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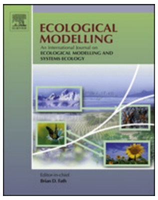

Assessing geobiosphere work of generating global reserves of coal, crude oil, and natural gas

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ABSTRACT

A teacher of ours used to say, “Like ice in a fire, something for nothing you will never acquire”, which is a poetic equivalent of “there is no such a thing as a free lunch”. Human economies are dependent on high quality fossil fuels and will likely continue depending on them for some time to come. Value of a resource is not only what one pays for it, or what can be extracted from it, but also value can be attributed to the “effort” required in its production. In this analysis we apply the emergy synthesis method to evaluate the work invested by the geobiosphere to generate the global storages of fossil energy resources. The upgrading of raw resources to secondary fuels is also evaluated. The analysis relies on published estimates of historic, global net primary production (NPP) on land and oceans, published preservation and conversion factors of organic matter, and assessments of the present total global storages of coal, petroleum, and natural gas. Results show that the production of coal resources over geologic time required between 6.63E4 (±0.51E4) seJ/J and 9.71E4 (±0.79E4) seJ/J, while, oil and natural gas resources required about 1.48E5 (±0.07 E5) seJ/J and 1.70E5 (±0.06E5) seJ/J, respectively. These values are between 1.5 and 2.5 times larger than previous estimates and acknowledge a far greater power of fossil fuels in driving and shaping modern society.

1. Introduction

Fossil fuels are important. Human society depends on them and will likely continue doing so for many decades to come, in spite of concerns for climate change, peak oil, increasing prices, and national security. We are well aware of the importance of fossil fuels and as a consequence need to assign an energetic and environmental value that is commensurate with their quality. That different energies have different qualities and thus have different costs of production and abilities to do work is a major conceptual principle of the emergy synthesis methodology (Odum, 1988, 1996; Brown and Ulgiati, 1997, 2004a,b). This principle is the foundation of the concept of transformity and specific emergy. Transformity (in units of seJ/J) and specific emergy (in units of seJ/g) are examples of the more general term, unit emergy values (UEVs), which is defined as the ratio of available emergy of one type (emergy) that is required directly or indirectly to produce a unit output from a process. UEVs are ratios that allow the conversion of different forms of energy into a single form named emergy.

Within the framework of emergy synthesis the quality of energy (and any other resource) is measured by the inputs of energy, materials and information required to make it. The unit emergy value (UEV) is a measure of those inputs when the inputs are expressed in the same units. UEVs for the fossil fuels are extremely important as they form the basis for the calculation of most second order energies (e.g., electricity), products, and services. It has long been recognized that there is no single unit emergy value (UEV) for a particular substance or product as there are a multitude of possible processes that can produce them (Brown and Ulgiati, 2004a,b). Yet emergy analysts often use a single UEV assuming that the differences in UEVs are negligible (which is sometimes the case) or that the particular published UEV value is representative of a larger set of values. However, relying on a single UEV from a single case study is less than desirable because it may not always be representative of the global set of processes that lead to a given product. A weighted average of many processes that yield the same product would be a much more preferable option if the actual source of an input is not known.

There have been previous evaluations of the UEVs for fossil fuels, first by Odum (1996) and more recently by Bastianoni et al. (2005). In both instances the evaluations were based on a single case study. Odum (1996) reported interdependent transformities for oil, natural gas, and coal using a technique of back calculation from the transformity of electric power plants and assumption of the relative efficiencies of coal and oil thermal plants. Bastianoni et al. (2005) computed the transformity and specific emergy of oil and

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Table 1
Quantity and available energy of coal by geologic period of production.

Period	% of resource[a] coal	Quantity[b] (E9 MT)		Available energy[c] (E18 J)	
		Anthracite and bituminous	Sub-bituminous and lignite	Anthracite and bituminous	Sub-bituminous and lignite
Devonian	0.1%	0.5	0.4	11.5	7.7
Carboniferous	24.3%	116.9	103.7	2806.4	1866.8
Permian	31.7%	152.5	135.3	3661.0	2435.3
Triassic	0.4%	1.9	1.7	46.2	30.7
Jurassic	16.8%	80.8	71.7	1940.2	1290.6
Cretaceous	13.3%	64.0	56.8	1536.0	1021.8
Tertiary	13.5%	65.0	57.6	1559.1	1037.1
Total	100%	481.7	427.2	11560.3	7690.1

[a] Data are from Bois et al. (1982) and Bestougeff (1980) as reported by Veizer et al. (1989) and Walker (2000).
[b] Total quantity of hard and soft coal from EIA (2010).
[c] Available energy computed using the following: available energy in hard coal = 2.4E10 J/kg; available energy in soft coal = 1.8E10 J/kg.

petroleum natural gas based on the biogeochemical processes that contributed to their formation in a particular site, located in Russia, which was suggested as the most productive oil formation site known, translating into conservative UEV estimates. However, they included only the biological processes and did not include the additional geothermal "treatment" that is a necessary input to convert the buried biomass into kerogen and finally oil and gas.

In this study we carry the analysis further by using the total known conventional reserves of oil,[1] natural gas, and coal over geological ages, and separating the production process into two separate processes governed first by biological process and second by geothermal processes. By separating the processes, we compute the emergy required to produce the organic matter, which is the precursor to kerogen and then the geothermal emergy required to generate the final product.

2. Methods

The production of coal and petroleum are similar in that there is a biological phase and a geothermal phase, yet the biological phases differ since the source for coal is largely peat derived from terrestrial production and petroleum's sources are largely of marine origin; therefore we evaluate their UEVs separately.

