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Ecological Modelling 186 (2005) 212–220

ECOLOGICAL MODELLING

www.elsevier.com/locate/ecolmodel

The solar transformity of oil and petroleum natural gas

Simone Bastianoni[a, *], Daniel Campbell[b], Ludovico Susani[a], Enzo Tiezzi[a]

[a] Department of Chemical and Biosystems Sciences, University of Siena, Via A. Moro 2, Siena, Italy
[b] United States Environmental Protection Agency, Office of Research and Development, National Health and Environmental Effects Research Laboratory, Atlantic Ecology Division, Narragansett, RI, USA

Received 4 November 2003; received in revised form 30 November 2004; accepted 10 January 2005

Abstract

This paper presents an emergy evaluation of the biogeochemical process of petroleum formation. Unlike the previous calculation, in which the transformity of crude oil was back calculated from the relative efficiency of electricity production and factors relating coal to transportation fuels and transportation fuels to crude oil, we analyzed the geochemical process of petroleum formation (naftogenesis) to determine the transformities of oil and natural gas. We assumed that the process of oil and gas production is a steady state process in which all the emergy required is captured in the initial input. For such a system, we can use the mass concentration of the initial input to determine the specific emergy and transformity of the products. We used the maximum photosynthetic yield in Joules of phytoplankton organic matter per Joule of sunlight as the starting point. From this initial assumption, we traced the energy transformations in the oil and gas formation process through photosynthesis, death and decay of the phytoplankton, and diagenesis to kerogen production and from kerogen through catagenesis to petroleum formation. Our results show that both methods converge to similar values for oil (∼54,200 solar emJoules per Joule (sej/J)) and petroleum natural gas (43,500 sej/J) increasing our confidence in the results of past emergy analyses and providing a firm basis for the calculation of transformities for oil and gas derivatives.

Keywords: Solar transformity; Emergy; Oil and natural gas

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1. Introduction

Emergy analysis is a fundamental tool for gaining an understanding of the concept of sustainability. Sustainability is based on the amount of energy/matter, time and space needed to replace depleted goods (see, for example, Tiezzi, 1984). Emergy provides a comprehensive viewpoint from which we can read all the phenomena in nature on a common scale: the amount of solar energy directly and indirectly needed to produce each item (Odum, 1988, 1991, 1996).

In industrial societies, the use of fossil fuels plays a fundamental role in transporting goods, heating and producing electricity. Emergy analysis quantifies

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[*] Corresponding author. Tel.: +39 0577 234358; fax: +39 0577 234177.
E-mail address: bastianoni@unisi.it (S. Bastianoni).

doi:10.1016/j.ecolmodel.2005.01.015

the relative importance of the role of different kinds of energy through the value of their transformities (the emergy or the solar emJoules per Joule (sej/J) of product) or, more generally, through the value of the emergy per unit (regardless of the way in which the item is measured). Evaluation of the emergy of petroleum from its formation means to consider the solar energy that was needed in the past together with the time of formation, i.e., the work that the biosphere has performed during past eras, to obtain a certain amount of oil (or petroleum gas). The ratio of the solar energy required over the time of formation to a joule of exergy (available energy) in oil is the solar transformity of the oil as determined through an analysis of the biological and geological processes of its formation. It is very difficult to evaluate the problem in this way; however, it may be simplified using certain assumptions. Where all the required emergy sources support a single interconnected production process operating at steady state, an approximation to the specific emergies and transformities of products in a series of energy transformations can be obtained by determining the emergy inflow to the system and the mass or energy remaining at each stage of transformation. Because of the difficulties that spatial and temporal variability introduce into determining the transformity of oil and gas by a complete accounting of energy expenditures over time, the latter approach was used in this paper.

In general, the contribution of fuels to the total emergy use at various levels of political organization is highly relevant to developed societies. For example, around 50% of the total emergy supporting Italy in 1989 was directly connected with fuels and electricity (Ulgiati et al., 1994). Therefore, emergy evaluations are, in general, sensitive to changes or errors in the transformity of fuels and a strong effort should be made to ascertain the most reliable values possible.

