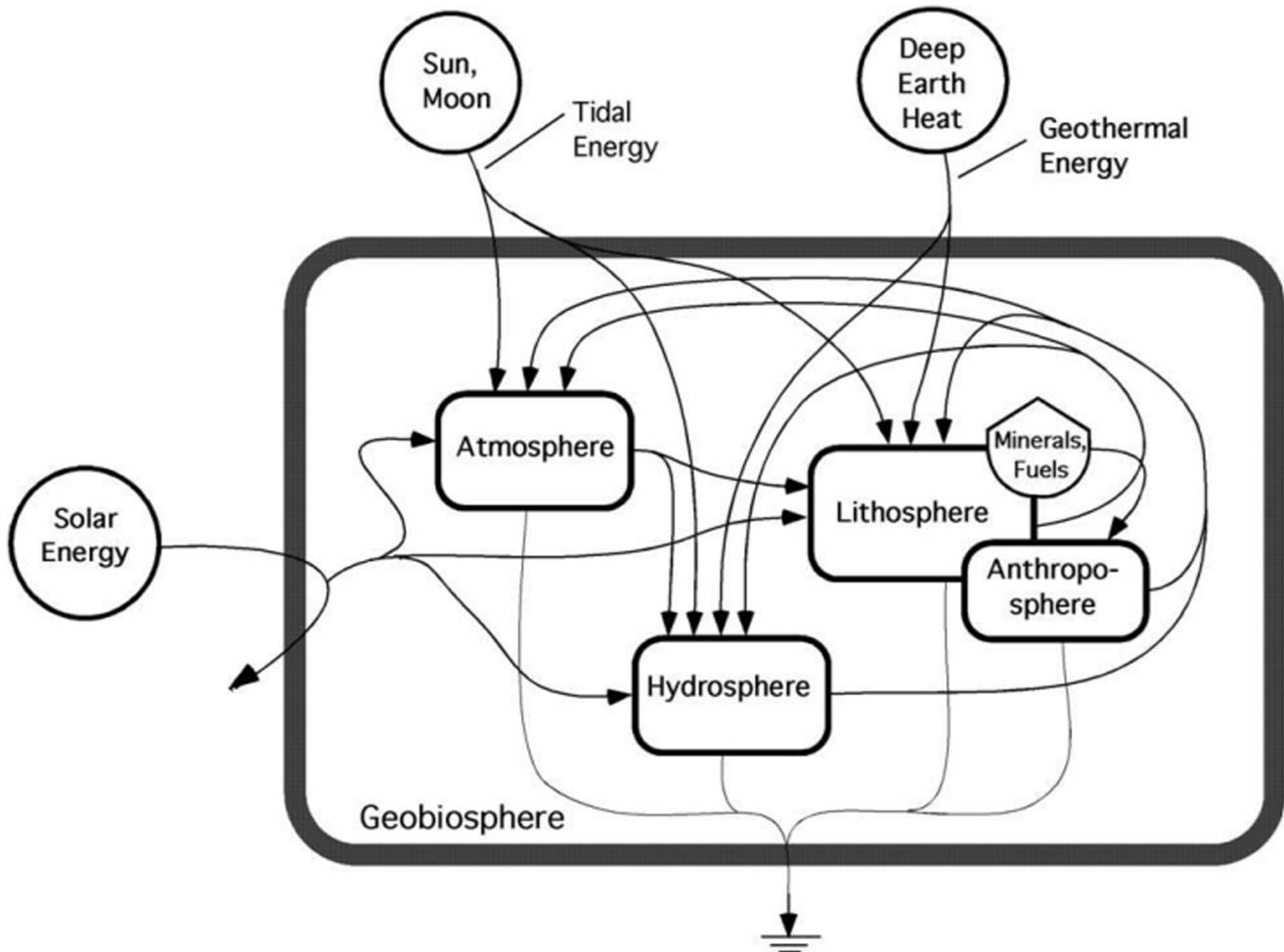# The Unit Emergy Value (UEV) Library for Characterizing Environmental Support in Life Cycle Assessment

The Unit Emergy Value (UEV) Library for Characterizing Environmental Support in Life Cycle Assessment

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ABSTRACT

In the field of environmental sustainability assessment, there are different integrated metrics used to quantify the total natural resource use, raw materials (i.e., minerals, water, fuels) and environmental impacts. In a resource-constrained world, it is essential to quantify the environmental support that these resources provide to economic activities, that includes the work provided by Nature such as chemical potential in rain water or in fossil fuel formation. The integrated measures involving the comparisons of different units or scales require a "common currency." Life cycle assessment (LCA) has been extensively used to assess the potential environmental impacts of goods and services over their full life cycles. Traditional environmental impacts in LCA have been focused on impacts of emissions with limited information regarding the impacts of resource uses such as fossil fuel, minerals, land, water, and soil. It is critical to not only quantify the impact of uses of these resources in LCA but also capture the environmental inputs to these resources in any industrial processes or economic activities. Therefore, the resource true values and resource scarcity can be captured, and sustainability can be evaluated. An environmental accounting method that provides a means of estimating resource value based on the geobiophysical work required to make and sustain those resources is the Emergy Accounting approach. Emergy is defined as the available energy (exergy) of one kind used up to make and sustain a resource directly and indirectly. Emergy values can be provided to estimate the value of renewable and nonrenewable resources in a common energy unit (solar emjoule, sej). The unit emergy value (UEV) library was developed for quantification of the environmental support associated with elementary resource use in emergy accounting and LCA studies. The library provides emergy characterization factors (EmCFs) for different types of renewable energy sources, minerals and metals, land occupation, water flows and storages, biomass, soils, fossil fuels and etc. Only elementary resources are included, while refined commodities and manufactured goods are not and their EmCFs can be calculated based on the elementary ones and a sufficient knowledge of each production process. The EmCFs rest on a common set of estimates and assumptions regarding geobiosphere processes and were calculated in a dynamic model from the ground up according to consistent algebra, rules, and assumptions. The calculation procedure is constructed in such a way that changes to an underlying estimate or assumption (such as the value of the global emergy baseline) will propagate through the library to update all the factors and avoid introducing human errors. The UEV library will provide a consensus set of emergy values for emergy accounting, LCA and various other sustainability analyses. This library uses the consensus global emergy baseline 1.2 E25 seJ/y. The intended audience for UEV library includes emergy practitioners, LCA practitioners, sustainability practitioners, academics, policy makers, public, consulting firms, etc.