2.1. Coal

There are two very distinct processes that contribute to coal formation (Fig. 1). The first phase is the production of living biomass and accumulation of partially decomposed organic matter that is transformed through a second phase of coalification. Both phases are separated in time and in space, since ecological production ceases at some point and the accumulated organic matter is buried to achieve the second geothermal phase. The first phase, the ecological phase, is driven by the energy and ecological processes that support primary production, while geothermal processes drive the second phase (accumulation and further processing). Determination of the emergy driving the formation of coal is divided into these two phases accordingly. In addition to evaluating the two phases, we also evaluated the coal resource based on geologic age and also divided the coal resource into hard coal (anthracite/bituminous = 53% of total resource) and soft coal (sub-bituminous/lignite = 47% of total resource) based on estimates by the Energy Information Administration (EIA, 2010). Table 1 lists the quantity and available energy of the hard and soft coal resource by geologic age. The low coal productivity shown by Devonian period is likely due to still incomplete colonization of continents by organisms and therefore an insufficient amount of terrestrial peat-forming biomass; the similar low productivity in the Triassic can be attributed to the well known "coal gap", i.e. the extinction of peat-forming plants at the end of the Permian, about 250 Ma ago (Retallack et al., 1996; Beerling, 2002).

2.1.1. Phase 1: net primary production to peat

It is generally accepted that coal was formed from terrestrial sources, largely in prehistoric swamps (Teichmuller and Teichmuller, 1986). The anoxic and acidic environment of wetland soils resulted in relatively slow decomposition of organic matter leading to its accumulation over time in large deposits of peat. In modern times, accumulation rates of peat in swamps average about 2.5 mm/yr. In some geologic ages accumulation may well have been higher. Rather than trying to estimate accumulation rates, in this analysis, we use estimates from the literature of the coal resource that was produced in each geologic age and back calculate the net primary production (NPP) that was required, using the preservation factors (PFs) or efficiencies of conversion. Following Dukes (2003), a preservation factor is the fraction of carbon that remains at the end of a transition from one fossil fuel precursor to the next, for example the fraction remaining from plant matter to peat, on the path to coal formation. Shown in Fig. 1 are two stages in the formation of the coal resource where PFs were applied (PF_1, PF_{2a}, and PF_{2b}). The preservation factors used in calculating NPP requirement for hard and soft coal were based on literature values and are given in Table 2.

The first PF is the percent of organic matter that is preserved as peat. Dukes (2003) suggested that preservation of organic matter in peat could range from 4% up to a high 39%, while Tissot and Welte (1984) estimated it at less than 10%. Frolking et al. (2002) suggested a value around 6.5% based on a 8500 yr Holocene Peat Model (HPM) of peat accumulation with carbon–water feedbacks in Ontario, Canada. In our analysis we use 7% as a reasonable estimate extracted from these two sources.

The emergy required for the NPP in each geologic age was derived from literature sources related to the global NPP in each age and assuming constant global emergy driving all Earth processes of 15.2E24 seJ/yr (Brown and Ulgiati, 2010). Table 3 lists the geologic ages, estimated NPP in each age, and UEVs of NPP. The specific emergy of NPP ranges from 9.8E7 to 3.34E7 seJ/gC. NPPs and UEVs for Devonian and Triassic are not much different than for the other ages; their low coal production was therefore not due to insufficient amount of biomass, but instead more likely to unsuitable characteristics and (for Triassic) early extinction of peat-forming plants.

2.1.2. Phase 2: coalification

As the peat is buried by sediment and becomes compressed (diagenesis), it slowly releases water and minor gases resulting in an

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[1] Unless otherwise stated, in this analysis the term oil means crude oil through out.

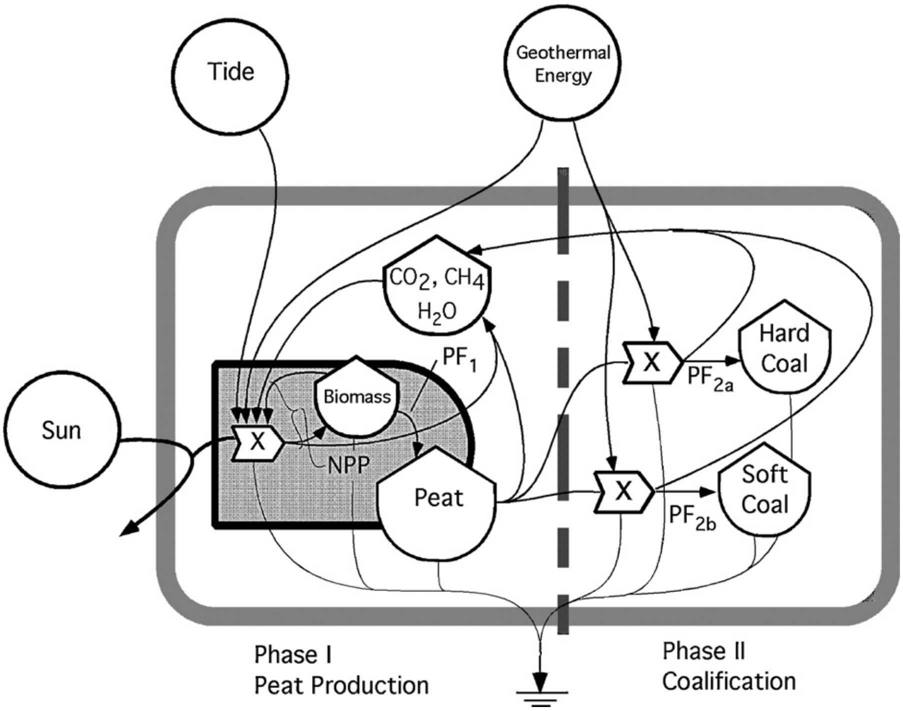

Fig. 1. The two phases of coal formation. Phase I: peat production is dominated by ecological processes that are driven by solar, tidal, and geothermal energies of the geobiosphere. Phase II: coalification is driven by geothermal energy. PF_{1-2} are preservation factors (fraction of carbon that is preserved and passed to the next step): PF_1 is the preservation between organic matter production and peat accumulation. Hard coal and soft coal have two different preservation factors PF_{2a} and PF_{2b} between peat and coal.

Table 2
Preservation factors for hard and soft coal.

Coal type	Percent carbon[a]	PF_1, percent of NPP that becomes peat[b]	PF_2, preservation of peat to coal[b]
Anthracite/bituminous	90%	7% (±1.05%)	69% (±17.25%)
Sub-bituminous/lignite	70%	7% (±1.05%)	95.6% (−24%)

Numbers in parentheses are the variation programmed in the Monte Carlo simulation.

