45

Emergy of Algal Systems Revisited

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ABSTRACT

In the 1960s H. T. Odum performed an early form of emergy analysis on algal systems that were being proposed by some researchers as a solution to world food shortages because of their high productivity. Odum's analysis revealed the fallacy in these proposals, primarily due to hidden energy subsidies. Algae grown for food have several limitations and Odum showed that algal production systems generate no more net energy yield than other forms of agriculture. In this paper Odum's early analyses are re-evaluated and compared with a preliminary assessment of a recent algal system used for wastewater treatment. Algal turf scrubbers use primary productivity as a mechanism for treating wastewater through metabolic uptake of nutrients, followed by mechanical harvest of biomass in order to remove the nutrients from the water source. These systems achieve high levels of productivity from the subsidy of nutrient-rich wastewaters and from ecological engineering design. The transformities of algae are contrasted to provide perspective on Odum's original energy analysis and on a modern form of algal technology.

INTRODUCTION

After World War II, there was a high level of interest in using algal systems in bioengineering designs by the U. S. research community (Bush, 1953). Algae were easy to grow and to study under laboratory conditions and many possible uses for the products and byproducts of their photosynthesis were envisioned (Burlew, 1953). However, with the passage of time, most of these algal systems proved not to be economically beneficial because of misguided extrapolations and high costs associated with large-scale culture. H. T. Odum anticipated these limitations with an early version of the present-day emergy analysis (Odum, 1967; 1971). The purpose of this paper is to re-evaluate Odum's early study and to provide a preliminary emergy analysis of a new algal-based technology that is being tested for wastewater treatment.

"ALGAL CULTURE AND FALLACIOUS DREAMS"

Odum was developing field techniques and making measurements of primary productivity (photosynthesis at the scale of the ecosystem) at the same time that the early laboratory algal studies were taking place. Led by Odum's work and the work of others, ecological energetics was emerging as a dominant paradigm of the discipline of ecology. Measurements were being made in a variety of ecosystems and the efficiency of primary productivity was always found to be low, about 1 % of solar radiation. Thus, the claims for high photosynthetic efficiency made by some scientists working on laboratory algal cultures were viewed critically. An example of this laboratory-scale science is given by Burk, et al. (1962), who illustrate photosynthetic efficiency in relation to sunlight with a side-by-side comparison showing a cornfield at 1% and an algal culture at 90%. Odum realized that it was possible to achieve these high levels of efficiency in the lab but only by subsidizing photosynthesis with auxiliary energy sources so that more biomass yield is produced per unit of solar radiation than could occur in nature. Moreover, it was misleading to suggest a high efficiency by only dividing the output of algal biomass energy by the input of solar energy, when the output energy could only be achieved with additional, auxiliary energy inputs as subsidies. Odum became especially alarmed when the high efficiencies of algal lab cultures were extrapolated to suggest that large-scale algal production could solve the world hunger problem. He called these projections "thermodynamic science-fiction" (Odum, 1963) and wrote a critique of them in a section entitled "Algal Culture and Fallacious Dreams" in his classic text (Odum, 1971).

H. T. ODUM'S EARLY ENERGY CALCULATION

Odum developed one of the first examples of energy analysis (before energy quality correction) by evaluating energy subsidies in order to demonstrate some of the fallacy with the lab projections of algal culture for human food production (Odum, 1967; 1971). In this early energy analysis he used a reference that included some economic cost values of a potential algal pilot plant experiment (Fischer, 1961). Only dollar values were available to be used in Odum's analysis because the algal culture system was never built and only projections of costs were reported in the literature. He converted these dollar costs into energy by multiplying by an energy-to-dollar ratio (10,000 Cal of fossil fuel/$ spent) in order to quantify the energy value of the subsidies. He then made comparisons with other agricultural systems to demonstrate that the potential large-scale algal culture would be no more efficient (yield per total energy input) than other forms of agriculture.

Figure 1 illustrates the emergy budget of Odum's original analysis using recent information (see Appendix). The dominant emergy inputs would have been from labor along with materials & infrastructure, while direct solar insolation would have been an insignificant contribution. The transformity of the algae produced from the projected pilot plant would have been 4.5E+5 sej/J.