Notice

The views expressed in this report are those of the author(s) and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency (EPA). Although the research in this document has been partially funded by the United States Environmental Protection Agency under Contract EP-11-C-000197 to University of Florida (Draft Report) and EPA Contract No. EP-C-15-010 to Pegasus Technical Services, Inc. (Draft Report), any mention of trade names, manufacturers or products does not imply an endorsement by the United States Government or the U.S. Environmental Protection Agency.

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Definitions

Areal empower intensity (AEI): emergy per unit area per year

Biomass: the total mass of living matter within a given habitat (usually expressed in terms of dry weight per unit area).

Biome: a community of plants and animals that occupy a contiguous area with similar climatic conditions

Characterization factor: a quantity derived from a life cycle impact assessment method that represents a unit of a quantity of impact per unit of a resource of consumed or an emission produced. Depending on the methodology these factors may be equivalent to a resource or emission based on its impact potential (e.g., CO_2-eq) or an actual measure of impact on an endpoint (e.g., disability-adjusted life year).

Co-product: the allocation of total inputs to the system to each output

Coupling: feedback in hierarchically organized open thermodynamic systems

Ecosystem: A spatially explicit unit of the Earth that includes all the organisms, along with all components of the abiotic environment within its boundaries (Likens, 1992)

Elementary flow: material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation (ISO 14044:2006)

EmCF: Emergy characterization factor; the emergy per unit exergy or mass of something

EmCFdb: Emergy Characterization Factor database; see accompanying excel workbook

Emergy: the sum of all direct and indirect available energy (exergy), expressed in the same form of energy required to produce a system or resource; units are solar emjoule (sej)

Empower: emergy per unit time, the emergy unit of power, emjoules per second, is an emwatt, or emW

Exergy: the portion of the total energy of a system that is available for conversion to useful work

Ga: Giga-annum; 1E+09 years

GEB: Geobiosphere (or Global) Emergy Baseline

gej: gravitational emjoules. The unit of gravitational emergy. Gravitational emergy defined as the amount of gravitational exergy required directly or indirectly in the fusion reactions to resulted in sunlight and the radionuclides.

LCA: Life Cycle Assessment − a framework for assessing the environmental impacts of goods and services over their life cycle (ISO 14044:2006)

NPP: net primary production, typically refers to photosynthetic plants and algae

OLCA: OpenLCA. Software for sustainability assessment designed by GreenDelta

ppt: parts per thousand.

ppm: parts per million.

sej: solar emjoules. The unit of solar emergy. Emjoules are not available energy, but instead a measure of the exergy used in the past to create a storage or flow of exergy in the present. Emjoules are not joules in the thermodynamic sense of the unit and the "j" should not be capitalized.

seJ: solar equivalent Joule. This is the unit of solar equivalent exergy or solar equivalent joules between sunlight and other sources (gravitational energy and Earth geothermal heat) that comprise global emergy baseline.

SER: solar equivalent ratios. Solar equivalent exergy per unit of exergy (seJ/J). It is neither transformity nor UEV, rather solar equivalent exergy/joule. It is used to establish the equivalence between sunlight and other sources of energy.

Specific emergy: the ratio of emergy to mass (sej/g).

Split: as opposed to a co-product a split allocates emergy in proportion to divergent exergy flows and results in identical transformities of the diverted flows.

TDS: Total dissolved solids in water

Transformity: the ratio of emergy to available energy (sej/J)

Turnover Time: the quantity of a stock (storage) of material or energy present in a particular system divided by the flux rate into or out of the stock.

Unit Emergy Value (UEV): the ratio of the emergy required to make something to its available energy or mass. It is equivalent to EmCF for elementary flows.

1.0 Introduction

Life cycle assessment (LCA) is an internationally-standardized framework for assessing the potential environmental impacts of goods and services over their full life cycles (U.S. EPA, 2006). A number of environmental impacts have traditionally been characterized in life cycle assessment, including impacts of emissions from processes to air and water quality, climate, and human health. The EPA's TRACI 2.1 impact assessment methodology provides characterization factors for a dozen impact categories (Bare, 2012). Most of these impact categories are related to impacts from process emissions; only one impact category characterizes impacts to resources (fossil fuel use). Other impact methodologies, such as ReCiPe, provide methods for impacts to other specific categories of resources, including waters, metals, and fossil fuels. All resources from the environment that are used in human-driven processes (the technosphere) can be considered means of environmental support to enable the sustainability of our economy and society in a "resource-constrained world" (NRC, 2012). A means of measuring this type of environmental support underlying the life cycle of a product or process would provide additional and valuable information to complement traditional LCA results to support sustainable decision making about the manufacture and use of goods and services.