2. Previous determinations of the transformity of oil

The transformity of oil that is commonly used in all emergy analyses was obtained by H.T. Odum in a manner different from evaluating the process of its formation. The present transformity of oil was derived backwards starting from the transformity of electricity taken as 1.7×10^5 sej/J, which was the average value of all determinations in Odum (1996). Odum estimated the transformity of coal to be 4.3×10^4 sej/J[1] from the above transformity for electricity and the assumption that the average yield of a coal-fired electric power plant is approximately 25%. In addition, the transformity of coal was found to be 3.4×10^4 sej/J from an analysis of the sedimentary cycle of coal production (Odum, 1996). Averaging these two numbers gives a transformity for coal of 3.9×10^4 sej/J, which Odum rounded to 4×10^4 sej/J. This number was multiplied by 1.65, the energy ratio between coal and transportation fuels suggested by Slesser (1973), to deduce an approximate transformity (66,000 sej/J) for fuels derived from oil. Cook (1976) proposed a ratio of 1.23 between the energy of crude oil and the sum of the energies in oil derived fuels. From this ratio the transformity of crude oil was obtained (54,000 sej/J). The transformity, 2.0×10^5 sej/J, for electricity determined from an emergy analysis of a wood burning electric power plant at Jari, Brazil (Odum and Odum, 1983) is close to the average value upon which the determination of oil transformities was based. While Odum considered this difference to be within the margin of error for the calculation methods (Odum, 1996), it can be shown that this transformity for electricity gives the transformities, 69,000 sej/J for oil-based fuels and 56,100 sej/J for crude oil. This method is not based on an analysis of a production system using the rules of emergy algebra proposed for evaluating networks (Odum, 1996; Brown and Herendeen, 1996), and the transformities for fuels and crude oil determined in this way can be traced back to a solar energy base through the solar emergy required for the rain forest wood used to produce electricity in the Jari plant.

In this paper, we present a calculation of the transformity of oil and petroleum natural gas based on the biogeochemical processes that contribute to their formation, from photosynthesis through catagenesis. Data were taken from the literature using values valid, in general, for the formation process and from data available for a particular site, located in Russia, which ap-

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[1] Transformities used in this paragraph are based on the approximate planetary baseline 9.44×10^{24} sej/y used in Odum (1996). Multiply by 0.981 to convert to the more accurate 9.26×10^{24} sej/y baseline used in the rest of this paper or by 1.68 to convert to the 15.83×10^{24} sej/y baseline used in some emergy studies. To convert transformities reported in this paper to the 15.83 baseline multiply by 1.7.

pears to be most favorable for oil formation. In this way, we have reached a value that represents the transformity of oil and petroleum natural gas obtained under almost ideal conditions; thus, the transformities that we determined using this method should be nearly the smallest ones possible.

Recoverable oil and gas are assumed to be a single product in this analysis, and therefore, they are analyzed together. This can be intuitively verified by noting that they almost always occur together in geological formations and are separated only by a difference in phase. In fact, the so-called wet gas is a mixture of the two phases. In addition, the purposes for which oil and gas can be used are largely similar, which again indicates that these two substances are a split of what is essentially the same "stuff". The final determination of the transformity for each was made using the rules of emergy algebra for splits (Brown and Herendeen, 1996), i.e., the individual mass fractions of the quantity have the same emergy per gram carbon. Each step in the production process also includes gas generated as a co-product (Fig. 1). In this case, the gas is a waste and is either dissipated or bound as gas hydrates, which have a different emergy per gram carbon than the recoverable oil and petroleum gas.

3. Emergy evaluation of petroleum formation

Petroleum (oil and petroleum natural gas) is formed in various ways and places, and the chemical composition varies as well. Nonetheless, there are common characteristics that allowed us to build a simplified model of the mechanism of formation, using estimates that were consistently chosen to obtain the minimum transformity, thus the minimum emergy required to replace the oil and gas used.

The model assumes that the various steps in oil and gas formation are separated and consequential; however, there are often overlaps among the phases. In the model in Fig. 1, the energy forces that drive all the processes on earth, of which naftogenesis (petroleum formation) is a part, are represented, while in Fig. 2, we show the phases we have considered: photosynthesis, bacterial degradation and diagenesis, and catagenesis. Diagenesis and catagenesis have kerogen as the result and the starting point, respectively.

