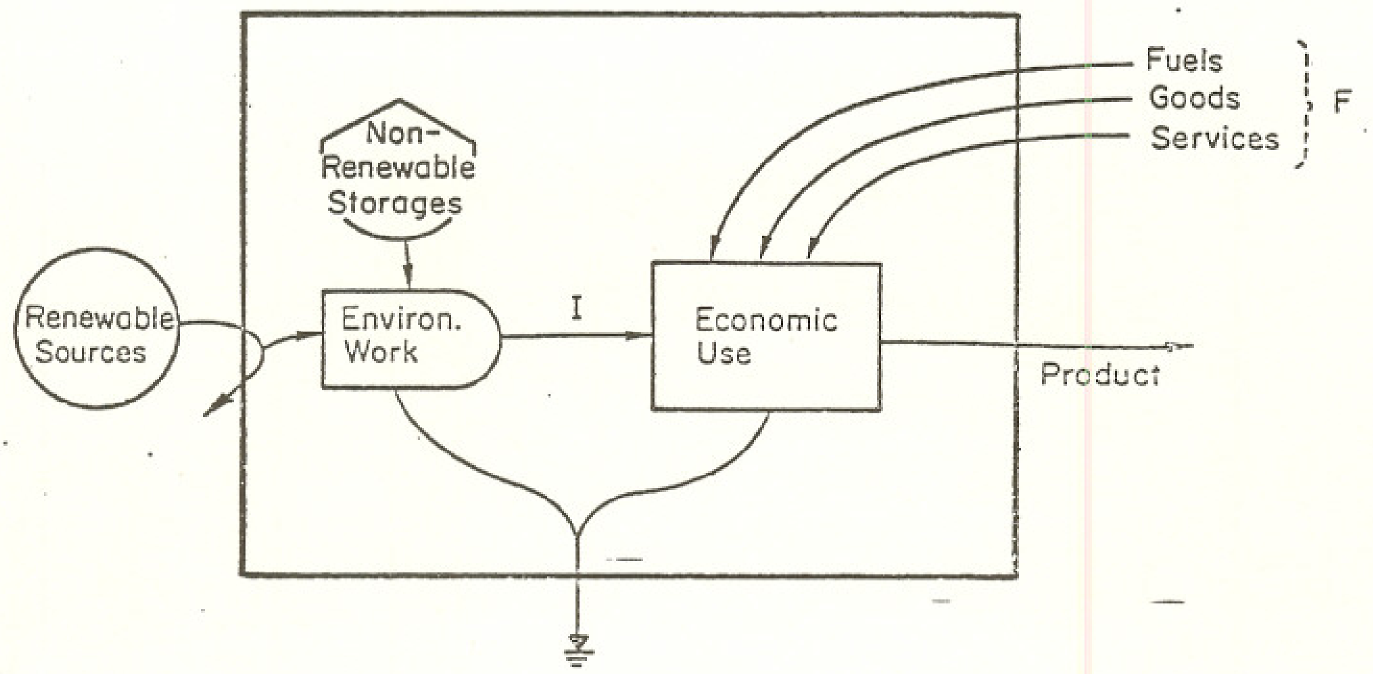
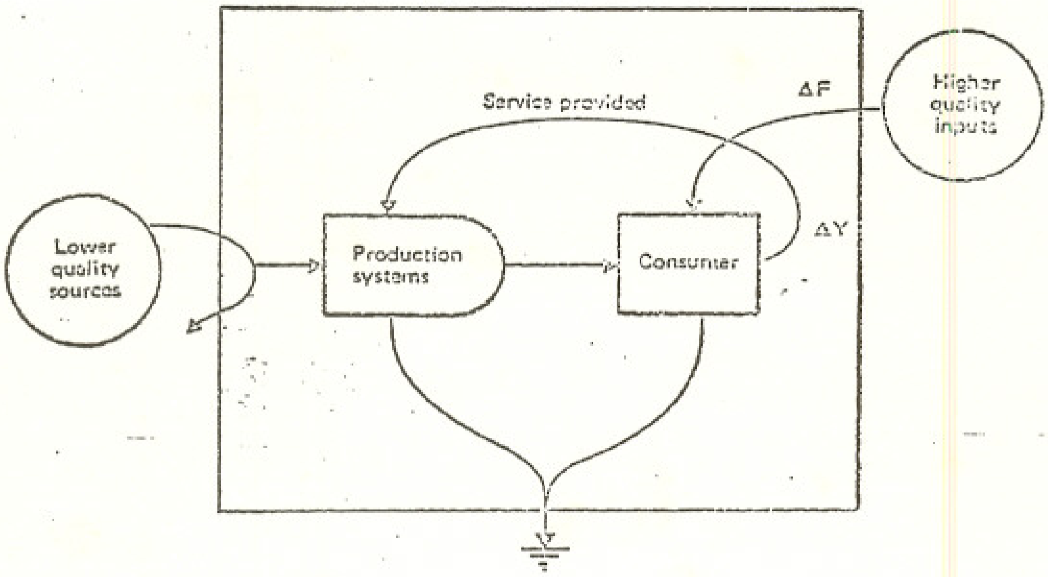


Figure 4. Diagram defining the net energy yield ratio for evaluating primary energy sources. Both F and Y should be in embodied energy units of the same quality. (a) nonrenewable source; (b) renewable resource.



Energy Investment Ratio = $\frac{F}{I}$
using Energy Units of the Same Quality

Figure 5. Diagram defining the energy investment ratio for evaluating whether matching of investments with environmental contributions is competitive and its loading of environmental systems.



Consumer efficiency amplifier $\frac{\Delta Y}{\Delta F} = \frac{\text{Service increase}}{\text{Investment increase}^{*}}$

*High quality feedback

Figure 6. Diagram defining consumer efficiency amplifier.

Footnotes to Table 4 continued.

(P - S/X) where X is Gross National Product

For 1975: $(3.4\ \mathrm{E12\ SEJ/\$}) - \frac{(1.40\ \mathrm{E23\ SEJ/y})}{(\$1.32\ \mathrm{E12/y})} = 3.31\ \mathrm{E12\ SEJ/\$}$

($782/y)(3.31 E12 SEJ/$) = 2.59 E15 SEJ/y

7. Pesticide

Oil equivalents used in pesticide manufacture, 2.87 E5 kcal/ha Pimentel, 1979).

(2.87 E5 kcal/y)(4186 J/kcal) = 1.20 E9 J/y

8. Phosphate (7.2 E4 g/y)(348 J/g) = 2.51 E7 J/y

9. Nitrogen

2.17 E9 J/T from Appendix A16

(128 kg/y)(2.17 E6 J/ky) = 2.79 E8 J/y

10. Potassium

702 J/g from Table A15, footnote 8

(80 E3 g/y)(702 J/g) = 5.62 E7 J/y

11. Seeds

Oil equivalents of seed production,
5.25 E5 kcal/ha (Pimentel, 1979)

(5.25 E5 kcal/y)(4186 J/kcal) = 2.20 E9 J/y

12. Corn yield

(19.5 E6 kcal/ha)(4186 J/kcal) = 8.02 E10 J/y

ETR: $\frac{\text{sum of inputs in SEJ}}{\text{output J}}$

ETR = $\frac{(549\ \mathrm{E12\ SEJ/y})}{(8.02\ \mathrm{E10\ J/y})} = 6.84\ \mathrm{E4\ J/y}$

13. Corn stalks

2 times corn yield

ETR = $\frac{(549\ \mathrm{E13\ SEJ/y})}{(16.\ \mathrm{E10\ J/y})} = 3.43\ \mathrm{E4\ J/y}$