ENVIRONMENTAL ACCOUNTING

EMERGY and Environmental Decision Making

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JOHN WILEY & SONS, INC.
New York / Chichester / Brisbane / Toronto / Singapore

This text is printed on acid-free paper.

Library of Congress Cataloging in Publication Data:

Odum, Howard T., 1924–
Environmental accounting : EMERGY and environmental decision making / Howard T. Odum.
p. cm.
Includes bibliographical references (p.).
ISBN0-471-11442-1 (acid-free paper)
1. Natural resources—Accounting. 2. Environmental impact analysis. I. Title.
HF5686.N3038 1996
657'.73–dc20 95-11683

Printed in the United States of America

10 9 8 7 6 5 4 3 2

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APPENDIX C

TRANSFORMITIES

Ten methods are suggested for calculating solar transformities (Table 14.3). Main environmental energy flows are calculated from data on the hierarchical energy web of the geobiosphere (methods 1 and 2). Other transformities are calculated from analysis of subsystems of energy production and transformation (3). Solar transformities may also be calculated from storage development times (4), by combining other transformities (5), from data on energy flows in networks (6), by means of a computer-solved matrix evaluation (7), by source tracking in an energy network (8), from hierarchical distribution graphs (9), and turnover time (10).

This appendix contains solar transformities used in this book, indicating tables or references where they were calculated.

TABLE C.1. Solar Transformity of Electric Power

Note	System	Solar Empower (sej/yr)*	Electric Power (J/yr)	Transformity
1	Coal power plant	160,000	1	160,000
2	World stream geopotential	9.44×10^{24}	10×10^{20}	94,400
3	Hydroelectric power, Sweden	1.95×10^{24}	2.43×10^{17}	80,246
4	Wood power plant, Jari, Brazil	2.38×10^{20}	1.17×10^{15}	203,418
5	Solar voltaic grid, Austin, Tex.	7.5×10^{17}	1.8×10^{12}	416,666
6	Hydroelectric, Tucurui, Brazil	1.65×10^{22}	1.0×10^{17}	165,000
7	Wood power plant, Thailand	2.42×10^{14}	3.6×10^{9}	67,222
8	Oil power plant, Thailand	7.14×10^{14}	3.6×10^{9}	197,777
9	Coal power plant, Thailand	6.10×10^{14}	3.6×10^{9}	169,444
10	Lignite power plant, Thailand	5.47×10^{14}	3.6×10^{9}	151,944
11	Lignite power plant, Texas	5.4×10^{21}	2.65×10^{16}	204,384
	Mean			173,681

* 18% added to those EMERGY evaluations that were made before tide values were added to global solar EMERGY budget (items 6 and 11)

[1] Assuming 4 coal emj/J of electric power and 40,000 sej/J coal.

[2] Global calculation made with assumptions about the empower required for the mountain uplift, the carving of basins, and the construction of dams. Global solar empower, 9.44×10^{24} sej/yr, generates an average stream flow over land of 39.6×10^{3} km^3 runoff (Todd 1970) and maintains an average land elevation of 875 m (Ryabchikov, 1975). Average land and average streams were taken as by-products of shared empower.

Stream geopotential:

$$(39.6 \times 10^{12} \text{ m}^3/\text{yr})(875 \text{ m})(1000 \text{ kg/m}^3)(9.8 \text{ m/sec}^2) = 3.39 \times 10^{20} \text{ J/yr.}$$

Electric power potential = stream geopotential times efficiency of hydroelectric conversion taken as 80%:

$$(3.39 \times 10^{20})(0.8) = 2.7 \times 10^{20} \text{ J/yr electrical.}$$

For a 25% feedback of empower from the economy for dam and operation, the net yield of electricity could be:

$$\tfrac{3}{4}(2.7 \times 10^{20} \text{ J/yr}) = 2.0 \times 10^{20} \text{ J/yr.}$$

If stream energy in the long run has to carve a basin half the time to allow for generation of electricity the other half, then the electric output is half, or 1×10^{20} J/yr.