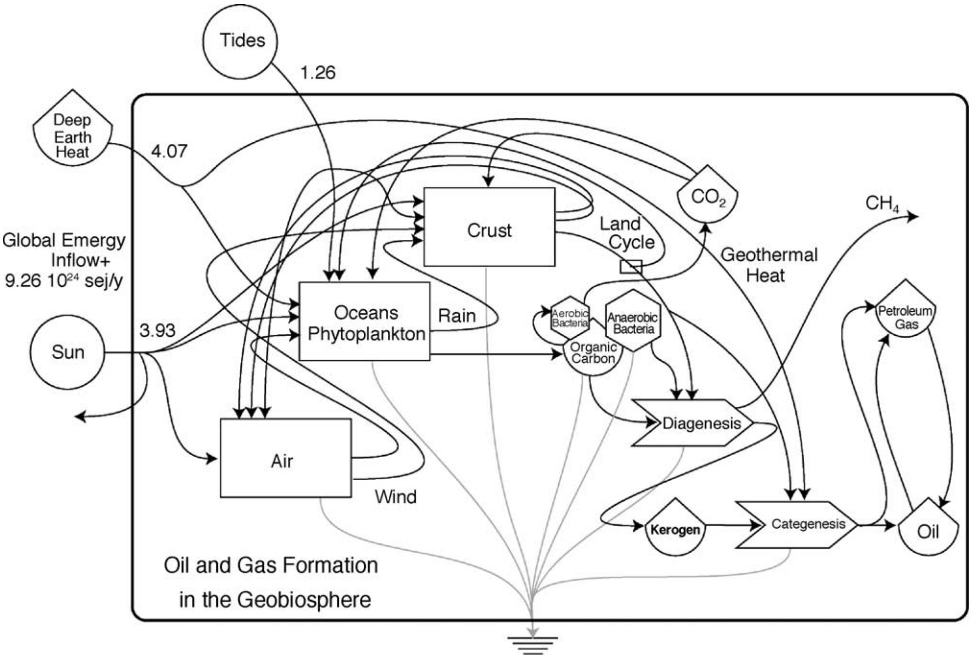

Fig. 1. Energy system diagram of oil and gas formation in the geobiosphere.

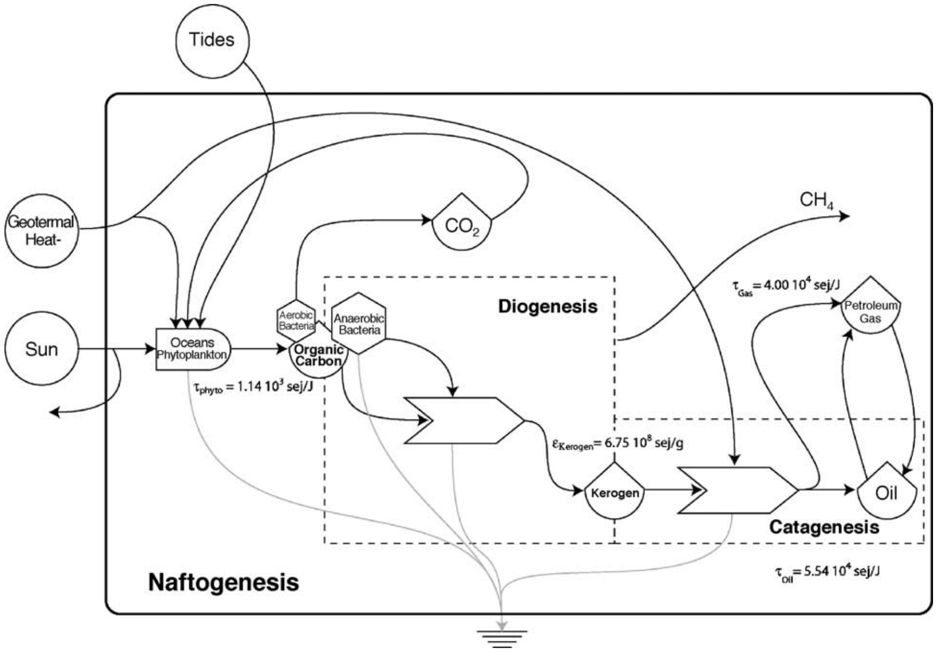

Fig. 2. Energy system diagram of naftogenesis used for calculation.

3.1. Photosynthesis

The photosynthetic microorganisms that are responsible for oil formation are mainly marine phytoplankton, which transform solar energy to chemical energy, by reducing atmospheric carbon (CO$_2$). The photosynthetic yield has been deduced from the productivity of an ideal ecosystem suitable for oil production (an estuary) (Tissot and Welte, 1978).