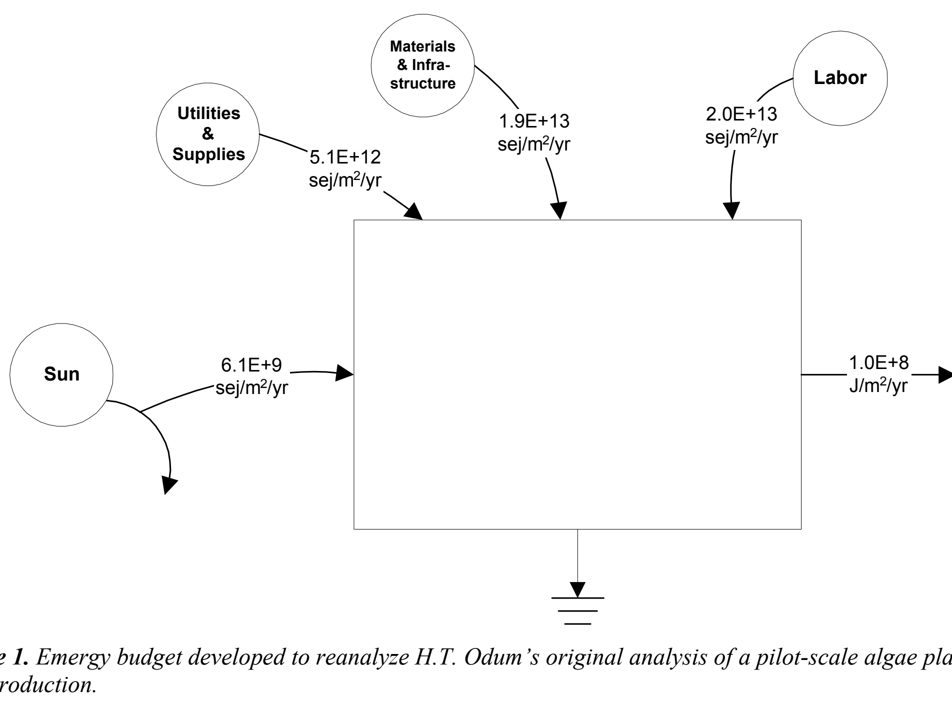

Figure 1. *Emergy budget developed to reanalyze H.T. Odum's original analysis of a pilot-scale algae plant for food production.*

COMPARISON WITH A RECENT ALGAL TECHNOLOGY

Algal systems continue to be studied and incorporated into bioengineering designs. One use is for wastewater treatment. Pollutants are taken up by algal communities and they can be removed from the water source when algal biomass is harvested from the system. An example of this kind of system is the algal turf scrubber (Adey and Loveland, 1998). In this system polluted water is passed through a trough containing a film of benthic algae (Figure 2). Harvest of the algae improves water quality since pollutants are advected from the system. A generalized energy circuit diagram of an algal turf scrubber is shown in Figure 3. Although the system is designed to treat wastewater, there are two outputs: clean water and algal biomass.