[3] Realized electric power in 1988: 72 terawatt-hr (Sweden, 1990):

$$(72 \times 10^{9} \text{ kWh/yr})(860 \text{ kcal/kWh})(4186 \text{ J/kcal}) = 2.60 \times 10^{17} \text{ J/yr}$$

For 80% efficiency, input geopotential is:

$$2.6 \times 10^{17}/0.8 = 3.25 \times 10^{17} \text{ J/yr.}$$

Time for erosion to make a basin may be assumed to be similar to the time for filling with sediment. Thus the dam in the long run operates for half the time as it fills with sediment, eroding for half using the same stream energy. Either consider the long-range electric yield as half, or consider the short-term operation as receiving the prorated EMERGY of the carved basin as equivalent to the input geopotential (2 times geopotential in use):

$$(2)*(3.25 \times 10^{17}\ \text{J/yr}) = 6.5 \times 10^{17}\ \text{J/yr input geopotential.}$$

For third-order streams, solar transformity from Figure 2.8 on the Mississippi River is 3 × 10^4 sej/J and therefore the input solar EMERGY is:

$$(3 \times 10^4\ \text{sej/J})(6.5 \times 10^{17}\ \text{J/yr}) = 1.95 \times 10^{22}\ \text{sej/yr}$$

Using $\frac{1}{4}$ of empower feedback for dam and operation, net electric yield is:

$$(3.25 \times 10^{17})(0.75) = 2.43 \times 10^{17}\ \text{J/yr}$$

[4] Rainforest logs are supplied in a steady state from a 100-yr rotation requiring 2.324 × 10^9 m^2. Solar EMERGY from the main use of rain by trees and 3 mm transpiration, 4.94 J Gibbs free energy per gram of rainwater and solar transformity of rain, 1.82 × 10^4 sej/J:

$$(3\ \text{mm/day})(365\ \text{days/yr})(1 \times 10^{-3}\ \text{m}^3/\text{mm})(1 \times 10^6\ \text{g/m}^3)(4.94\ \text{J/g water})(2.3 \times 10^9\ \text{m}^2)(1.82 \times 10^4\ \text{sej/J}) = 2.27 \times 10^{20}\ \text{sej/yr}$$

plus solar EMERGY from fuels use (0.085 × 10^{20} sej/yr) and services used (0.025 × 10^{20} sej/yr). Electricity produced (1.67 × 10^{15} J/yr) minus electricity used in the processing: 0.032 J/yr debarking and chipping and 0.46 × 10^{15} J/yr in plant operations.

[5] Power grid evaluated by R. King and Schmandt (1991). See Table 8.2.

[6] Modified from M. T. Brown (1986b). Energy analysis of the hydroelectric dam near Tucurui, Brazil, pp. 82–91 in H. T. Odum et al. (1985). Electricity produced: 1.0 × 10^{17} J/yr based on 0.8 capacity factor and 4000 MW. Contribution to dam and operation from the economy: 4.25 × 10^{21} sej/yr. Contribution of geopotential of inflowing water and also the prorated contribution of the basin that was developed by the same streamflows earlier (see note 3):

$$(2.06 \times 10^{17}\ \text{J/yr})(2.36 \times 10^4\ \text{sej/J}) = 4.87 \times 10^{21}\ \text{sej/yr}$$

Total input includes this factor twice (present inflow + prorated basin emergy). In a full cycle of damming and allowing reerosion of basin, there is no net sediment diversion:

$$(4.87 + 4.87 + 4.25) \times 10^{21}\ \text{sej/yr} = 13.95 \times 10^{21}\ \text{sej/yr}$$
$$(13.95 \times 10^{21}\ \text{sej/yr})(1.18\ \text{tidal correction}) = 1.646 \times 10^{22}\ \text{sej/yr}$$

[7] Wood power plant (25 MW generating 173.5 × 10^3 kWh/yr) using eucalyptis plantation wood; evaluations by S. Doherty and Bo Hector (Doherty and Nilsson, 1992). Values estimated per megawatt-hour electric:

$$(1\ \text{mWh})(1000\ \text{kWh/mWh})(860\ \text{kcal/kWh})(4186\ \text{J/kcal}) = 3.59 \times 10^9\ \text{J/yr}$$

Solar EMERGY inputs in sej/mWh: Rain, 44 × 10^{12}; fertilizer, 6 × 10^{12}; labor, 7 × 10^{12}; plantation capital, 29 × 10^{12}; plant operational service, 96 × 10^{12}; power plant capital, 55 × 10^{12}; transmission, 6 × 10^{12}; total, 242 × 10^{12} sej/mWh.