By means of estimates of the phytoplankton's maximum photosynthetic yield (Y_p) in Joules of organic matter per solar joule (Wessells and Hopson, 1988) we have calculated the total solar radiation and estimated the solar emergy required to obtain 1 J of phytoplankton (τ_p) (see Appendix A for a demonstration that the solar transformity of phytoplankton net production approaches the transformity determined from maximum photosynthetic yield in ideal oil-forming environments):

$$\tau_p = \frac{1}{Y_p} = \frac{1}{8.8 \times 10^{-4}} = 1.14 \times 10^3 \text{sej/J}$$

We have also considered the free energy in an average phytoplankton ($G_p = 1.78 \times 10^4$ J) (Wessells and Hopson, 1988), as well as the concentration of organic carbon present in the phytoplankton cells ($[C]_p = 0.45$ g C/g) (Morowitz, 1978), which will be used in the next calculations.

From this, we have obtained the emergy per gram of phytoplankton (ε_p) and the emergy per gram of carbon ($\varepsilon_{p[C]}$) in that phytoplankton, respectively:

$$\varepsilon_p = \tau_p G_p = 1.14 \times 10^3 \text{sej/J} \cdot 1.78 \times 10^4 \text{J/g}$$

$$= 2.03 \times 10^7 \text{sej/g}$$

$$\varepsilon_{p[C]} = \frac{\varepsilon_p}{[C]_p} = \frac{2.03^3 \times 10^7 \text{sej/g}}{0.45 (\text{g C})/\text{g}}$$

$$= 4.50 \times 10^7 \text{sej/(g C)}$$

For oil to form, sediment morphology must be suitable for the accumulation of organic biomass, so that diagenesis can take place (Tissot and Welte, 1978). The best conditions for this phase occur in almost enclosed marine areas where there is a high production of plant biomass, e.g., a gulf or lagoon, where water exchange with the open sea is limited as well as the mixing between surface and deep water. Another favorable aspect is the presence of an estuary with a good supply of organic detritus from inland.

3.2. Bacterial degradation and diagenesis

After the production of biomass, the second phase of oil formation (*diagenesis*) starts with bacterial degradation of the organic matter deposited on the bottom of the sea. Initially, aerobic bacteria oxidize the carbon of the dead phytoplankton to get energy. Carbon, once oxidized to CO_2, enters the carbon cycle in the atmosphere. In this phase, if the oxidation is complete, there is no accumulation of biomass in the sediments. The oxidation process can be incomplete in waters with a low level of mixing. When the oxygen concentration is low, anaerobic bacteria start to degrade the biomass, which becomes compact and insoluble.

The data we used for this analysis are taken from a real situation, the most favorable one for oil formation: the site is the Azov sea, where the quantity of petroleum per unit biomass is reported to be the highest ever found (Tissot and Welte, 1978). Nonetheless the percentage of organic matter that completes diagenesis and forms *kerogen* (R_D) is only around 5%. Kerogen is a solid, waxy, organic substance that forms when pressure and heat from the Earth act on the remains of dead biomass (Saoiabi et al., 2001). By means of these data, we are able to calculate the emergy per gram of carbon in kerogen ($\varepsilon_{k[C]}$), and the emergy per gram of kerogen (ε_k), which is composed of about 75% of carbon:

$$\varepsilon_{k[C]} = \frac{\varepsilon_{p[C]}}{R_D} = \frac{4.50 \times 10^7 \text{sej}/(\text{g C})}{0.05} = 9.00 \times 10^8 \text{sej}/(\text{g C})$$

$$\varepsilon_k = \frac{\varepsilon_{p[C]} \cdot [C]_k}{R_D} = \frac{4.50 \times 10^7 \text{sej}/(\text{g C}) \cdot 0.75(\text{g C})/\text{g}}{0.05} = 6.75 \times 10^8 \text{sej}/\text{g}$$

3.3. Catagenesis and oil formation

In this section we evaluate the emergy requirements for *catagenesis*. Catagenesis is the next step in oil formation following diagenesis. In this phase, kerogen is transformed into petroleum. Kerogen converts to oil and gaseous hydrocarbons at burial depths from 2 to 6 km and at temperature between 50 and 115 °C (Tissot and Welte, 1978). The main difference between kerogen and petroleum is carbon content and moisture; kerogen also has a higher percentage of unsaturated carbon chains compared to oil, which contains linear hydrocarbon chains. The transformation of kerogen is basically a function of the quantity of heat coming from the deep earth. To reach a temperature at which the cracking reaction can occur, kerogen must reach a certain depth in the earth, which is determined by the temperature gradient in the sediment where it is contained. The temperature gradient is important for the determination of the other key parameter in petroleum formation: time.