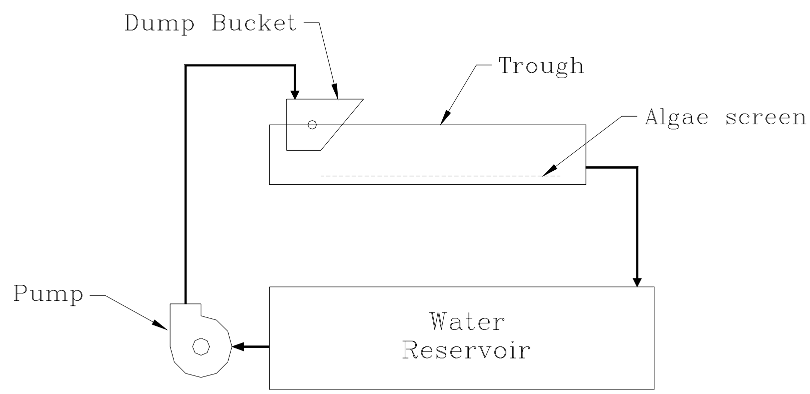

***Figure 2**. Schematic representation of a recirculating algal turf scrubber.*

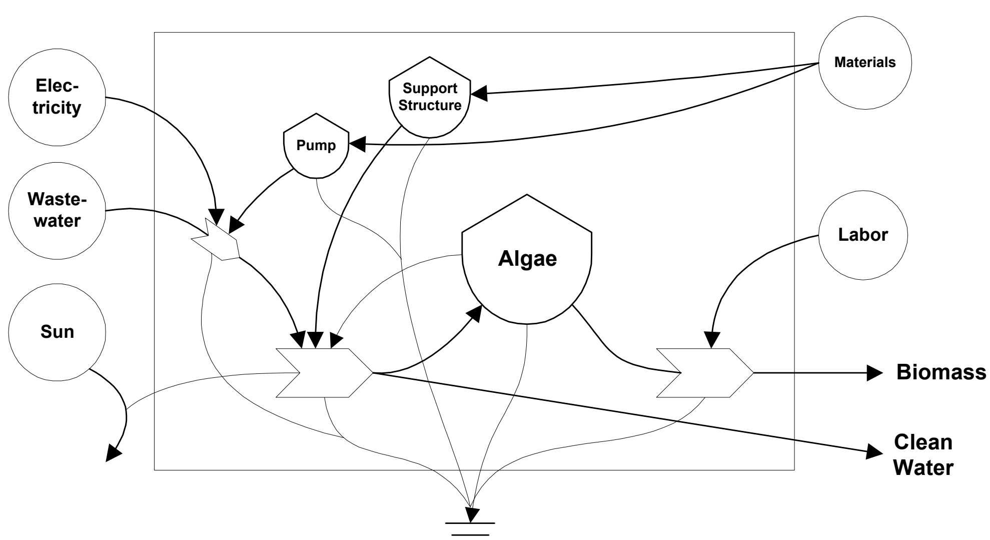

***Figure 3**. Energy circuit diagram of an algal turf scrubber.*

We evaluated an experimental study of an algal turf scrubber with emergy analysis for perspective on H. T. Odum's original analysis (described earlier). An overview diagram of the emergy balance for a system at the USDA Agricultural Research Service Laboratory in Beltsville, Maryland, is shown in Figure 4. This system is operated in the laboratory, utilizing artificial lighting, and it is being studied for treating wastewater from a dairy operation. Unlike the early studies of algal systems undertaken after World War II, our intention is to analyze all of the different energy inputs to the system. A large number of energy subsidies are required to operate the system, with electricity and labor contributing the largest emergy inputs (Figure 4 and Appendix). The transformity of the algae produced from the algal turf scrubber is 5.4E+7 sej/J.

CONCLUSIONS

H. T. Odum's original energy analysis of an algal pilot plant is historically important. It represents one of the first examples of energy analysis, which was later revised with corrections for energy quality. Odum's analysis quantified the magnitudes of energy subsidies to a biomass yield system that had previously been ignored in assessments of the system. It was a breakthrough in the development of emergy theory in showing a technique for accounting for energies reported in different units (at least in terms of dollars). The analysis also exposed some incorrect thinking about the performance of the system that could have lead to inappropriate policy advocating algal aquaculture.

Because Odum had not yet fully developed the concept that different energies have different abilities to do work (i.e., the energy quality concept) when he evaluated algal cultures, his early energy calculation is probably inaccurate. He was only able to convert dollar values into energy equivalents, but it is now understood that a more accurate assessment is possible by evaluating all flows with basic physical units and then by multiplying the flows by transformities to account for energy quality. This problem may explain why the transformity for algal biomass from the algal turf scurbber (5.4E+7 sej/J) is so much higher than the transformity from Odum's early energy calculation (4.5E+5 sej/J). An analysis of one of the existing specialized operations that produce microalgae, such as Spirulina, for the health food industry would provide further perspective on the value of algal biomass.

