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Emergy evaluation of an OTEC electrical power system

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Abstract

An energy analysis was made of a land-based OTEC system proposed for Taiwan using emergy evaluation methods (emergy spelled with an 'm'). An emergy yield ratio of 1.4 indicates a small net contribution of electric power, but less than from forest wood, fossil fuel, and nuclear fission. Comparing the emergy fed back from the economy to that from the sea, the large investment ratio (218) suggests the system is not likely to become economical. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Determining the potential for conversion of solar energy over the vast areas of oceans to electric power has both theoretical and practical interest. Anticipating scarcity and higher prices for fuels in future years, solar alternatives need to be evaluated with emergy methods that include all the inputs on a common basis. In reviewing ocean thermal energy conversion (OTEC) Charlier and Justus [1] describe net energy yield ratios of 5 and imply large economic potential. However, solar insolation may be inherently too dilute for much net contribution after the emergy requirements of concentrating energy have been appropriately subtracted. Valid energy analysis requires that all inputs from environment and economy, including services, be put on a common emergy basis (emergy spelled with an 'm').

The publication of detailed resource and economic requirements for operating an OTEC plant on the shore of Taiwan [2] provides data for an emergy evaluation of this proposed electric power system. This note includes an emergy evaluation table, a summarizing energy systems diagram and indices for interpretation.

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2. Concepts and methods

Emergy evaluation methods were used as summarized in a recent publication [3]. For readers' convenience some essential definitions follow:

Emergy, a measure of real wealth, is defined as sum of the available energy of one kind previously required directly and indirectly through input pathways to make a product or service (unit: emjoules). In this paper solar emergy (E_{ms}) is used with the unit solar emjoule (abbreviation: sej).
Empower (J_{ems}) is the emergy flow per unit time (units: solar emjoules per year (abbreviation: sej/yr).

$$\text{Solar emergy flow} = J_{ems} = \Sigma(T_{rs1} * J_{e1} + T_{rs2} * J_{e2 \ldots} T_{rsi} * J_{ei})$$

where T_{rs}=solar transformity and J_e is a flow of available energy.
Transformity is the emergy per unit available energy. Example: solar transformity in solar emjoules per joule (abbreviation: sej/J). Transformity is the intensive unit of emergy and measures the quality of energy [4].

$$T_{rs} = J_{ems}/J_e$$

Emergy per unit mass, is useful where data are in mass units.T_m=J_{ems}/J_m where J_m is a flow of mass
Emergy/money ratio (Ems/$) is a measure of the real wealth buying power of money calculated for a state or nation in a given year. It is useful where data on human services are in money units.

$$E_{ms}/\$ = J_{ems}/J_{\$}$$

Emdollars (abbreviation Em$) are the dollars of gross economic product based on a contribution of emergy.

$$E_{m\$} = E_{ms}/(E_{ms}/\$)$$

Net emergy ratio is the ratio of the yield emergy (Y_{em}) to the emergy of inputs purchased and fed back from the economy (F_{em}). This ratio measures the net contribution to the economy or loss from it.

$$\text{NER} = Y_{em}/F_{em}$$

Emergy Investment Ratio is the ratio of inputs purchased and fed back from the economy (F_{em}) divided by the free environmental emergy input (I_{em}). It is a measure of economic viability. This ratio is low when the environmental source is providing more so that costs are less.

$$\text{EIR} = F_{em}/I_{em}$$

The evaluation procedure starts with a complex energy systems diagram to identify inputs, outputs, and main processes (not shown here). This diagram is used to identify line items in an evaluation table (Table 1). For a steady state analysis, annual values of required inputs from nature and from the human economy are listed in usual units (g, J, $). Initial capital requirements (materials, energy, and money units) are averaged over the anticipated life of the plant structure. In an adjacent column, emergy values per unit are derived from previous studies and cited in footnotes. Next, requirements in column 2 are multiplied by the emergy/unit values in column 3 to obtain empower value in sej/yr in column 4. To show the equivalent monetary value, the items in the empower column 4 are divided by the emergy/money ratio for 1992 to get an estimate of annual emdollars (abbreviated Em$), which give monetary perspective.

An aggregated energy systems diagram is drawn showing the environmental and purchased inputs, the money flows, yields, and by- products all given in empower units (Fig. 1).

For interpretation of net benefit, the net emergy ratio is calculated. To anticipate whether the investment is well matched by free resources, the emergy investment ratio is calculated. To evaluate the quality of the energy flows, transformities can be calculated and compared with other energy forms.