There is an almost linear relation between time of residence at a certain temperature and the amount of kerogen transformed into petroleum (Tissot and Welte, 1978). However, the relation of kerogen to the petroleum formed with temperature is – instead – exponential: even a small increase in the temperature drastically reduces the time of formation (Tissot and Welte, 1978). Nonetheless, at temperatures lower than 30 °C no oil is formed, independent of the residence time of the source rocks in the ground.

To estimate the transformity (or the emergy per mass) of petroleum including oil and petroleum natural gas, we formulated the problem as described above and in Figs. 1 and 2 to avoid the uncertainties due to the time and heat necessary for petroleum formation. Instead, we concentrated our attention on the quantity of carbon in kerogen needed to produce a certain amount of petroleum, R_C, i.e., on average 10 g of carbon in kerogen yield on average about 3.3 g of carbon in oil and natural gas (Tissot and Welte, 1978). The yield in the cracking reaction strongly depends upon the heat flow. Therefore, to consider the yield (in mass) of the petroleum formed from kerogen means to (indirectly) consider the enthalpy needed for the reaction. We can then obtain the formula:

$$\varepsilon_{\text{pet}[C]} = \frac{\varepsilon_{k[C]}}{R_C} = \frac{9.00 \times 10^8 \text{sej}/(\text{g C})}{0.33} = 2.73 \times 10^9 \text{sej}/(\text{g C})$$

At this point, we have to consider the fact that part of the carbon remains in the form of oil, while another part becomes natural gas. Using our hypothesis given above, this represents a split in emergy algebra. The two “branches” of a split (oil and petroleum gas) each have the same transformity, or in this case, emergy per mass of carbon, independent of the mass fractions of gas and oil obtained. Therefore, we can calculate the emergy per mass and the transformity of these two outputs considering the portion of the respective masses that is carbon and the enthalpy (or free energy, or exergy) of oil and gas.

Since 85% of the weight of oil is due to organic carbon, we have a specific emergy:

$$\varepsilon_{\text{oil}} = 0.85(2.73 \times 10^9 \text{sej/g C}) = 2.32 \times 10^9 \text{sej/g}$$

and finally, using an average enthalpy for petroleum (H_{oil}) of 4.19×10^4 J/g, we can obtain the transformity of oil as

$$\tau_{\text{oil}} = \frac{\varepsilon_{\text{oil}}}{H_{\text{oil}}} = \frac{2.32 \times 10^9 \text{sej/g}}{4.19 \times 10^4 \text{J/g}} = 5.54 \times 10^4 \text{sej/J}$$

which is within 5% of the transformity calculated by Odum (1996).

In the same way, 12/16 of the mass of petroleum natural gas (for sake of simplicity considered as methane) is represented by carbon, therefore:

$$\varepsilon_{\text{gas}} = 0.75(2.73 \times 10^9 \text{sej/g C}) = 2.05 \times 10^9 \text{sej/g}$$

and using an enthalpy of 5.13×10^4 J/g for methane (H_{gas}), we obtain the transformity of petroleum gas as:

$$\tau_{\text{gas}} = \frac{\varepsilon_{\text{gas}}}{H_{\text{gas}}} = \frac{2.05 \times 10^9 \text{sej/g}}{5.13 \times 10^4 \text{J/g}} = 4.00 \times 10^4 \text{sej/J}$$

which is 15% less than the transformity 47,000 sej/J, that is regularly used for natural gas in emergy analyses (Odum, 1996).

4. Discussion

In general, transformities calculated for the same material using different methods that are within an order of magnitude of each other are considered to be within the expected uncertainty associated with different calculation methods and conditions of formation. The fact that the estimates for the transformity of oil and petroleum natural gas converge strongly to a common value (±3% of the mean for oil and ±11% of the mean for natural gas) indicates that both methods for determining transformities are valid. For comparison the different methods of estimating the transformity of coal (Odum, 1996) produced a 26% difference between the transformity of coal as estimated from its geological production cycle (3.34×10^4 sej/J) compared to that estimated from the efficiency of electricity generation (4.22×10^4 sej/J) using an energy quality factor of 4 coal J/J of electricity. This difference translates into a determination for the transformity of coal that is within ±16.5% of the mean value. If the transformity of electricity is determined from a wood-fired power plant rather than by assuming an average value from several methods of generation, there is a 47% difference in the coal transformities calculated using the two methods. This difference (21%) gives us an idea of the uncertainty in calculating a transformity for coal associated with the process used to generate electricity. From this perspective, our analysis indicated that the uncertainty in the calculation methods for the transformity of oil and natural gas is somewhat less than might be expected from the uncertainties associated with the estimation of the transformity of coal.