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[8] Oil-fired power plant; evaluations by S. Doherty and Bo Hector (Doherty and Nilsson, 1992). Values estimated per megawatt-hour electric:

$$(1 \text{ mWh})(1000 \text{ kWh/mWh})(860 \text{ kcal/kWh})(4186 \text{ J/kcal}) = 3.59 \times 10^{9} \text{ J/yr}$$

Solar EMERGY inputs in sej/mWh: oil, 402×10^{12}; oil services, 100×10^{12}; plant operational services, 131×10^{12}; capital, 40×10^{12}; transmission, 41×10^{12}; total, 714×10^{12} sej/mWh.

[9] Coal-powered plant; evaluations by S. Doherty and Bo Hector (Doherty and Nilsson, 1992). Values estimated per megawatt-hour electric:

$$(1 \text{ mWh})(1000 \text{ kWh/MWh})(860 \text{ kcal/kWh})4186 \text{ J/kcal}) = 3.59 \times 10^{9} \text{ J/yr}$$

Solar EMERGY inputs in sej/MWh: Coal, 380×10^{12}; oil services, 80×10^{12}; plant operational services, 109×10^{12}; capital, 58×10^{12}; transmission, 43×10^{12}; total, 610×10^{12} sej/mWh.

[10] Lignite power plant; evaluations by S. Doherty and Bo Hector (Doherty and Nilsson, 1992). Values estimated per megawatt-hour electric:

$$(1 \text{ mWh})(1000 \text{ kWh/MWh})(860 \text{ kcal/kWh})(4186 \text{ J/kcal}) = 3.59 \times 10^{9} \text{ J/yr}$$

Solar EMERGY inputs in sej/MWh: Lignite, 279×10^{12}; mining services, 93×10^{12}; plant operational services, 100×10^{12}; capital, 44×10^{12}; transmission, 30×10^{12}’ total, 547×10^{12} sej/MWh.

[11] Big Brown lignite power plant, Texas (Odum et al., 1987a):

$$(7.27 \times 10^{13} \text{ J/day})(365 \text{ days/yr}) = 2.65 \times 10^{16} \text{ J/yr electric power produced}$$

Inputs evaluated in sej/day:
Mining inputs: Lignite mined for power plant, 73.7×10^{17}; topsoil lost, 3.1×10^{17}; fuel used, 0.032×10^{17}; electric power used, 0.49×10^{17}; equipment maintenance, 0.93×10^{17}; goods and services, 6.2×10^{17}; total, 84.45×10^{17} sej/day. Power-plant inputs: cooling water, 0.10×10^{17}; equipment maintenance, 1.24; goods and services, 40×10^{17}; total, 41.34×10^{17}; sej/day. Mining and power plant on a 1-year basis.

$$(365)(84.45 + 41.34) \times 10^{17} = 4.59 \times 10^{21} \text{ sej/yr}$$

Tidal correction to global transformities:

$$(4.59 \times 10^{21})(1.18) = 5.4 \times 10^{21} \text{ sej/yr}$$

TABLE C.2. Solar Transformity for Fuels

Note	Item	Solar Transformity ($\times 10^4$ sej/J)
1	Rainforest logs	3.2
2	Rainforest wood, transported and chipped	4.4
3	Liquid motor fuel	6.6
4	Crude oil	5.4
5	Natural gas	4.8
6	Coal	4.0
7	Peat	1.9
8	Lignite	3.7
9	Plantation pine	0.7
10	Charcoal	10.6

[1] Energy and EMERGY (Odum and Odum, 1983)

$$\frac{(8.3 \times 10^{12}\ \text{sej/m}^2/100\ \text{yr})}{2.58 \times 10^6\ \text{J/m}^2/100\ \text{yr}} = 3.23 \times 10^4\ \text{sej/J}$$

[2] Energy and EMERGY (Odum and Odum, 1983)

$$\frac{2.0 \times 10^5\ \text{sej/elect J}}{4.56\ \text{wood J/elect J}} = 4.38 \times 10^4\ \text{sej/J}$$

[3] 1.65 coal J/J liquid motor fuel (Slesser, 1978):

$$(4 \times 10^4\ \text{sej/J coal})(1.65\ \text{coal J/motor fuel J}) = 6.6 \times 10^4\ \text{sej/J motor fuel}$$