Measuring the total environmental support from different types of resources in a single metric presents a challenge, because resources such as land, water, fossils fuels, nutrients, soils, etc. are not traditionally measured in a single unit. One alternative is to use an integrated sustainability metric for resource use/environmental support. Integrated metrics draw upon existing scientific principles and methods to integrate multiple impacts into a single measure based on a system approach (Ingwersen et al., 2014). An integrated metric proposed and previously used by EPA as a measure of environmental support is based on the principles and methods of environmental accounting using emergy, a concept closely related to energy and exergy as well as to ecosystems dynamics. Emergy is defined as the available energy of any kind previously used both directly and indirectly to make another form of energy, product, or service (Odum, 1996).

In the emergy method, all direct and indirect sources of material and energy input to a product system are tracked and quantified in units of a common type of energy. Solar energy is used as the reference and the common type of energy used in environmental assessments. The unit is called solar emjoules. Solar emjoules embodied in any resource are based on the use of sunlight that was directly or indirectly required to make a resource. For instance, solar emjoules of a tree in an unmanaged forest would include the emergy of the sunlight, wind, and rainfall (chemical potential and geopotential), all of which resulted either directly or indirectly from inputs of sunlight or other primary emergy sources. In emergy, models of natural processes on global and local scales underlying the formation of these basic resources, including renewable and nonrenewable resources, are used to estimate the amount of emergy in these resources. The

emery from these resources is included in the total emergy used to make a product from the respective quantity of these resources. In this sense, emergy is like the "energy and resource memory" of a product system.

Some previous research and implementation of emergy in the LCA context has been performed and the added value of using emergy in the LCA context has been extensively discussed (Rugani et al., 2011, Raugei et al., 2014). Currently, there is no consensus on a set of impact characterization factors through which emergy can be integrated into lifecycle databases, although a methodology and some initial work towards incorporating emergy into LCA datasets has been done (Baral and Bakshi, 2009; Ingwersen, 2011; Raugei et al., 2006, Rugani et al., 2011 Zhang et al. 2010). Thus, there is a need for a standardized library for using emergy in LCA that can be used to provide a measure of environmental support to accompany LCA studies.

This report describes the calculations for emergy characterization factors (EmCFs) for the accompanying excel database called EmCFdb (emergy characterization factor database). The term characterization factor is derived from Life Cycle Assessment (ISO 14044, 2006). The library is designed to serve as a Life Cycle Impact Assessment (LCIA) method with multiple impact categories all related to emergy for use in LCA studies and independent emergy accounting; however, the EMCFdb is also useful for other methods and models, including traditional emergy synthesis, for the reasons stated below. We build upon the library of Rugani et al. (2011) through further compilation of EmCFs from sources and development of several new EmCF computations. The refinements are detailed progressively to build on each other as described in the following paragraphs.

First, we discuss fundamental theories and assumptions that underlie EmCF calculations, then we discuss methods of computing EmCFs in a sequence of resource 'groups' which generally build in space and time on the previous groups. We close with a discussion of knowledge and conceptual gaps, which require further research.

The emergy method is fast evolving. Numerous hurdles must be overcome to integrate emergy with LCA software while minimizing opportunities for ad-hoc decisions by users. Here we have aimed to avoid tedious case-by-case examination of the rules of emergy algebra (Brown and Herendeen, 1996) by using a common framework for all EmCF calculations. The framework consists of updated calculations of the geobiosphere emergy baseline (GEB) (Brown et al., 2016) and the recalculation of the energy inputs to the geobiosphere according to their available energy content (exergy) to be consistent with Odum's (1996) definition of emergy. All material and energy elementary flows are expressed as exergy flows and therefore EmCFs are computed as emergy divided by exergy. In the cases of localized evaluations, common output units (e.g., m^2) are used to homogenize EmCF calculations. These will all be explained in the following sections.

2.0 The EmCF library

Because of the size and complexity of the Emergy EmCF database, it is submitted separately from this written report in electronic form. The Microsoft EXCEL database (Microsoft 365 MSO Version 2302) is titled "EmCF_database_yyyy_mm_dd" where the yyyy,mm,dd corresponds to the year, month, and day of the latest version. We refer to this database throughout this report as EmCFdb. The database is comprised of several worksheets, the third of which, titled **EmCF Library,** contains the EmCFs for all elementary flows so far identified, total 203 flows. Additional supporting worksheets are also included. Table 1 lists and describes each of the supporting worksheets included in the EmCFdb.