The transformities for coal, natural gas and oil as determined from their geological formation processes fall in the expected order, in which the transformity of petroleum natural gas is 20% greater than the transformity of coal and oil is 66% greater than coal. The transformity of oil relative to natural gas is somewhat greater (38.5% larger compared to 12.5%), when determined by this method than when determined by the relative efficiency of electricity production. Thus, the transformity of crude oil is relatively high compared to other products derived from the organic matter produced in photosynthesis. Note that the specific emergy of petroleum is 2.7 times greater than rock products of the sedimentary cycle (Odum, 1996). Its transformity is lower because of the greater energy content of organic matter.

This emergy analysis of the biogeochemical process of petroleum formation from thermodynamic and geologic perspectives showed that the transformity of oil is approximately 55,400 sej/J and that the transformity of natural gas is approximately 40,000 sej/J.

In addition, we believe that these estimates, based on the thermodynamics of the biogeochemical production process, have given us values close to the minimum estimate for the transformity of oil and petroleum natural gas (Odum, 1996). Our estimate of the transformities for crude oil and petroleum natural gas are based on the analysis of a nearly ideal system for the generation of petroleum, from the biogeochemical viewpoint. This conservative assumption resulted in a transformity for oil that was approximately equal to the previous one based on the relative efficiencies of electricity production. It is clear from these results that emergy analysts can have a high degree of confidence in the transformities for oil and natural gas that are currently in use. However, we recommend that those values be modified to reflect the results of this study. This is not a moot point because of the possible sensitivity of emergy analyses and emergy indices to the relative difference between the transformities of oil and other fuels and because of the importance of oil in the emergy evaluation of territories and processes (it is often the largest emergy input). If we follow the precedent for coal set by Odum (1996), we would average the transformities determined from the biogeochemical formation process and electricity production efficiency methods to get a 54,200 sej/J for crude oil and 43,500 sej/J for natural gas. These transformities are determined relative to the 9.26×10^{24} sej/y planetary emergy base line from Campbell (2000a). This analysis gives a strong footing for future determinations of transformities for petroleum derivatives, such as gasoline, kerosene, jet fuel, etc.

The transformities calculated in this paper are based on the concept of emergy (Odum, 1996) and the quantity of emergy to produce oil and petroleum natural gas in a system assumed to be in steady state. Petroleum is far from being a renewable resource because the time needed for its replacement is extremely long compared to the time of its use by society. Furthermore, the emergy needed for the reestablishment of the previous state following the use of fossil fuels is higher than the emergy provided by the fossil fuels used. The environmental impact of fossil fuels (greenhouse effect, etc.) can be evaluated using emergy measures and this topic will be considered further at another time (see Tiezzi et al., 1996).

Appendix A. Solar transformity of phytoplankton net production in petroleum-forming environments

We tested our initial assumption that the maximum photosynthetic yield for phytoplankton gives a reasonable estimate of the minimum solar transformity for phytoplankton net production in oil forming areas. The key questions to be answered to verify our initial assumption are “How concentrated are the earth’s emergy resources in the areas that are most suited for oil formation?” and “What is the net productivity of these areas?”. To know these answers for sure, we would have to perform a complete emergy evaluation of one or more of these areas, but a quick test of our hypothesis can be made using existing data. If we assume that shallow enclosed areas in evaporative environments are ideal for petroleum formation and that productivity in these environments approaches the high end of the observed range, we estimate that the transformity for phytoplankton biomass lies between 1590 and 3200 sej/J using literature measurements for maximum net production. It is known that better environments for oil formation existed in the past (Tissot and Welte, 1978). Given this fact, we determined that a 58% increase over the highest phytoplankton production rates would be required to reach our assumed transformity of 1140 sej/J. These rough estimates show that the solar transformity of phytoplankton net production in oil-forming environments may approach Wessels estimate of maximum photosynthetic yield as conditions become more favorable for petroleum formation.

The following data and assumptions were used to determine the emergy base for the Mosquito Lagoon system.

(a) The total emergy from Table A.1 divided by the area of the Mosquito Lagoon is (1.9×10^8 m^2) gives empower density, 2.62×10^{11} sej m^{-2} y^{-1}.