[a] Ward (1984).

[b] Dukes (2003) and Tissot and Welte (1984).

increasingly compact and carbon rich substance. The process of coalification proceeds through several different stages, first forming lignite, then sub-bituminous coal, then bituminous coal and finally anthracite coal. Organic substances in peat that are converted to coal are sensitive to heat exposure. Normally they are coalified with increasing depth of burial because of the increasing rock temperature with depth. The degree of coalification or "rank" of coal depends primarily on the maximum temperatures achieved and only to a minor degree on the heating time (Teichmuller and Teichmuller, 1986).

Table 3
Unit emergy values for NPP by geologic age (coal).

Geologic age	Terrestrial NPP[a] (gC/Ma)	Specific emergy[b] (seJ/gC)	Transformity[c] (seJ/J)
Devonian	4.50E+22	9.80E+07	2.34E+03
Carboniferous	4.23E+22	1.04E+08	2.49E+03
Permian	5.40E+22	8.16E+07	1.95E+03
Triassic	5.40E+22	8.16E+07	1.95E+03
Jurassic	1.60E+23	2.76E+07	6.58E+02
Cretaceous	1.39E+23	3.17E+07	7.57E+02
Tertiary	1.32E+23	3.34E+07	7.98E+02

[a] Estimates of NPP using mass balance analysis of the stable isotopes ($^{18}O/^{16}O$) (Beerling, 1999) and Beerling et al. (1999). NPP for each age was allocated based on weighted average of values from Beerling since geologic ages were overlapping.

[b] Specific emergy = emergy divided by the quantity of carbon in NPP. Emergy = 1E6 yrs × 1.52 E25 seJ/yr (total emergy drivng geobiosphere) × 29% (percent of global emergy driving terrestrial production) = 4.4E30 seJ/Ma.

[c] Conversion of gC to Joules is based on 10 kcal gC (Platt and Irwin, 1973) and 4187 J/kcal as follows: Transformity = specific emergy divided by (10 kcal/gC × 4187 J/kcal).

The fraction of carbon in peat that remains as coal depends on the type of coal. Dukes (2003) referencing Mott (1942, 1943) suggested that 69% of the original carbon of peat remains in hard coal and 95.6% remains in soft coal. We used these values as the second preservation factors (PF_{2a} and PF_{2b}).

Coalification is driven by geothermal processes. The available geothermal energy necessary to achieve coalifications was based on the ratio of the mass of coal produced to the mass of the continents times annual available geothermal energy times the time needed for coalification (20 millions years; Teichmuller and Teichmuller, 1986) as follows:

$$\text{Geothermal emergy} = \frac{\text{coal mass}}{\text{continental mass}} \times \text{annual geothermal emergy} \times 20\text{E6 yrs} \tag{1}$$

The available geothermal energy required was calculated using the geothermal energy released by Earth (4.6E13 W = 1.45E21 J/yr) multiplied by the Carnot efficiency at the temperatures required for coalification (237.5 °C mean for anthracite/bituminous and 97.5 °C mean for sub-bituminous/lignite; Teichmuller and Teichmuller, 1986) relative to the reference environmental temperature (20 °C), as follows:

$$\text{Annual geothermal emergy} = 1.45\text{E21 J/yr} \times \text{Carnot efficiency} \tag{2}$$

where: Carnot efficiency at 237.5 °C = 0.24; and at 97.5 °C = 0.08 for coal produced in each different geologic period. Finally, we provide weighted average UEVs for both hard and soft coal.

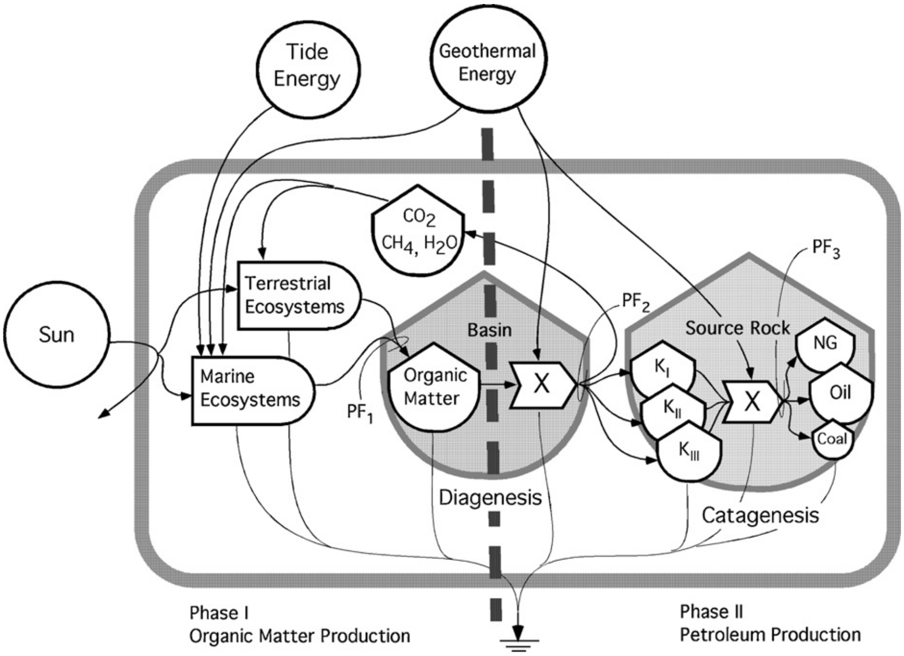

Fig. 2. The two phases of petroleum formation. Phase I: organic matter production is dominated by ecological processes driven by solar, tidal and geothermal energies of the geobiosphere. Phase II: petroleum production is driven by geothermal energy. PF_{1-3} are preservation factors (fraction of carbon that is preserved and passed to the next step): PF_1 is the preservation between organic matter production and organic matter accumulation in basins, PF_2 is the preservation between accumulated organic matter and kerogen, and PF_3 is the preservation between kerogen and oil/natural gas (K_I = kerogen type I; K_{II} = kerogen type II, K_{III} = kerogen type III).