When using emergy as an impact assessment in LCA to capture more complete resource use than traditional LCA, the emergy used to make a product is calculated to be the sum of all elementary flow totals used in all life cycle processes in making the product multiplied by the emergy characterization factor (EmCF) for that specific flow as in Equation 1. The EmCF library provides characterization factors, equivalent to UEVs in the emergy literature (EmCF = UEV) (Brown and Ulgiati, 2004) for elementary flows in a life cycle inventory (LCI). This library provides a complete set of characterization factors for common types of elementary flows in LCA to provide a full accounting for the emergy of processes and products. Elementary flows are raw energies or materials (resources) taken in from the environment or emitted by (emissions) from one or more human activities (a process). Environmental impact assessment in LCA is a function of the sum of the quantities of each elementary flow for the product system times its respective characterization factor for the impact of interest.

$$LCI_p \times EmCF = UEV_p \tag{1}$$

Where,

LCI_p = a vector of all elementary flow totals in the life cycle of product, p

$EmCF$ = a vector of characterization factors for all elementary flows (mostly resources)

UEV_p = unit emergy value of product p

In order to develop a list of elementary flows useful for existing and future life cycle inventory, the complete list of elementary resource flows from two major commercial databases, Ecoinvent v2.2 (Weidema and Hischier, 2010) and GaBi v4 (PE International GMBH and University of Stuttgart, 2007), were extracted and analyzed. From these lists, resource elementary flows were then categorized by type. Types determined were resources from atmospheric gases, biological resources, land resources, fossil fuels, minerals and metals, raw renewable resources, rocks and aggregates, and water resources. The list of resource flows from the two commercial databases were then used as a reference for the development of a comprehensive list of resources. Due to

differences and peculiarities in elementary flow nomenclature, an original list of clearly defined names and resources was developed for which EmCFs are provided.

Table 1: List of supporting worksheets in the EmCFdb.

Worksheet	Title	Description
1	Readme and Changinglog	Documentation of what changes were done by who and when
2	Table of Content	The list of the worksheets in the database
3	EmCF Library	The summary table of all elementary EmCFs listed by major category
4	Renewable Earth flows	Summary of the constants and emergy computations of the annual primary secondary and tertiary renewable emergy flows driving the geobiosphere
5	Crust element composition	Table of the abundance and molar mass of elements used in computation of EmCFs for minerals
6	Precipitation Matrix Inversion	Table of precipitation flows over the terrestrial, ocean and in the atmosphere using Matrix Inversion method
7	Water	Table summarizing the computation of EmCFs of different freshwater storages and flows based on Gibbs free energies
8	Singular minerals	Table of the EmCFs for elementary flows of singular minerals
9	Multiple mineral deposits	Tables of mineral EmCFs that are principally mined from several different parent minerals
10	Aggregate minerals	Tables of aggregates of minerals that are held together mechanically, not chemically
11	Ocean ions	Ocean ion fluxes and exergy enrichment ratio computation of EmCFs
12	Atmospheric gases	Summary table of the EmCF computations for the main atmospheric gases using exergy enrichment ratio

Worksheet	Title	Description
13	Land, biomass & soil	Tables of computations for EmCFs associated with land, including NPP, biomass and soil organic matter
14	Wood	Tables of the computation for wood from different types of ecosystems
15	Coal	Tables leading to the computation of EmCFs for coal
16	Oil & NG	Tables leading to the computation of EmCFs for crude oil and natural gas
17	References	List of references

Elementary resources are also categorized as nonrenewable vs. renewable. Renewability is determined by generation time of the resource compared with a preselected renewable cutoff threshold, set at 100 years as a first approximation. The renewability threshold, which influences the category designations, can easily be modified.

Using emergy has also been suggested as a method of tracking use of ecosystem services in LCA (Zhang et al., 2010). Ecosystem services (e.g., water purification, air quality regulation, wood fuel, etc.) associated with each of the flows are listed in the database. Information is also provided for each flow on whether the flow is considered a resource stock or resource flow, and examples of some technosphere activities commonly associated with the flows are provided to help guide users to where they might be used in a life cycle inventory.

A summary table of EmCFs for elementary flows is provided at the end of this document (Table A-1). While it summarizes the list of elementary flows we have evaluated to date, for a full understanding of the methods, assumptions and calculations employed, we suggest the library spreadsheet should be used as a reference.

2.1   Emergy Algebra

Calculations performed within the EmCFdb assume steady state and are performed following standard emergy accounting procedures, which are also referred to as *Emergy Algebra* (Odum, 1996). Emergy algebra is based on the following set of rules:

> **Rule 1:** *Emergy is the available energy (exergy) of one kind that is used up in transformations directly and indirectly to make a product or service.*

Rule 2: In processes having one output, all independent emergy inputs are assigned to the processes' output.

Rule 3: When a pathway splits, the emergy is assigned to each branch of the split based on its percent of the total available energy flow (or mass) on the pathway before the split.

Rule 4: In processes having two or more co-products, all independent input emergy is assigned to each co-product.

Rule 5: The emergy assigned to by-product flows is proportional to the ratio of the by-product's available energy to the available energy of input flows.

Rule 6: Within a system, emergy cannot be counted twice:

  a) *emergy in feedbacks cannot be double-counted*
  b) *co-products, when reunited cannot be added to equal a sum greater than the source emergy from which they were derived*

Numerous authors have elaborated upon the details, consequences, and applications of the above emergy algebra rules. As this detail is beyond the scope of this report, the reader is referred to Odum (1996), Brown and Herendeen (2006), Brown and Ulgiati (2004), Rugani (2010).

The EmCFdb elementary flows are organized hierarchically, which has direct implications for the calculation of their transformities. **Primary flows** are the main driving exergies and consist of solar radiation, tidal dissipation, and deep earth heat. Collectively, the annual sum of these exergies is referred to as the geobiosphere emergy baseline (GEB) (Odum, 1996). **Secondary flows** are directly dependent on the GEB and generally consist of global cycles. For example, rainfall is part of a global hydrologic cycle that depends on inputs from each part of the GEB. Likewise, crustal dynamics consist of the continental uplift, subduction and erosion of crustal material that is driven, both directly and indirectly, by the GEB (Odum, 1996; Brown and Ulgiati, 2004; Campbell, 2016). Secondary transformities are calculated by parsing the GEB over the entirety of each energy cycle. **Tertiary flows** are driven by secondary flows, and the remaining flows are driven by some combination of secondary and tertiary flows.