[4] 19% crude oil used in refining and transport (Cook, 1976)

$$\frac{6.6 \times 10^4\ \text{sej/J motor fuel}}{1.23\ \text{crude J/motor fuel J}} = 5.37\ \text{sej/J motor fuel}$$

[5] Natural gas is 20% more efficient in boilers than is coal (Cook, 1976):

$$(4 \times 10^4\ \text{sej/J coal})(1.2\ \text{coal J/natural gas J}) = 4.8 \times 10^4$$

[6] $(1.7 \times 10^5$ sej/J elect power)/(4 coal J/J elect power) $= 4.3 \times 10^4$ sej/coal J
From sedimentary cycle calculation, Table 3.5, 3.4×10^4 sej/coal J:

$$\text{Average } (4.3 \times 10^4 + 3.4 \times 10^4/2 = 3.9\ \text{sej/J}$$

Rounded to 4.0 as a temporary standard.

[7] Table 5.4.

[8] Lignite analysis (Odum et al., 1987a).

[9] Monterey pine (Table 5.2).

[10] Charcoal (Sundberg et al., 1991).

TABLE C.3. Solar Transformities and Mass EMERGY of Global Flows

Item	Transformity (sej/J)*	EMERGY/gram ($\times 10^9$ sej/g)*	Source
GLOBAL solar insolation	1	—	By definition
Surface wind	1,496		Table 3.2
Convective Earth Heat	6,055		Table 3.1
Oceanic rain, chemical potential	7,435		Note 1
Physical energy, rain on land	10,488		Table 3.2
Tidal energy absorbed	16,842		Table 3.1
Volcanic heat	18,000		Fig. 8.9
Chemical energy, rain on land	18,199		Table 3.2
Physical stream energy	27,874		Table 3.2
Waves absorbed on shores	30,550		Table 3.2
Continental earth cycle, heat flow	34,377		Table 3.2
Chemical stream energy	48,459		Table 3.2
Oceanic upwelling, inorganic carbon	7.8×10^5	0.18	Note 2
Oceanic upwelling, nitrate-nitrogen	2.6×10^6	1.05	Note 2
Oceanic upwelling, phosphate	3.8×10^7	9.5	Note 2

* sej/J = solar emjoules per joule; sej/g = solar emjoules per gram.

[1] $(9.44 \times 10^{24}$ sej/yr$)/[(2.57 \times 10^{14}$ m^3/yr$)(1 \times 10^6$ g/m$^3)(4.94$ J/g$)] = 7435$ sej/J.

[2] Phosporus upwelling flux from Garrels et al., (1975); nitrogen/phosphorus (9.0) and carbon/phosphorus (53.0) ratios from Redfield (1934); Gibbs free energies between deep water and the surface based on concentration ratios: phosphorus, 83/3; nitrate, 500/50; inorganic carbon, 600/20. The results are: 228 J/g C, 410 J/g N, 251 J/g P.

TABLE C.4. Transformity and EMERGY per Unit Mass in Earth Substances

Item	Transformity (sej/J)	EMERGY/gram ($\times 10^9$ sej/g)	Source
Oceal floor			
Oceanic basalt	0.15		Table 3.3
Pelagic and abyssal sediments	0.97		Table 3.3
Continents			
Granitic rocks	0.50		Table 3.3
Mountains on land	1.12		Table 3.3
Metamorphic rocks	1.45		Table 3.3
Continental sediment	1.88		Table 3.3
Volcanic extrusion at surface	4.5		Table 3.3
Global sedimentary cycle		1.0	Table 3.5
Shale	1.0×10^9	1.0	Table 3.5
Limestone	1.62×10^6	1.0	Table 3.5
Sandstone	2.0×10^7	1.0	Table 3.5
Evaporites	3.3×10^6	1.0	Table 3.5
Coal	4.0×10^4	1.0	Table C.2
Sedimentary Iron ore	6.2×10^7	1.0	Table 3.5
Bauxite (Aluminum ore)	1.5×10^7	1.0	Table 3.5
Soil clay from shale	—	2.0	Table 3.5
Top soil organic matter	7.4×10^4		Note 1
Clay from weathering	—	1.71	Note 2
Potassium fertilizer	3.0×10^6	1.1 (1.74/g K)	Note 3
Ammonia fertilizer	1.86×10^6	3.8 (4.6/g N)	Note 4
Phosphate fertilizer	1.01×10^7	3.9 (17.8/g)	Table 7.7

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[1] Replacement time, 500 yr (Jenny, 1982); 3% organic content, 5.4 kcal/g dry in upper 0.45 m with density 1.4 g/ml.