2.2. Petroleum

Conventional reserves of crude oil are usually found in association with natural gas. The production of crude petroleum and natural gas is known to take place over geologic time. Similar to coal, the process can be separated into 2 distinct phases (Fig. 2). The first phase is dominated by the biological production of organic matter, while geologic processes dominate the second phase. Biological carbon sources for petroleum are produced in both terrestrial and marine environments although marine sources dominate total production of reserves (87% vs 13%) An important distinction does occur in that during certain geologic ages, the production of natural gas is almost entirely from terrestrial sources.

Each geologic age is responsible for differing quantities of known petroleum reserves. Table 4 shows the percentage amounts of known reserves by geologic age[2] and marine vs terrestrial origin; data are from Klemme and Ulmishek (1991). Petroleum formation on the continental margins and in large land-locked, isolated basins is primarily the result of productivities of algae and zooplankton with additional inputs from terrestrial sources of organic matter (Tissot and Welte, 1984). Data are given as percentages in Table 4 because the calculation procedure that follows assigns emergy proportional to the fraction of NPP that becomes hydrocarbons. The absolute amounts of hydrocarbons do not affect the final emergy results, while percentages of total resource per age will have an effect. We also assume that percentages of hydrocarbons generated in each geological age will not be appreciably changed by new discoveries or more accurate estimates of total resource.

2.2.1. Phase I: net primary production to organic sediments

In this phase of the evolution of petroleum, biological net primary production (NPP), which converts biosphere energies into organic matter is the main process. As in the coal calculation, we begin with the quantity of petroleum and natural gas that was produced in each geologic age and back calculated to the quantity of NPP that was required to produce it using preservation and conservation factors from literature. Table 5 lists the conversion factors for marine and terrestrial carbon becoming hydrocarbons (the numbers in parentheses are percent variation used in Monte Carlo simulations, below). The conversion efficiencies are based on data from Tissot and Welte (1984). The second and third columns in the table list the percent of NPP from marine and terrestrial sources that is preserved as kerogen. The fourth and fifth columns list the percent of marine and terrestrial kerogen that is converted to hydrocarbons. Tissot and Welte show that for the most part, organic matter from marine sources becomes kerogen types I and II, while terrestrial organic matter becomes kerogen type III. It can be seen from Table 5 that the conversion efficiencies of terrestrial organic matter are much lower than those for organic matter derived from marine NPP. This is an important consideration and has significant impact on overall transformities, which we will address in Section 5.

We allocate the emergy driving the geobiosphere (sum of solar radiation, tidal momentum and geothermal energy: 15.2E24 sej/yr) to terrestrial and marine systems based on their percent of the total surface area of the Earth (terrestrial = 30%; marine = 70%) assuming such percent to be constant over the geological ages (the large uncertainty of information over very long time periods makes this assumption reasonable). The analysis separates terrestrial and marine organic matter production since they have different productivity and UEVs (Table 6). Each geologic age has differing overall NPP as estimated by Beerling (1999) and Beerling et al. (1999) and is responsible for differing amounts of oil production (Klemme and Ulmishek, 1991). Calculating backward from the petroleum resource produced in each geologic age and using the efficiencies in Table 5 we allocated geobiosphere emergy driving NPP that becomes petroleum organic matter. Once the quantity of NPP as grams carbon is known, the geobiosphere emergy is assigned to this quantity based on the UEVs given in Table 6.

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[2] The literature on petroleum production refers to a different system of naming geologic ages and thus the ages in Table 4 are slightly different than those used in the coal evaluation above. The coal data were given in geologic periods, while the petroleum data were given in a combination of periods and sub-periods.

Table 4
Percent of known global reserves of petroleum hydrocarbons generated by geologic age.

Geological age	Geological ages (Ma, million years) before present		Percent of hydrocarbons generated[a]	Percent of hydrocarbons generated per kerogen type			
	From	To		From kerogen types I and II (mainly marine)		From kerogen type III (mainly terrestrial)	
				Oil	Natural gas	Oil	Natural gas
Silurian	438	408	9.0%	15%	85%	–	–
Upper Devonian-Turonian	374	352	8.0%	80%	20%	–	–
Pennsylvanian-Lower Permian	320	286	8.0%	35%	43%	–	22%
Upper Jurassic	169	144	25.0%	74%	26%	–	–
Middle Cretaceous	119	88.5	29.0%	61%	10%	4%	25%
Oligocene-Miocene	36.6	5.3	12.5%	28%	7%	39%	26%

[a] Data are from Klemme and Ulmishek (1991). Percentages do not add to 100% because 8.5% of global reserves produced in a number of miscellaneous time periods not included.

Table 5
Efficiencies of conversion of biomass to kerogen and from kerogen to hydrocarbons.

Time period	Marine biomass conversion to kerogen[a]	Terrestrial biomass conversion to kerogen[a]	Marine kerogen conversion to hydrocarbons[b]	Terrestrial kerogen conversion to hydrocarbons[b]
All geologic ages	4% (±1%)	2% (±0.5%)	75% (±15%)	20% (±5%)

Numbers in parentheses are the variation programmed in the Monte Carlo simulation.

[a] Conversion efficiencies are from Demaison and Murris (1984).

[b] Conversion efficiencies are from (Klemme and Ulmishek, 1991) and hydrocarbons/kerogen ratios from Behar et al. (1997), Tissot et al. (1987), Kenneth et al. (1994), Waples (1994), and Klemme (1994).

2.2.2. Phase II: petroleum generation

The three main geologic stages of the evolution of organic matter in sediments (diagenesis, catagenesis, and methanogenesis) are geologic processes driven by geothermal processes. During diagenesis, the temperature increases are small and CO_2 and water are released. The main form of carbon is organic carbon. During catagenesis the temperature increases reaching between 50 and 150 °C. The main carbon form is hydrocarbons, as this stage is the principle stage of crude oil formation (early) followed by wet gas in the latter stages. The methanogenesis stage results in only the production of dry gas at higher temperatures (up to 200 °C); thus the main carbon form is methane.