Figure 1 is a visual representation of the database. Renewable inputs are circles on the outside of the system boundary (Figure 1 and 2). It is only a snapshot of the system to highlight the hierarchy embedded the elementary flows. However, many flows and storages are dynamic and cross spatial and temporal boundaries. For example, rain and water storages such as lakes and groundwater are part of the hydrological cycle (

Figure 3Figure 4). Descriptions of the symbols used in the figures, which are part of an energy system language, can be found in Appendix A of Odum, 1996.
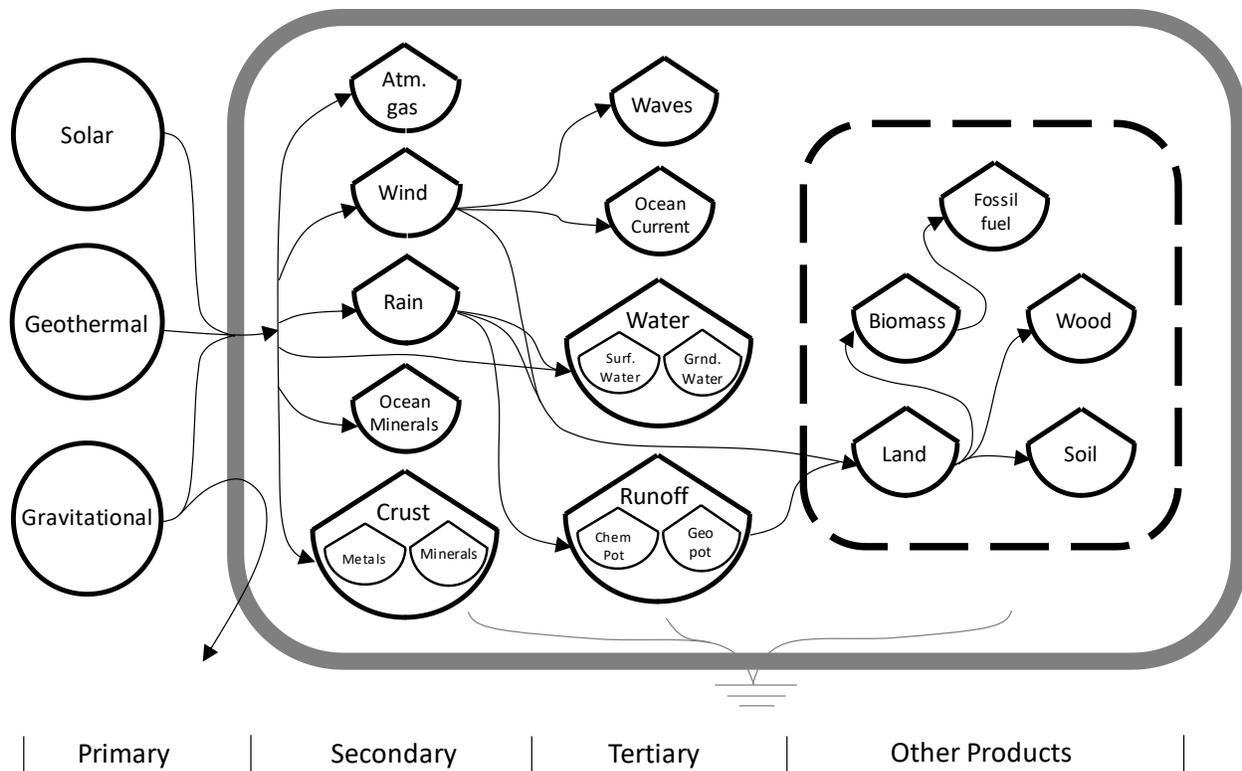
Figure 1 The major elementary flows in Earth geobiosphere described in this ECF library are organized in primary, secondary and tertiary flows.

3.0 Renewable Primary Earth Emergy Inputs

The geobiosphere is primarily driven by a tripartite of exergy sources (Odum, 1996; Brown and Ulgiati, 2010) comprised of incoming solar radiation, tidal dissipation, and deep earth heat (Figure 1, Figure 2). Tides and earth heat are related to the largest and most ubiquitous source, sunlight, and expressed in solar equivalent Joules (seJ)[1]. The Earth's planetary emergy baseline has been estimated many times (Brown and Ulgiati, 2016a; Campbell, 2016). The various baselines, ranging from 9.26 E24 to 15.2 E24 seJ/yr were based on different methods of computation and assumptions regarding geobiosphere system organization.

Following the Eighth Biennial Emergy Conference held in January of 2014, the need for revisiting the procedures and assumptions used to compute the Geobiosphere Emergy Baseline emerged as a necessity to strengthen the method of Emergy Accounting and remove some

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[1] We distinguish between solar equivalent Joules (seJ) and solar emjoules (sej). The tide and deep heat are expressed as solar equivalent Joules because solar processes do not directly produce them. All other emergy that is produced by the tripartite is expressed as solar emjoules (sej), using a lowercase "j". An emjoule is not available energy and therefore is not actually a joule, thus the lowercase "j".

sources of ambiguity and potential misunderstanding. Three studies (Brown and Ulgiati, 2016a; Campbell, 2016; and De Vilbiss et al., 2016) were undertaken in an effort to move towards a single, agreed upon baseline. A synthesis document was published to clarify the baseline issue and produce a single, agreed upon value. The result of that effort was a synthesis of the methods into a single baseline equal to 12.0 E24 seJ/yr (Brown et al., 2016), which is the baseline adopted in this EmCF library. Table 2 lists the solar equivalent joules for the Earth tripartite. In the future, if there is a need to update the baseline, the change can be easily propagated through the library to update all the factors.