Table 1
Emergy evaluation of land-based ocean thermal energy conversion to electric power[a]

Item	Data units (J, g or $)	Solar emergy/unit (sej/unit)	Solar emergy (E19 sej/yr)	1992 Em$ (E6 $/yr)[b]
Warm water use[c]	3.04 E16 J	2.2/J	0.0067	0.048
Equipment per year[d]	2.28 E7 g	2 E10/g	0.046	0.33
Investment costs[e]	5.79 E6 $	2 E12/$	1.16	8.3
Services[f]	1.32 E6 $	2 E12/$	0.20	1.4
Sum of purchased inputs	(#2, 3, and 4)		1.46	10.0
Gross power (J)[g]	1.44 E14	1.74 E5/J	2.51	17.9
Net power production[h]	1.19 E14	1.74 E5/J	2.07	14.8

[a] Most data from an 8 module, optimal design for maximum power per unit investment for Taiwan from [2].

[b] Solar emergy in column 4 divided by 1.4 E12 sej/$ for 1992.

[c] Warm water use: $3.14\times(2.5/2)^2=4.9\ m^2$ cross-section; 2.32 m/s. Temperature differentials: 20.3°C (mean of monthly values: 19.1, 19.3, 19.5, 19.8, 20.2, 21.7, 23.3, 21.5, 22.4, 19.9, 19.7, 17.7). High temperature, (20.3+273=290.3 K). Potential in warm water differential: Carnot fraction times water flow (2.32 m/s)(4.9 m^2)(3.15 E7 s/yr)(1 gcal/cm^3/°C)(1 E–3 kcal/gcal)(290.3 K)(1 E6 cm^3/m^3)(20.3 deg diff./290.3)(4186 J/kcal)=3.04 E16 J/yr.

[d] Main equipment the cold water pipe: 2.1 E3 m long, 2.5 m diameter; circumference ($2\pi r=2\times3.14\times1.25=7.85$ m); wall thickness 5 mm. (5 E–3 m)(2.9 E3 m)(7.85 m)(2 gm/cm^3)(1 E6 cm^3/m^3)/10 yr=2.28 E7 g/yr. Aluminum pipe studied for corrosion at 0.015 mm/yr [6]. Transformity of aluminum used: 2 E10 sej/g (ingots 1.6 E10 sej/g) [3].

[e] Investment costs with 10 year replacement interval; Emergy/money ratio in 1990 2.0 E12 sej/US $ (1.447 E9 1990 NT $)/(25 US $/NT $)/10 yr=5.79 E6 US 1990$.

[f] Assume services the price of power, 0.05 $/kwh (0.05 $/kwh)(365 d/y)(24 h/d)(0.8 load)(3.79 E3 kw) =1.32 E6 $/yr.

[g] Gross Electric Power Production, 4.57 MW. (4.57 E6 W)(1 J/s/W)(3.15 E7 s/yr)=1.44 E14 J/yr.

[h] 17.3% of electric power used in plant. Net power by difference:(1−0.173)(1.44 E14 J/yr=1.19 E14 J/yr. Transformity of electric power from mean of power plants [3, Appendix D].