During the geologic stages of petroleum formation, time and temperature are important, although Tissot and Welte (1984) suggest that transformation is more influenced by temperature than by time. We allocate geothermal emergy to catagenesis and methanogenesis processes based on the time and temperature. In a study of petroleum basins in Wyoming, the USGS (2005) estimated average times and temperatures for oil and gas formation, confirming previously published research. They estimated 20 million years at between 50 °C and 150 °C for oil generation during catagenesis and further 12 million years at between 150 °C and 200 °C for gas generation during methanogenesis, respectively. Gas formation follows oil formation in a second step separated from the first by about 5 million years. Tissot and Welte (1984) also reported temperatures for significant generation of oil as between 50 °C and 150 °C. We used 100 °C for catagenesis and 175 °C for methanogenesis.

The geothermal available energy necessary to achieve catagenesis and methanogenesis was based on the ratio of the mass of oil and natural gas produced to the mass of the continents multiplied by the annual geothermal available energy times the time for each (20 millions years for catagenesis and 12 million years for methanogenesis) and using Eqs. (1) and (2) above. The geothermal available energy was calculated using Carnot efficiencies of 21% for 100 °C and 34% for 175 °C.

2.3. Monte Carlo simulation of UEVs for coal, oil, and natural gas

There are obvious uncertainties in the data used to calculate the emergy required for each phase of production of fossil fuels. Taking these uncertainties into consideration, we developed Monte Carlo simulations for coal as well as for petroleum oil and natural gas. We allowed each of the preservation factors, conversion efficiencies, and the NPP UEVs for geologic ages to vary by predetermined amounts depending on the range of values found in the literature for each variable. In the coal simulation, peat preserva-

Table 6
Net primary production, total emergy, and unit emergy values of NPP by geologic age (oil and nat. gas).

Geological age	Marine NPP (g C)[a]	Terrestrial NPP (g C)[a]	Total emergy driving marine NPP[b] (seJ)	Total emergy driving terrestrial NPP[b] (seJ)	UEV of Marine NPP[c] (seJ/gC)	UEV of Terrestrial NPP[c] (seJ/gC)
Silurian	1.23E+24	1.43E+24	3.19E+32	1.37E+32	2.61E+08	9.59E+07
Upper Devonian-Touronian	4.23E+23	9.30E+23	2.34E+32	1.00E+32	5.54E+08	1.08E+08
Pennsylvanian-Lower Permian	1.38E+24	1.52E+24	3.62E+32	1.55E+32	2.62E+08	1.02E+08
Upper Jurassic	3.66E+24	4.03E+24	2.66E+32	1.14E+32	7.27E+07	2.83E+07
Middle Cretaceous	3.31E+24	3.79E+24	3.25E+32	1.39E+32	9.81E+07	3.67E+07
Oligocene-Miocene	2.58E+24	3.12E+24	3.33E+32	1.43E+32	1.29E+08	4.58E+07

[a] NPP estimates according to Beerling (1999) and Beerling et al. (1999).

[b] Calculated as the time per geologic age multiplied by the geobiosphere emergy flow (15.2 E24 seJ/yr) and multiplied by 29% for terrestrial and 71% for marine recognizing the global split between terrestrial and marine systems.

[c] Emergy in columns 4 and 5 divided by the NPP in columns 2 and 3.

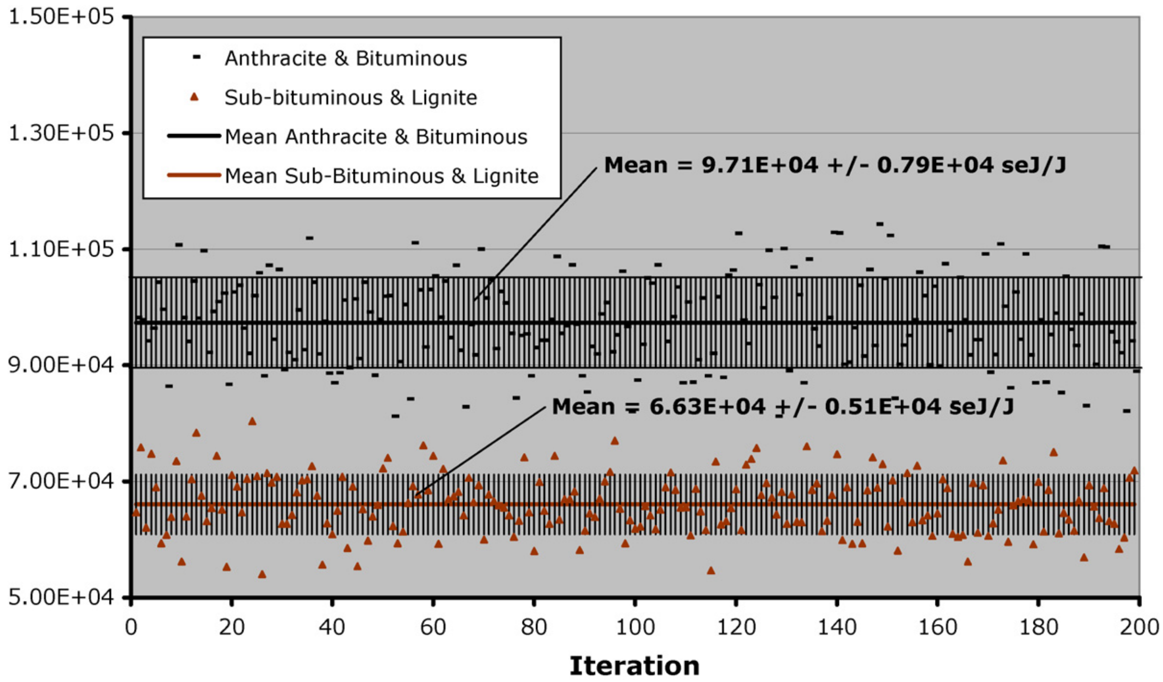

Fig. 3. Results of the Monte Carlo simulation for the transformity of anthracite and bituminous coal (top) and sub-bituminous and lignite coal (bottom). The gray bands on either side of the mean represent one standard deviation about the mean.

tion values (PF_1) were programmed to vary between ±15% and coal preservation (PF_2) varied ±25% but the sub-bituminous/lignite PF was constrained below 95.6% assuming that the reported value was near the maximum preservation factor. The UEVs of NPP were programmed to vary between ±25% from the values listed in Table 3. In the petroleum and natural gas simulations, the conversion efficiencies (Table 5) were programmed to vary ±25%. UEV values of NPP (Table 6) were also programmed to vary ±25%

Each simulation was allowed to run for 1000 iterations while all variables were programmed to vary randomly between minimum and maximum values. We report mean values for each geologic age and a weighted mean for each fossil fuel type based on percent of total reserve in each geologic age.