The resulting GEB is expressed as <u>solar equivalent exergy,</u> whose unit abbreviation is seJ. Solar equivalent exergy is computed as an equivalence between sunlight and the other sources comprising the GEB, because Earth geothermal heat, and the gravitational energy absorbed are not direct transformations of sunlight. We have adopted the convention that solar equivalent energy uses the abbreviation seJ (note the capital J). Emergy computed for subsequent products of the Earth's geobiosphere (e.g., rain, wind, waves, etc.) is computed as solar emergy, whose units are solar emjoules and whose abbreviation is sej (note the lowercase j).
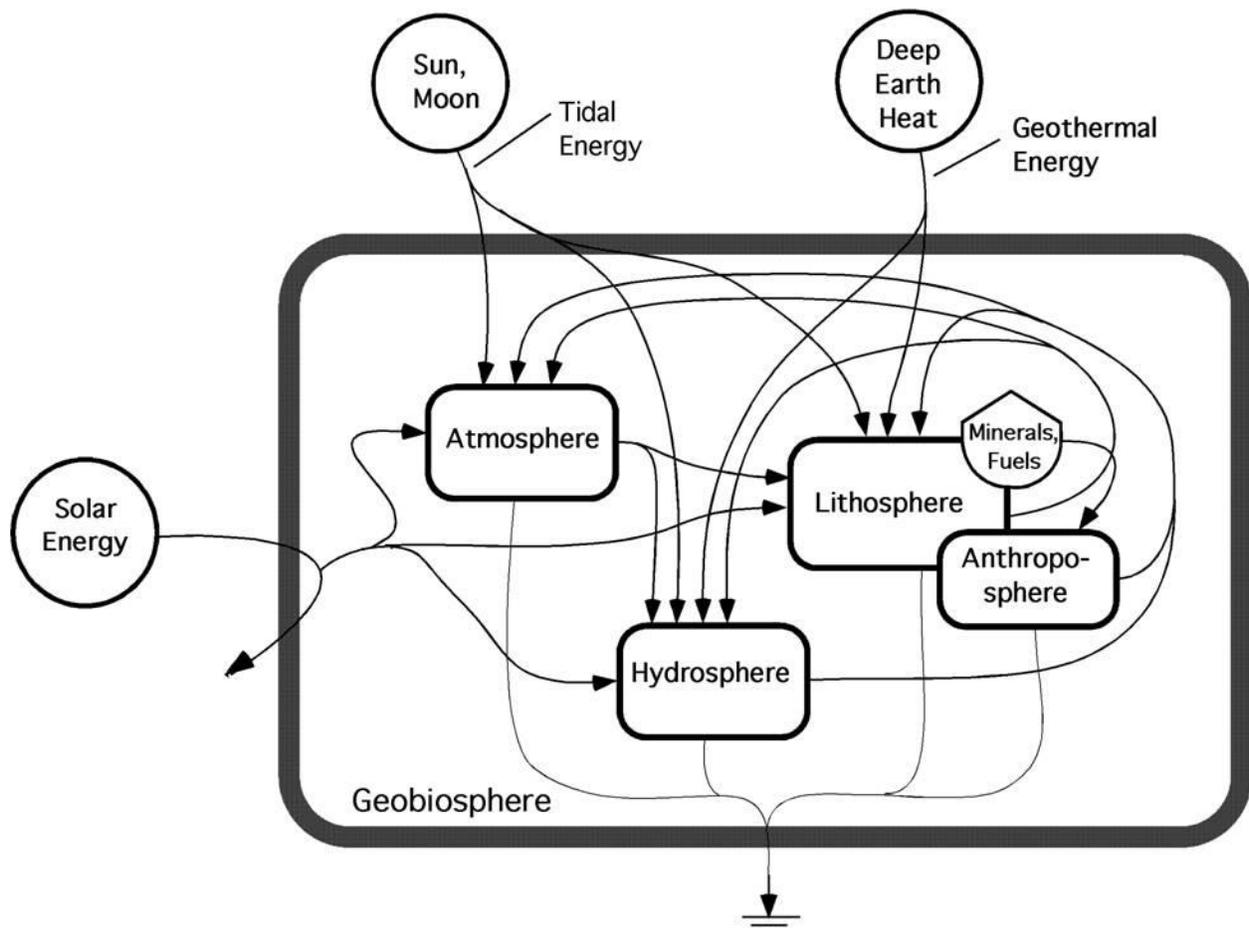
Figure 2 The Earth system, or geobiosphere, is composed of 4 main subsystems, the Atmosphere, Hydrosphere, Lithosphere and the Anthroposphere. The geobiosphere is driven by three main energy sources, solar energy, the gravitational pull of the sun and moon that creates tidal energy, and the geothermal energy from deep earth heat which is largely responsible for geologic processes. In recent times, the fossil fuel energies released by humans have added considerably to the total energy budget of the Earth.