[2] Earth formation and erosion rate: Uplift and erosion rate from Garrels et al., (1975); half of weathered uplift is clay (Siegel, 1974, after Krauskopf, 1967, and Goldick 1938):

$$(2.4 \times 10^{-5}\ \text{m/yr})(2.6 \times 10^{6}\ \text{g/m}^3\ \text{rock density})(0.5) = 31.2\ \text{g/m}^2/\text{yr}$$

$$(9.44 \times 10^{24}\ \text{sej/yr})/(31.2\ \text{g/m}^2/\text{yr})(1.5 \times 10^{14}\ \text{m}^2\ \text{continent area}) = 1.71 \times 10^{9}\ \text{sej/g}$$

[3] Potassium chloride from Dead Sea works in Israel (H. T. Odum and Odum, 1983, p. 477). EMERGY based on solar energy of evaporating water, energy in dry air, fresh water in processing, fuel, electricity, services, and hydrostatic head of water processing.

[4] Odum and Odum (1983).

TABLE C.5. Transformity and Solar EMERGY per Mass in Plant Products and Fuels

Item	Transformity (sej/J)	EMERGY/gram $\times 10^9$ sej/g	Source
Gross production, estuary	4.7×10^3		Note 10
Net production, estuary	9.0×10^3		Note 10
Plantation pine wood	6.7×10^3	0.10	Table 5.2
Estarine organic matter	1.1×10^4		Note 10
Peat	1.7×10^4	0.36	Table 5.4
Mulberry leaves	2.4×10^4		Table 4.2
Lignite	3.7×10^4		Note 1
Cornstalks	3.9×10^4		Note 8
Coal	4.0×10^4		Table C.2
Rainforest logs	4.1×10^4	0.39	Table C.2
Natural gas	4.8×10^4		Table C.2
Crude oil	5.4×10^4		Table C.2
Ethanol	6.0×10^4		Note 2
Liquid motor fuel	6.6×10^4		Table C.2
Corn	8.3×10^4	1.43	Note 8
Charcoal	1.07×10^5		Note 9
Electric power	2.0×10^5	—	Table C.1
Cotton	8.6×10^5		Note 1
Butter	1.3×10^6		Note 4
Smaller estuarine animals	1.5×10^6		Note 10
Caterpillar pupae	2.0×10^6		Table 4.2
Mutton	2.0×10^6		Note 6
Silk	3.4×10^6	72.	Table 4.2
Veal	4.0×10^6		Note 5
Wool	4.4×10^6		Note 7
Upper consumers, estuary	$30. \times 10^6$		Note 10
Aquaculture shrimp	13.0×10^6		Note 3

[1] Odum et al. (1987a).

[2] E. C. Odum and Odum (1984).

[3] H. T. Odum and Arding (1991).

[4] Energy analysis of Indian cattle by Mitchell (1979) using as solar EMERGY input that of the rain:

$$\frac{(4.10 \times 10^{10}\ \text{solar emkcal/yr}}{3.25 \times 10^4\ \text{kcal}} = 1.3 \times 10^6\ \text{semkcal/kcal} = 1.3 \times 10^6\ \text{sej/J}$$

[5] Data same as in note 4:

$$\frac{4.22 \times 10^{10}\ \text{sekcal/yr}}{1.06 \times 10^4\ \text{kcal/yr}} = 3.98 \times 10^6\ \text{semkcal/kcal} = 3.98 \times 10^6\ \text{sej/J}$$

[6] H. T. Odum and Odum (1983 p. 421); EMERGY inputs of rain, phosphate fertilizer, fuels, electricity, services, and government subsidy totaled 252×10^{13} sej/ha/yr (including tidal correction for world rain transformity) divided by annual production per hectare (1.27×10^9 J/yr).

[7] EMERGY data as in note 6:

$$\frac{252 \times 10^{13}\ \text{sej/yr}}{5.68 \times 10^8\ \text{J/yr wood production}} = 4.43 \times 10^6\ \text{sej/J}$$