3. Results

Shown in Figs. 3 and 4 are graphs of the simulation results of the Monet Carlo models for calculating transformities of coal and crude oil and natural gas, respectively. The variation around the mean value in each graph results from varying the NPP, preservation and conservation factors. The light gray band on both sides of the mean value represents one standard deviation about the mean. The graphs show 200 iterations out of 1000 as representative of the entire simulation. Data points in the graphs are weighted means of UEVs for coal, crude oil and natural gas using the percent of total fossil fuel produced in each geologic age. Fig. 3 shows the weighted mean for hard and soft coal for each geologic age as 9.71E4 seJ/j and 6.63E4 seJ/j respectively. In Fig. 4, the mean weighted UEV of oil is 1.48E5 seJ/J while the weighted mean natural gas UEV is 1.70E5 seJ/J.

Tables 7 and 8 list mean UEVs for coal and oil/natural gas, respectively, by geologic age. Mean values for each age are representative of the work of the biosphere to generate the fossil fuels and were computed as the mean of the values obtained from the Monte Carlo simulation. The weighted mean was computed based on the percent of each resource that was produced in each geologic age. These UEVs are appropriate values to use when evaluating the inputs of raw resources to the global economy as they represent the UEVs of the raw resources, more or less still in the ground. Coal mining and oil well production is emergy intensive and adds to the transformity of fossil fuels as they approach their end use. They are not appropriate UEVs to use when evaluating inputs to economic processes where, in reality, the inputs are refined fuels such as gasoline, residual oil (heavy fuel oil) or diesel fuel or coal that has been mined and transported.

4. End use UEVs

The UEVs computed for the coal, oil, and natural gas resource are UEVs of the geologic resource and do not include mining, production and transportation. A UEV for the final consumption of these fossil energies should include all the emergy required to produce them. In the following sections we compute UEVs for fossil fuels that include mining, production, and transportation.

4.1. UEV for extracted and transported fossil fuels

Table 9 lists the emergy costs of extraction (mining and well drilling, etc.) and transportation of the fossil fuels. The final column is the transformity for coal, oil and natural gas, at the gate prior to either burning (coal and natural gas) or refining (oil). The computed transformities for coal are significantly larger than the raw resources while natural gas and oil have lower extraction and transportation costs. The transformities for soft and hard coal are 68% and 36% higher respectively than the resource transformity, while those for oil and natural gas are 6% and 4% higher. These higher transformities are due to mining and transport of the coal resource, and refining of the oil resource.

4.2. UEVs for end use of petroleum fuels

Fuels used in machines and transportation are refined petroleum products and thus have higher UEVs than the crude petroleum UEVs. Table 10 lists the UEVs for refined petroleum products. Using data from Argon National Laboratory, USA (Wang, 2008),

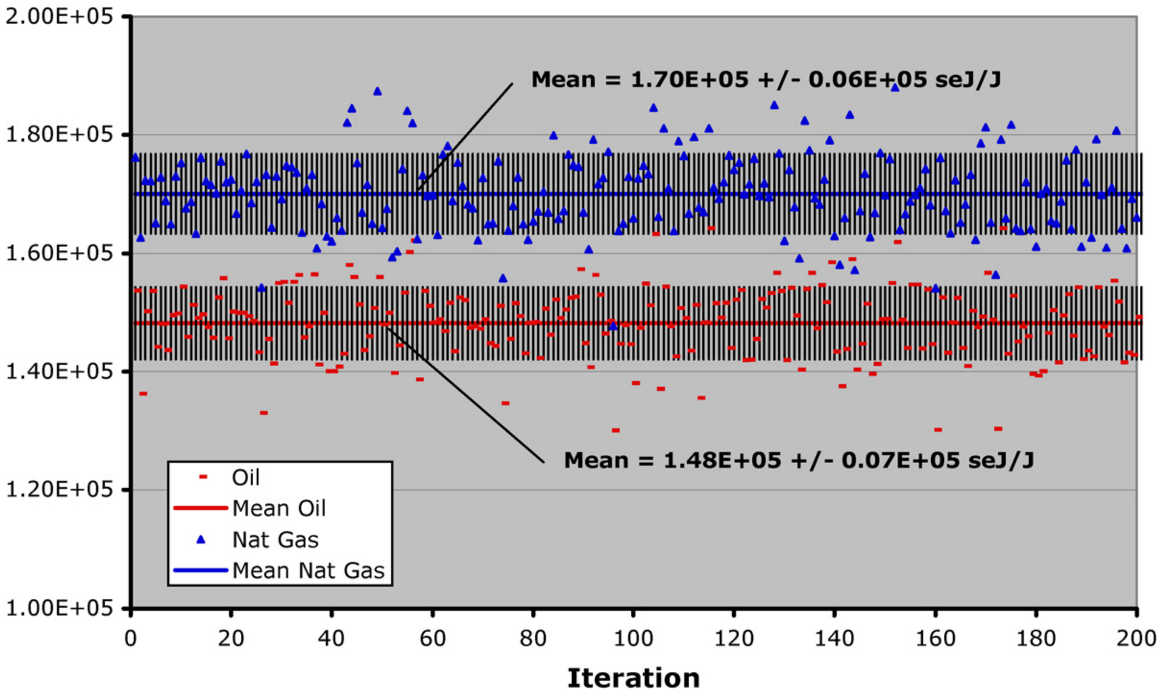

Fig. 4. Results of the Monte Carlo simulation for the transformity of natural gas (top) and crude oil (bottom). The gray bands on either side of the mean represent one standard deviation about the mean.