Table 2: Solar Equivalent Joules for Earth's tripartite (Brown et al., 2016)

Inflow	Exergy[a.]	Solar Equivalent Ratio (SER) [b.] (seJ/J)	Solar Energy Equivalence [c.] (E+24 seJ yr^{-1})
Solar energy absorbed	3.73E+24	1	3.7
Geothermal Flows	9.52E+20	4,900	4.7
Tidal energy absorbed	1.17E+20	30,900	3.6
Total Global Empower			**≈ 12.0**

a. Average of the exergy from Brown & Ulgiati (2016a), Campbell (2016)
b. Average of the solar equivalent energy from Brown & Ulgiati (2016a), Campbell (2016)
c. rounded to two significant figures

4.0 Renewable Secondary Earth Emergy Flows

The primary energy driving the geobiosphere is transformed into secondary global flows that include, e.g., wind and rainfall. The following sections summarize the methods of computing the secondary flows. Calculations are included in the EmCFdb – Renewable Earth Flows worksheet.

4.1 Wind

Wind transformity is calculated as the ratio between driving emergy and the amount of wind energy dissipated. As wind is a global circulation process, its driving emergy is the GEB. Wind dissipation occurs due to friction associated with upper-level atmospheric turbulence and surface drag. Global wind dissipation is a complex, nonlinear process, and estimations of its value have been made using a variety of methods. Here, we follow the approach of Lee and Brown (2019), as it provides an estimate of global surface dissipation that agrees with estimates made using alternative approaches and provides a standardized approach to calculating local wind dissipation, which is useful for emergy analyses that account for wind input.

Surface wind dissipation is calculated using the difference between geostrophic and surface wind speeds, which assumes the reduction in surface wind speed is indicative of energy dissipation from surface roughness. Geostrophic wind speed is calculated using Equation 2. For the estimation of global surface wind dissipation, Lee and Brown (2019) obtained measured wind speed from NASA's Surface meteorology and Solar Energy (SSE) dataset, which provides average 50 m wind speed at a one arc degree resolution. Surface roughness is characterized using data from Chandler et al. (2005) applied to NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) land cover data.

$$V = V_{ref} * (\frac{Z}{Z_{ref}})^\alpha \qquad\qquad (2)$$

Where,

V = geostrophic wind velocity
V_{ref} = Reference velocity at 50 m
Z_{ref} = Reference height = 50m
Z = height for velocity V = 1000m
α = surface roughness exponent

Next wind energy dissipated between the geostrophic wind and ground surface is computed using Equation 3.

$$E_{wind} = \frac{1}{2} \rho K_{GN} V^3 AT \qquad (3)$$

Where,

E_{wind} = wind energy dissipated

ρ = Air density = 1.23 kg/m^3

K_{GN} = geostrophic drag coefficient 1.26 E-3 (over sea, N=11) and 1.64 E-3 (over land, N=7) from Garratt (1992)

A = area of each cell

T = 3.15 E7 s/yr

The resulting energy dissipation rates are provided, by major biome, on the Land, Biomass and Soil worksheet of the EmCFdb. Summed over the Earth's surface, total dissipation is 2.31 E22 J/yr, which is equivalent to 1.44 W/m^2.

Wind transformity is the ratio of the GEB to global wind dissipation.

The estimate of surface energy dissipation (2.31 E22 J/yr or 1.44 W/m^2) is higher than past analyses used for wind transformity calculations (e.g., Brown and Ulgiati, 2016b; Campbell and Urban, 2016) but is in line with past estimates made in the general atmospheric circulation literature (Table 3). Early estimates (Lorenz, 1967; Ellsaesser, 1969; Gustavson, 1979) were based on mechanistic, idealized physical models generally based on first principles – conservation of energy, mass, momentum, etc. and yielded estimates of total dissipation (surface plus upper atmosphere turbulence) that ranged from 2.35-7.06 W/m^2. Peixoto and Oort (1992) and Winn-Nielsen and Chen (1993) are largely review texts, though they provide useful critiques of the work that had occurred in the preceding decades. Peixoto and Oort (1992) and Winn-Nielsen and Chen (1993) estimate total dissipation as 1.65-2.02 W/m^2. Beginning in the early 21st century, results from early global circulation models (GCMs) used conservation of energy to estimate losses due to friction, or wind energy dissipation, in the entire atmosphere. Estimated dissipation was approximately 2 W/m^2, similar to the widely used estimates of Peixoto and Oort (1992) and Winn-Nielsen and Chen (1993). Also, using the improved resolution of these new models, Boville and Bretherton (2003) estimated that the surface layer accounts for 83% of total dissipation, or 1.65 W/m^2, which is more than double that estimated by Ellsaesser (1969) (Campbell and Erban (2016) used Ellsaesser (1969) as the basis for the fraction of dissipation occurring in the GBL). Boville and Bretherton (2003) also noted that surface heating (dissipation) was mostly due to surface stress from oceanic storm tracks. The total surface dissipation calculated using the methods of Lee and Brown (2019) generally aligns with this

estimation, as using average wind speeds likely underestimates the dissipative influence of major storms.

$$\tau_{wind} = \frac{GEB}{E_{global}} = \frac{12.0 \, E24 \, \frac{seJ}{yr}}{2.31 \, E22 \, \frac{J}{yr}} = 520 \, sej/J \qquad \textbf{(4)}$$