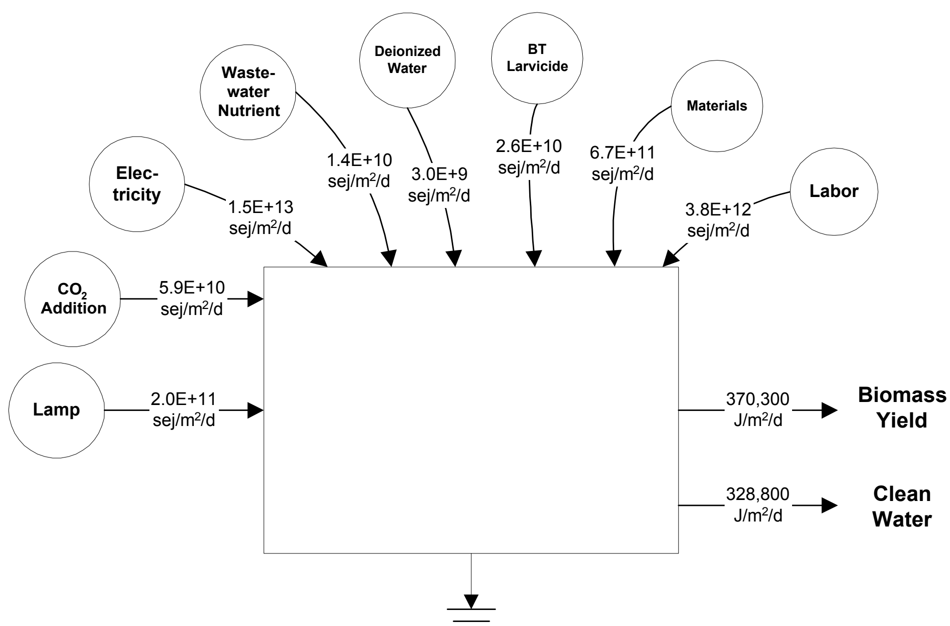

Figure 4. *Emergy budget diagram of the USDA algal turf scrubber, used to calculate the transformity of the outputs.*

Algal systems for general food production have never developed, perhaps for the reasons Odum studied. However, wastewater treatment applications are being studied that have potential for economic development. One benefit of systems such as the algal turf scrubber is that they generate both clean water and algal biomass. In the calculation given here the transformity of clean water from the algal turf scrubber (6.1E+7 sej/J) was on the same order of magnitude as the transformity of the algal biomass (5.4E+7 sej/J). The output of valuable byproducts from a technology should improve its commercial potential. In this regard further studies are in progress to evaluate the USDA algal turf scrubber system in terms of the energetics and economics of uses of the algae, for example as a fertilizer amendment.

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APPENDIX: CALCULATIONS

Table A.1. Transformity calculation for H.T. Odum's analysis of a pilot-scale algae plant for food production.

INPUTS

Note	Item	Data	Transformity	Emergy (sej/m^2/yr)	% of Total
1	Solar Insolation	1.5E+06 kcal/m^2/yr	1 sej/J	6.1E+09	0.0%
2	Materials & Infrastructure	1.2 \$/m^2/yr	15.8E+12 sej/\$	1.9E+13	43.3%
3	Labor	1.3 \$/m^2/yr	15.8E+12 sej/\$	2.0E+13	45.3%
4	Utilities & Supplies	0.3 \$/m^2/yr	15.8E+12 sej/\$	5.1E+12	11.4%
	TOTAL (sej/m^2/yr)			**4.5E+13**	

OUTPUTS

Note	Item	Data	Units	Emergy (J/m^2/yr)
5	Algal Biomass	4932	g/m^2/yr	1.0E+08

Transformity of Algae Biomass: **T = Σ(Inputs) / Σ(Outputs)**
T = 4.5E+05 sej/J

Notes:

1. Given by Odum (1971) as 1.46E+06 kcal/m^2/yr, where 1 kcal = 4184 J.
2. Calculated from materials costs reported for 100-acre facility in Fischer (1961), assuming two-thirds of initial investment cost is for materials and amortization over life span of 10 years, added with materials costs for daily operation. Transformed using 15.8E+12 sej/$ for 1955 from Table D.1, p. 313 in Odum (1996).
3. Calculated from labor costs for 100-acre facility as reported in Fischer (1961), assuming one-third of initial investment costs is for installation labor, added to total for engineering labor, all amortized over life span of 10 years. This is then added with daily operating labor cost. Transformed using 15.8E+12 sej/$ for 1955 from Table D.1, p. 313 in Odum (1996).
4. Calculated from utilities and supplies costs for daily operation of 100-acre facility as reported in Fischer (1961). Transformed using 15.8E+12 sej/$ for 1955 from Table D.1, p. 313 in Odum (1996).
5. Calculated from projected net algae productivity of 20 t/acre/yr as reported in Fischer (1961), and adjusted assuming gross productivity is 10% greater (Odum (1971)). Used heat value of biomass of 5 kcal/g given in Figure 4-10, p. 127 in Odum (1971).

Table A.2. Transformity calculation for USDA ARS Laboratory's bench-scale algal turf scrubber.