Table 7
Mean[a] UEVs for coal by geologic age.

Geologic age	Transformities of anthracite and bituminous (seJ/J)	Transformities of sub-bituminous and lignite (seJ/J)
Devonian	9.35E+04	5.79E+04
Carboniferous	9.73E+04	6.42E+04
Permian	7.79E+04	5.02E+04
Triassic	7.88E+04	5.09E+04
Jurassic	2.45E+05	1.68E+05
Cretaceous	3.73E+04	2.13E+04
Tertiary	3.85E+04	2.21E+04
Weighted mean[b]	9.71E+04	6.63E+04

[a] Mean values are based on 1000 iterations of the Monte Carlo simulation.
[b] Weighted mean is based on percent of coal resource in each geologic age.

we computed the UEVs for fuel types given in Table 10 based on refinery efficiencies. The refining process on average adds about nearly 30% to the emergy costs of transportation fuels (gasoline, jet fuel, and diesel) while only about 15% to LPG and residual oil.

5. Discussion

Unit emergy values of fossil fuels measure the biosphere work to generate the global reserves of these forms of energy. The UEVs obtained in this analysis exceed previous estimations (Odum, 1996; Bastianoni et al., 2005) by about 50% for coal, 66% for oil, and a 140% for natural gas (when differences in base lines are taken into account). Odum's estimate was based on a back calculation from a wood power plant using thermal efficiencies and relying on the heat values of wood compared to oil. Bastianoni et al.'s evaluation was based on only one case that was highly favorable for petroleum generation which yielded in their estimation, calculated transformities that"…should be nearly the smallest ones possible."

The highest UEVs computed in this study are for natural gas followed by petroleum, hard coal, and soft coal. In previous estimations of UEVs for fossil fuels (Odum, 1996; Bastianoni et al., 2005), petroleum was higher than natural gas by about 25%. Based on our analysis and understanding of the methanogenesis process, the higher UEV for natural gas is appropriate. All indications are that it is formed after petroleum with additional heat and time suggesting a higher quality product rather than one with a lower UEV. Comparing high heat values (HHV) of these fossil fuels also adds credence to the ranking of UEVs. The lowest HHV is soft coal, followed by hard coal, then petroleum and finally natural gas.

While the UEVs computed in each geologic age are sensitive to the overall productivity (NPP) of that age, it is important to note that the global quantity of coal, oil, or natural gas does not influence their overall UEV. So, while we have used best estimates of the

Table 8
Mean[a] UEVs for marine and terrestrial crude oil and natural gas by geologic age.

Geologic age	Transformities of marine oil (seJ/J)	Transformities of terrestrial oil (seJ/J)	Transformities of marine nat gas (seJ/J)	Transformities of terrestrial nat gas (seJ/J)
Silurian	2.10E+05		1.70E+05	
Upper Devonian-Touronian	4.50E+05		3.64E+05	
Pennsylvanian-Lower Permian	2.18E+05		1.77E+05	5.08E+05
Upper Jurassic	6.28E+04		5.11E+04	
Middle Cretaceous	8.41E+04	2.34E+05	6.83E+04	1.90E+05
Oligocene-Miocene	1.16E+05	3.00E+05	9.41E+04	2.43E+05
Weighted mean[b]	1.48E+05		1.71E+05	

[a] The mean is the result of 1000 Monte Carlo iterations.
[b] Weighted mean is based on percent of oil or natural gas resource in each geologic age.

Table 9
Fuel transformities including production and transport costs.

Fuel type	Mining/drilling[a] (seJ/J)	Transport-1[b] (seJ/J)	Resource trasnformity[c] (seJ/J)
Soft Coal	1.54E+04	2.97E+04	1.11E+05
Hard Coal	1.23E+04	2.23E+04	1.32E+05
Oil (crude)	8.07E+03	2.48E+02	1.56E+05
Natural gas	8.07E+03	–	1.78E+05

[a] *Coal mining*—Emergy used in coal mining derived from an LCA by Sagisaka (1999). Total emergy = 2.95 E14 seJ/t of clean coal. Energy in hard coal = 2.4E10 MJ/t. Energy in soft coal = 1.8E10 MJ/t. *Oil and Natural Gas Production*—Exploration, drilling and production data from a report by Life Cycle Associates (2009). Total energy = 4.1% of oil production, therefore 4.1% of UEV for oil = 0.041 × 1.48E5 seJ/J = 6.07E4 seJ/J. Added 33% to account for emergy of machinery = 6.1E4 × 1.33 = 8.07E4.

[b] *Rail transport of coal*—Data taken from Federici et al. (2008). Emergy cost of rail transport in Italy = 5.35E11 seJ/t-km (converted to new baseline and assumes no environmental costs. Since the other costs in this table do not include environmental costs, they have been omitted from rail transport). Assume 1000 km. Emergy per J transported—Soft Coal = (5.35E11 seJ/t-km × 1000 km)/1.8E10 MJ/t = 2.97E4 seJ/J. Emergy per J transported—Hard Coal = (5.35E11 seJ/t-km × 1000 km)/2.4E10 MJ/t = 2.23E4 seJ/J. *Oil transport via tanker*—Data are from Life Cycle Associates (2009). Estimate of GHG emissions from transport of oil = 1.0 g/MJ of oil transported = 0.3 g oil = 1.26 kJ/MJ. Emergy per J transported oil = (1.26E3 J × 1.48E5 seJ/J)/1E6J = 1.86E2 seJ/J. Assume 33% for emergy of infrastructure. Therefore total emergy per J transported = 1.86E3 seJ/J × 1.33 = 2.48E4.

[c] Sum of columns 2 and 3 and the following raw resource transformities: Soft coal = 6.63E4 seJ/J; hard coal = 9.71E4 seJ/j; oil = 1.48E5 seJ/J; natural gas = 1.71E5 seJ/J.