(b) Net productivity of hypersaline Texas lagoons (∼28°N latitude) estimated from Odum (1967) to be 12–13 g dry weight per day or 4562 g m^{-2} y^{-1}. We used 4.9 kcal/g dwt. for phytoplankton and 4187 J/kcal to convert dry weight to Joules. Additional data on daily net production were taken from page 88 in Parsons and Takahashi (1973). Table A.2.

Table A.1
The emergy base for Mosquito Lagoon, FL, ∼28°N latitude is modified from Campbell (2000b)

Note	Item	Energy (J/y)	Transformity (sej/J)	Emergy (sej/y)
1	Sun	1.07×10^{18}	1	1.07×10^{18}
2	Rain, chemical potential	1.14×10^{15}	18200	2.07×10^{19}
3	Tide	6.27×10^{13}	24500	1.54×10^{18}
4	Earth cycle	2.51×10^{14}	34400	8.63×10^{18}
5	Groundwater, chemical potential	1.08×10^{14}	166200[a]	1.79×10^{19}
6	River, organic matter	2.66×10^{12}	390300[a]	1.04×10^{18}
7	Total			4.98×10^{19}

(1) The annual average solar radiation at Daytona Beach, FL, is 4.8 kwh/d or 6.3×10^9 J m^{-2} y^{-1}. Albedo is approximately 11% and the radiation absorbed is 5.61×10^9 J m^{-2} y^{-1} or 1.07×10^{18} J/y.

(2) Rainfall is 1.42 m/y, solute concentration in the rain is 16.3 ppm, and salinity at the estuary mouth is 32 parts per thousand. The annual chemical potential energy inflow in rain is 1.14×10^{15} J/y using the formula in Odum (1996).

(3) Data used to determine the tidal energy absorbed were 0.35 m average tide height, over the North Inlet area of 7.22×10^7 m^2 with 706 tides per year and water density 1.03 g cm^{-3}. The formula in Odum (1996) gives 6.27×10^{13} J/y absorbed.

(4) The Earth cycle energy driving geologic uplift in this area is 42 mW m^2 (Lachenbruch and Sass, 1977), which results in a heat flux of 2.51×10^{14} J/y through the watershed area.

(5) The volume of ground water flow was estimated to be 11% of total precipitation or 2.59×10^7 m^{-3} y^{-1}. A solute concentration of 335 ppm gives an annual emergy input of 1.08×10^{14} J/y. A new calculation for the global transformity of ground water was made using data from Schlesinger (1993), Murray (1992) quoted and condensed by Reeburgh at http://www.ess.uci.edu/∼reeburgh/fig8.html. The global storage of active groundwater was estimated to be 4×10^6 km^3 with a turnover of ∼300 y which gives and annual flux of 1.33 10^4 km^3/y. If the average solute concentration of these waters is similar to Mosquito Lagoon groundwater the chemical potential energy flux 5.57×10^{19} J/y and the global transformity for ground water is ((9.26×10^{24} sej y^{-1})/5.57×10^{19} J/y) = 166247 sej/J.

(6) Average organic matter concentration in Spruce Creek at Samsula, FL, was 35.9 ppm and the volume of inflow was 3.54×10^6 m^3 y^{-1}. Using 5 kcal/g and 4187 J/kcal the energy inflow in organic matter was 2.66×10^{12} J/y. A revised transformity for organic matter in river water was determined using data quoted in Thurman (1985). Estimates for the total TOC delivered to the world oceans range from 33 (Schlesinger and Melack, 1981) to 83 (Ritchey et al., 1980) moles of C per year. Given these two estimates and using 5 kcal/g of organic matter the energy inflow to the world oceans ranges from 1.66 to 4.17×10^{19} J/y giving and average transformity of 390,300 sej/J.

(7) The total does not include sunlight; however, the double counting error is small if it is included. Rain and tide enter the system directly, whereas, ground water and organic matter are concentrated to the lagoon from a larger area. Uplift operates on the entire watershed.

[a] Revised transformities.

Table A.2
Variation of the transformity of phytoplankton net production for different assumptions about productivity of coastal waters given that the Mosquito Lagoon empower density (2.62×10^{11} sej m^{-2} y^{-1}) is typical of oil-forming ecosystems. Use 0.45 g C/g dwt. and 4.25 kcal/g dwt.