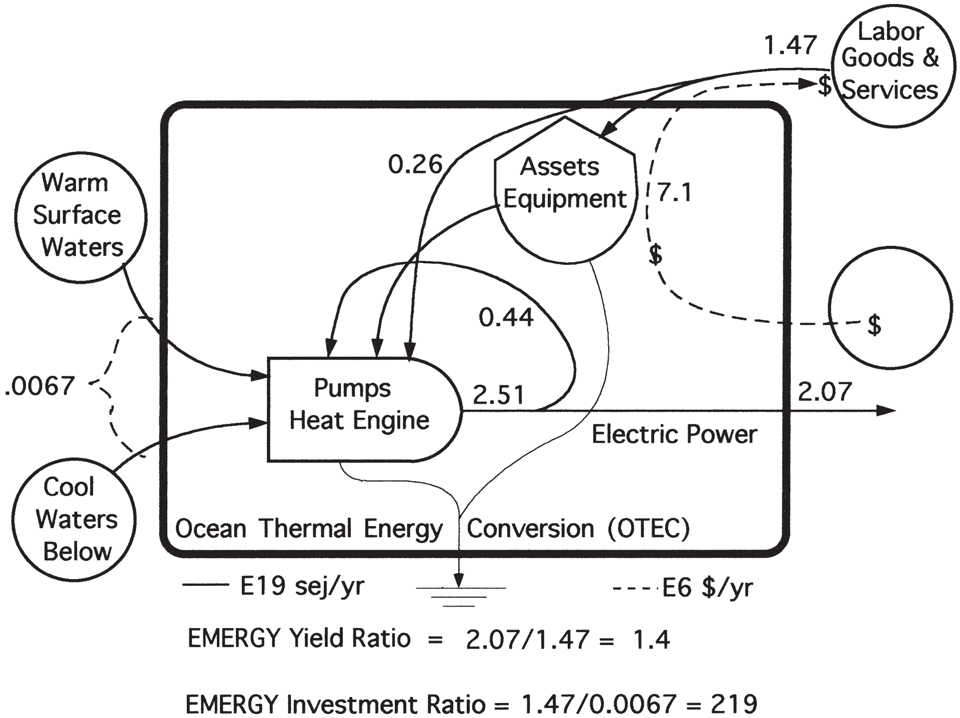

Fig. 1. Energy systems diagram and annual emergy flows of an ocean thermal energy conversion plan evaluated in Table 1.

3. Results and discussion

Table 1 is the emergy evaluation table of the Taiwan OTEC proposal, with numbered footnotes for each line item. Most of the data came from an economic analysis of the best of four alternative systems for converting ocean thermal energy differences to electrical power given by Tseng et al. [2]. Indices are calculated in Table 2. The summarizing energy systems diagram is given in Fig. 1.

Table 2
Indices from OTEC evaluation in Table 1

Theoretical efficiency: half of Carnot fraction for 20.3° C. difference: [(100)(0.5)(20.3°C)]/(290.3 K)=3.9%
Traditional efficiency: (net power/Carnot potential of heat inflow) (1.19 E14 J/yr)/(3.04 E 16 J/yr)×100=0.39%
Solar transformity of warm–cold difference
Heat stored under half of the ocean area: (0.5×1.5 E14 m^2)
Triangular hypsographic section [5] (0.5)(27.5×1000 m) =13,750 °m; storing time taken as 1 yr (0.5)(1.5 E14 m^2)(13,750)(1 E6 cm^3/m^3)(1 gcal/cm^3) (1 E–3 kcal/gcal)(4186 J/kcal)=4.3 E24 J
Global solar emergy 9.44 E24 sej/yr
Solar transformity of water: (9.44 E24 sej/yr)/(4.3 E24 J/yr)=2.2 sej/J
Net emergy ratio=(2.07 E19 sej/yr)/(1.47 E19 sej/yr)=1.4
Emergy investment ratio=(1.47 E19 sej/yr)/(6.7 E16 sej/yr)=218

First are given the traditional efficiencies of conversion of a heat difference into mechanical work: the theoretical reversible efficiency for the temperature difference is 3.9%. The efficiency of this energy converted to electrical power for this proposed OTEC system is 0.39%.

The transformity of solar heat accumulated in the upper waters of the sea is about 2.2 as compared to solar insolation which is defined as 1.0. Dilute solar insolation, as first captured by self organizing atmosphere–ocean processes, doubles in quality but is still small compared to that of the rain generated by the weather systems over land (18,000 sej/J), fossil fuels ($>$40,000 sej/J) or the electric power (170,000 sej/J). Emergy indices used to evaluate relationships of environment and economy are included in Fig. 1.

4. Summary and conclusion

In the proposed OTEC system there is a little net emergy yield, but the net emergy ratio (1.4) is less than electric power from old growth wood (3.6), fossil fuel (2.5–3.5) and from nuclear power (4.5) [3]. The emergy investment ratio (218) is much higher than typical values of 7 in developed countries, which means that the plan may be too costly in use of purchased resources to be economical. With a solar transformity of 2, the thermal gradient energy is little more concentrated than the original solar insolation. Emergy evaluation helps explain why solar technology is not competitive.

References

[1] Charlier FH, Justus JR. Ocean energies, environmental, economic and technological aspects of alternative power sources. Amsterdam: Elsevier, 1993.
[2] Tseng GH, Kao MY, Yang JC. Optimal design of a pilot OTEC power plant in Taiwan. J Energy Res Technol 1991;113:294–9.
[3] Odum HT. Environmental accounting, emergy and decision making. New York: John Wiley, 1996.
[4] Odum HT. Self organization, transformity, and information. Science 1988;242:1132–9.
[5] Sasscer DS, Morgan TO, Rivera C, Tosteson TR, Zaidi BR, Revuelta R, Iman SH, Axtmayer RW, De Vore D, Ballentine DL. OTEC biofouling, corrosion, and materials study from a moored platform at Punta Tuna, Puerto Rico. Ocean Sci Engng 1981;6(4):499–532.
[6] Sasscer DS, Morgan TO, Ernst R, Summerson TJ, Scott AC. Open ocean corrosion test of candidate aluminum materials for sea water heat exchangers. Corrosion 83 paper #67, International Corrosion Forum. Nat Assoc Corrosion Engng, Anaheim, CA 1983;67:1–13.