Table 10
Unit emergy values for petroleum derived fuels without services.

Fuel type	Drilling and production[a] (seJ/J)	Refining emergy[b] (seJ/J)	Transport[c] (seJ/J)	Transformity of fuel[d] (seJ/J)
Gasoline	8.07E+03	2.96E+04	1.26E+03	1.87E+05
Kerosene (Jet fuel)	8.07E+03	2.68E+04	1.26E+03	1.84E+05
Diesel	8.07E+03	2.40E+04	1.26E+03	1.81E+05
LPG	8.07E+03	1.30E+04	1.26E+03	1.70E+05
Residual oil	8.07E+03	1.54E+04	1.26E+03	1.73E+05

[a] From Table 9.

[b] Refinery efficiency data are from Wang (2008) (kerosene was estimated based on density and temperature of distillation) as follows: gasoline–83.30%; kerosene (Jet fuel)–85%; diesel–86.70%; LPG–92.10%; residual oil–92.10%. Refining emergy = ((100% − efficiency) × 1.48 E5 seJ/J)/(HHV_{fuel}/HHV_{crude}) × 1.33 (an additional 33% is added for emergy in infrastructure [estimate].

[c] Transportation emergy from Table 9 plus local transport of fuels—Data are from Federici et al. (2008). Emergy cost of truck transport in Italy = 1.78E11 seJ/t-km (converted to new baseline and assumes no environmental costs. Since the other costs in this table do not include environmental costs, they have been omitted from truck transport). Assume 400 km (250 round trip, but return trip empty). Each truck carries 34,000 l of gasoline, which equals 25,500 kg. Energy = 46.7 MJ/kg, therefore: total energy per truck = 255,000 kg × 46.7 MJ/kg = 1.2E12 J. Emergy cost = 25.5t × 400 km × 1.11E11 seJ/t-km = 1.12E15 seJ and Emergy per Joule gasoline transported = (1.12E15seJ)/1.2E12J = 9.35E2 seJ/J.

[d] Sum of the UEV for crude oil (148,000 seJ/J) and Columns 2, 3, and 4.

global reserves of these fossil energies that are available, changes in the known reserves will not affect the UEVs calculated.[3] A better understanding of the processes of diagenesis, catagenesis and methanogenesis as well as the preservation factors from organic matter to kerogen would sharpen the analysis and more than likely reduce the standard deviation of our simulation results, but would not substantially alter the final UEVs calculated.

This analysis represents a major departure from previous evaluations of fossil fuel as our results suggest that they are significantly more valuable (higher transformities) than previously computed UEVs would support. Since fossil fuels are primary drivers of all economic processes, changes in the UEVs of this order of magnitude represent a significant change that will require much recalculation of standard UEVs of many secondary products and processes. It would be convenient if a simple ratio could be used to transform UEVs of products and processes that were calculated using earlier fossil fuel UEVs, but unfortunately since every process and product contains differing amounts of fossil energies in relation to other inputs, there is no simple solution.

5.1. Applying fossil fuel UEVs

We have provided several UEVs in this paper for each of the fossil fuels. Each is appropriate under different conditions. When determining the inputs to national economies it will be important to separate crude oil from refined fuels and oils and applying the appropriate transformity. Coal inputs to a national economy, if mined within the country should carry the resource transformity (Table 7), while imported coal should carry the transformity of coal after mining and transport (Table 9). If oil or natural gas are obtained from resources within the country, use the transformity in Table 8, but if imported, use the transformities in Table 9 or 10 depending on fuel type.

We have computed UEVs for fossil resources and fuels without services. UEVs without services are based solely on the emergy content and the emergy costs of production, transportation, and refining. Labor is not included. A UEV with services can easily be computed at any stage of the energy supply chain by multiplying the average price of each resource or fuel type by the emergy money ratio for the economy of interest. Using average price data from the USA over the first 6 months of 2010, the UEVs of fuels would increase between 20% and 30%. Since the service inputs are highly dependent on the price of fuel, we leave the addition of the emergy in services to the individuals using these UEVs for evaluations in other places and at other times.

6. Summary

A major criticism of the emergy synthesis methodology in the past has been that a single transformity for oil or coal, for example, was applied worldwide despite the fact that it is well known that fossil fuels have been developed under wide ranging conditions at very different time scales, and thus a single transformity is an over simplification. There was no question in our minds that this critique was accurate and it has taken a number of years to assemble the data (and the time) to re-evaluate these previous attempts of computing fossil energy transformities.

We have therefore carefully computed UEVs for the fossil fuels based on geologic process and time scales. We have strengthened our evaluation by taking into consideration the uncertainties that

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[3] As pointed out by one reviewer, the calculated UEVs are for “conventional fossil fuels” and unconventional sources of hydrocarbons (oil sands, shale oil, shale gas) will have significantly different UEVs.

exist in the general understanding of coal and petroleum genesis through Monte Carlo simulations that incorporate uncertainty and nonlinearity of the interactions of time, temperature, biology and geology. We provide new mean UEVs of the coal resource over the entire geologic past range between 6.63E4 (±0.51E4) seJ/J and 9.71E4 (±0.79E4) seJ/J. Oil and natural gas resource UEVs have mean values of 1.48E5 (±0.07E5) seJ/J and 1.71E5 (±0.06E5) seJ/J, respectively. These UEVs quantify the effort of the geobiosphere in producing these resources and through such quantification provide a complementary point of view to the usual economic value.

Within the framework of the emergy synthesis method the quality and importance of these fossil energy resources has been revealed. Some resources are more important than others since they drive entire chains of processes, and fossil fuels in many respects, occupy a particularly central position in modern economies. Fossil fuels are a primary energy source and as such the estimation of their production costs by nature and their refining costs by humans is crucial to understanding their value to society, at least until fossil fuels are no longer the dominant source of energy.

We understand that even this more refined evaluation of a very complex paleogeochemical system cannot ignore the huge uncertainties that still exist. We look forward to further refinement, as these uncertainties are decreased through additional research.

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