Source	Insolation (l y/d)	Net production (g dwt. m^{-2} y^{-1})	Annual production (J m^{-2} y^{-1})	Transformity (sej/J)
Parsons and Takahashi (1973) <1 m, 260 mg chla m^{-2}	400	800	1.42×10^7	18400
High range rule of thumb		2500	4.45×10^7	5880
Parsons and Takahashi (1973)		055	7.22×10^7	3620
Low range maximum estimate from Odum (1967)		4745	8.44×10^7	3100
In hypersaline Texas lagoons Parsons and Takahashi (1973)		8111	1.44×10^8	1810
High range maximum 58% increase over present maximum		12,856	2.28×10^8	1150

Average insolation for Mosquito Lagoon is 412 l y/d.

References

Brown, M.T., Herendeen, R.A., 1996. Embodied energy analysis and EMERGY analysis: a comparative view. Ecol. Econom. 19, 219–235.

Campbell, D.E., 2000a. A revised solar transformity for tidal energy received by the earth and dissipated globally: implications for emergy analysis. In: Brown, M.T. (Ed.), Emergy Synthesis. Proceedings of the First Biennial Emergy Analysis Research Conference. The Center for Environmental Policy, Department of Environmental Engineering Sciences, Gainesville, FL.

Campbell, D.E., 2000b. Using energy systems theory to define, measure, and interpret ecological integrity and ecosystem health. Ecosyst. Health 6 (3), 181–204.

Cook, E., 1976. Man, Energy and Society. Freeman, San Francisco.

Lachenbruch, A.H., Sass, J.H., 1977. Heat flow in the United States and the thermal regime in the crust. In: Heacock, J.G. (Ed.), The Earth's Crust Geophysical Monographs, vol. 20. AGU, Washington, DC, pp. 626–675.

Morowitz, H.J., 1978. Foundations of Bioenergetics. Academic Press, New York.

Murray, J.W., 1992. The Oceans. In: Butcher, S.S., et al. (Eds.), Global Biogeochemical Cycles. Academic Press, San Diego.

Odum, H.T., 1967. Biological circuits and the marine systems of Texas. In: Olsen, T.A., Burgess, F.J. (Eds.), Pollution and Marine Ecology. Wiley Interscience, New York, pp. 99–157.

Odum, H.T., 1988. Self organization, transformity and information. Science 242, 1132–1139.

Odum, H.T., 1991. Emergy and biogeochemical cycles. In: Rossi, C., Tiezzi, E. (Eds.), Ecological Physical Chemistry. Elsevier Science Publisher, Amsterdam, The Netherlands, pp. 25–56.

Odum, H.T., 1996. Environmental Accounting. Wiley & Sons, NY, USA.

Odum, H.T., Odum, E.C. (Eds.), 1983. Energy analysis overview of nations. Working Paper. International Institute of Applied Systems Analysis, Laxenburg, Austria (WP-83-82), 469 pp.

Parsons, T.R., Takahashi, M., 1973. Biological Oceanographic Processes. Pergamon Press, Oxford.

Ritchey, J.E., et al., 1980. Organic carbon oxidation and transport in the Amazon river. Science 207, 1348–1351.

Saoiabi, et al., 2001. Schistes bitumineuxde Timahdit (Maroc): composition e propriété physicochimiques. C. R. Acad. Sci. Paris, Chimie, Chem. 4, 351–360.

Schlesinger, W.H., 1993. Biogeochemistry, an Analysis of Global Change. Academic Press, San Diego.

Schlesinger, W.H., Melack, J.M., 1981. Transport of organic carbon in the world's rivers. Tellus 33, 172–187.

Slesser, M., 1973. Energy subsidy as a criterion in food policy planning. J. Sci. Food Agric. 24, 1193–1207.

Thurman, E.M., 1985. Organic Geochemistry of Natural Waters. Martinus Nijhoff/Dr. W. Junk Publishers, Dordrech.

Tiezzi, E., 1984. Tempi storici, tempi biologici, Garzanti, Milano; in English as The End of Time, WIT Press, Southampton, 2002.

Tiezzi, E., Bastianoni, S., Marchettini, N., 1996. Environmental cost and steady state: the problem of adiabaticity in the emergy value. Ecol. Modell. 90, 33–37.

Tissot, B.P., Welte, D.H., 1978. Petroleum Formation and Occurrence: a New Approach to Oil and Gas Exploration. Springer, New York.

Ulgiati, S., Odum, H.T., Bastianoni, S., 1994. Emergy use, environmental loading and sustainability. An emergy analysis of Italy. Ecol. Modell. 73, 215–268.

Wessells, N.K., Hopson, J.L., 1988. Biology. Random House, New York.