INPUTS

Note	Item	Data	Transformity	Emergy (sej/m^2/d)	% of Total
1	Materials	0.9 \$/m^2/d	0.8 E+12 sej/\$	6.7E+11	3.4%
2	Labor	0.04 man-day/d	9.4E+13 sej/d/pe	3.8E+12	19.1%
3	Lamp	0.3 \$/m^2/d	0.8E+12 sej/\$	2.0E+11	1.0%
4	Electricity	9.5E+07 J/m^2/d	160,000 sej/J	1.5E+13	76.4%
5	Nutrients	3.1 g NH_4-N/m^2/d	4.6E+09 sej/g N	1.4E+10	0.1%
6	Deionized Water	33.3 L/m^2/d	18,199 sej/J	3.0E+09	0.0%
7	BT Larvicide	0.034 \$/m^2/d	0.8E+12 sej/\$	2.6E+10	0.1%
8	CO_2 Addition	0.1 \$/m^2/d	0.8E+12 sej/\$	5.9E+10	0.3%
	TOTAL (sej/m^2/d)			**2.0E+13**	

OUTPUTS

Note	Item	Data	Units	Emergy (J/m^2/d)
9	Algal Biomass	17.7	g /m^2/d	370,280
10	Clean Water	66.7	L/m^2/d	328,830

Transformities: **T = Σ(Inputs) / Σ(Outputs)**
T = 5.4E+7 sej/J Algae Biomass
T = 6.1E+7 sej/J Clean Water

Notes:

1. Calculated from cost data for materials to build 0.6 m^2 ATS trough out of PVC sheet (Blersch and Kangas, unpublished data), amortized over 5 year life; dump bucket amortized over 2 year life; and pump amortized over 1 year life; and transformed using 0.78E+12 sej/\$ extrapolated for year 2001 from data in Table D.1, p. 313 in Odum (1996).
2. Calculated from labor required to construct ATS trough and dump bucket, amortized over respective life spans, and labor required per week to maintain an operating ATS (Blersch and Kangas, unpublished data). Transformed using 9.35E+13 sej/day/person from Table 14.2, p. 265 in Odum (1996).
3. Calculated from cost data for two 400W metal halide lamps and bulbs (Kebede-Westhead, et al. 2003). Ballasts and housing amortized over 3 year life span, bulbs amortized over 20,000 hr life span. Transformed using 0.78E+12 sej/\$ extrapolated for 2001 from Table D.1, p. 313 in Odum (1996).
4. Calculated from electrical consumption of two lamps at 400W each (Kebede-Westhead, et al. 2003) and one pump at 330W (Mulbry 2004) for one ATS at 1 m^2. Transformed using

transformity for electricity from coal power plant of 160,000 sej/J (Table C.1, p. 305, Odum [1996]).

5. Calculated from weekly nutrient additions for 1 m^2 ATS operating in lab, as reported for maximum productivity in Kebede-Westhead et al. (2003). Assumed that nitrogen is limiting nutrient at maximum loading rate of 15.5 $mg/L/m^2/d$ and transformed using transformity of 4.6E+09 sej/g N for ammonia fertilizer from Table C.4, p. 310 in Odum (1996).
6. Calculated from data reported in Kebede-Westhead et al. (2003) for a 1 m^2 ATS: deionized water replaced at rate of 100 liters every 3 days. Chemical potential of water given by Odum (1996) as Gibbs free energy: $G = (RT/w) \ln (C_2/C_1)$, where R is the ideal gas constant (8.33 J/mol/K), T is the absolute temperature (assumed at 300K), w is the molecular weight of water (18 g/mol), C_1 is the relative chemical potential of dissolved solids in seawater (965,000 ppm), and C_2 is the relative chemical potential of dissolved solids of pure water (1 x 106 ppm). Transformed using transformity of 18,199 sej/J for chemical energy of rain on land from Table C.3, p. 309 in Odum (1996).
7. Calculated from data reported in Kebede-Westhead et al. (2003) for a 1 m^2 ATS: 20 mL of Aquabac-XT added every 3 days at highest productivity and assuming retail price of $96.25/5 gal. Transformed using 0.78E+12 sej/$ extrapolated for 2001 from data in Table D.1, p. 313 in Odum (1996).
8. Calculated for CO_2 addition rate of 1 mL/sec (Mulbry 2004), assuming ideal gas volume of 22.4 L/mol, MW of CO_2 of 44 g/mol, and retail price of $10 per 50 lb. Transformed using 0.78E+12 sej/$ extrapolated for 2001 from data in Table D.1, p. 313 in Odum (1996).
9. Maximum productivity data reported in Kebede-Westhead et al. (2003) for a 1 m^2 ATS operating in lab. Used heat value of biomass given in Figure 4-10, p. 127 in Odum (1971).
10. Calculated from data reported in Kebede-Westhead et al. (2003) for a 1 m^2 ATS: effluent water at total dissolved solids concentration of 117 ppm (estimated from available TN and TP data) produced at rate of 200 liters every 3 days. Chemical potential of water given by Odum (1996) (see note 6).