Table 3. Summary of modeled global wind dissipation rates

Reference	Planetary Boundary Layer (~100 mb)	Global Boundary Layer (~900 mb)	Fraction of Total in GBL
	Dissipation in W/m²		
Lorenz, 1967	2.35		
Ellsaesser, 1969			0.35
Gustavson, 1979	7.06	2.47	
Peixoto and Oort, 1992	1.65		
Winn-Nielsen and Chen, 1993	2.02		
Becker, 2003	1.90		
Boville and Bretherton, 2003	2.00	1.65	0.83
Brown and Ulgiati, 2016		0.94	
Campbell and Erban, 2016	2.02	0.76	0.38
Lee and Brown, 2019		1.44	NA

4.2   Precipitation

Precipitation is one part of the global hydrologic cycle, as illustrated in

Figure 3. The global hydrologic cycle is an energy cycle, transferring incoming solar radiation and absorbed thermal radiation across the globe using water as the medium. The transformity of precipitation is calculated assuming it is a secondary flow, meaning it takes the entire GEB to drive the entire cycle, similar to the wind global circulation process discussed in Section 4.1. Although inputs of driving exergies are not uniform across the globe, the cycle is interconnected, meaning, for example, rain on land cannot occur without transfers of atmospheric moisture that originate from evaporation over the ocean. Likewise, oceanic processes cannot occur without regular inputs of runoff from the land.

The chemical quality of precipitation is uniform regardless of where it falls and relative to seawater as the reference. Chemical quality is measured by total dissolved solids (TDS) content, which for rain is 10 ppm due to the dilution that results from evapotranspiration processes (

Figure 3). Because of this, rain has an energetic potential relative to runoff (assumed TDS of 100 ppm) and seawater and cellular interstitial fluid, both of which have a solute concentration of

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around 35,000 ppm. This chemical potential is referred to as Gibbs free energy, which is calculated using Equation 5. As an example, the Gibbs energy (ΔG_p) between average precipitation (S =10 ppm) and ocean or cellular interstitial fluid (S_0 =35,000 ppm) is 4.72 J/g, where R is the universal gas constant, 8.3143 J/mole.K, average Earth surface temperature $T = 287.25K$ (ncdc.noaa.gov), and molecular weight of water $w_{H_2O} = 18.01$ g/mole. The transformity for the terrestrial precipitation is 22,500 sej/J. The Water worksheet of the EmCFdb provides full calculation inputs and results of the flows in hydrological cycle based on Gibbs free energy.

$$\Delta G_r = \frac{RT}{w} ln \left(\frac{10^6 - S}{10^6 - S_0} \right) = 4.72 \, J/g \tag{5}$$

Although GEB has been used to derive terrestrial rainfall, there has been argument that the use of the entire GEB may not accurately reflect the emergy required for rainfalls. One of the alternative methods to explore different emergy flows for precipitation and other hydrological flows is the matrix inversion method. It was applied in partitioning flows of available energy in water between three main compartments/storages – ocean, continents and atmosphere (Brown and Ulgiati, 2016). The transformity of rainfall is calculated following Brown and Ulgiati (2016b), where major compartments of the hydrologic cycle are represented as a network and flows between compartments are calculated using matrix algebra.

Figure 3a shows pathways of water flowing between compartments, given in km^3 y^{-1} (Bengtsson, 2010).

Figure 3b shows the available energy of water flows between compartments, computed using the difference between chemical potentials (Gibbs free energy, Equation 5) of flows from one compartment to the next. Application of this method results in unique transformities for precipitation over land and precipitation over ocean of 7,010 sej/J and 4,230 sej/J, respectively. The Precipitation_Matrix Inversion worksheet of the EmCFdb provides full calculation inputs and results. T, S and DH in the worksheet mean tide, sun and deep heat emergy. L. Atmos and O. Atmos. Mean Land Atmosphere and Ocean Atmosphere, respectively.

One of the ways to test this hypothesis is to compare the driving forces for global biomes using respective transformities because the structure and productivity of world's ecological systems have been extensively studied (Lee and Brown, 2021). The heat map is shown in Table 4. Table 4a shows the emergy accounting for each biome using transformities for terrestrial precipitation of 7,010 sej/J. Table 4b shows the ones using 22,500 sej/J. The dominant emergy flows (highlighted) using matrix inversion indicate wind emergies for majority of the biomes while the dominant inputs using Gibbs free energy are terrestrial rain for majority of the biomes. It has been argued that the common classification schemes of global biotic communities rely on two abiotic elements, water and temperature. Although evapotranspiration is sometimes used, the

most common water parameter in most of the classification schemes is annual precipitation (Lee and Brown, 2021). Therefore, the most important driving energy sources would be highly correlated to these two variables. This suggests that rain should be the dominating emergy rather than wind. In this UEV library, Gibbs free energy derived transformities for precipitation are adopted, not matrix inversion method. The reason to include the comparison of matrix inversion method is to document the discussions and the underlying reasoning so others will not repeat the process.

Table I4. Emergy heat maps for global biomes using different transformities.

(a)

Transformities	1	4900	30900	520	7010 (Ocean UEV=4230)		7010	21300	3220	
EMERGY Table (rain UEV=7010 sej/J)										
Biome Type	Solar	Geothermal	Tidal	Wind	Rain Chem	Water Chemical sej/yr	AET Chem	Runoff Chem	Runoff Geo	MAX BIOME
Tropical & Subtropical Moist Broadleaf Forests	1.48E+23	1.31E+23	1.75E+22	6.00E+23	1.35E+24	8.67E+23	7.93E+23	7.35E+22	4.32E+22	**8.67E+23**
Tropical & Subtropical Dry Broadleaf Forest	2.46E+22	2.21E+22	1.74E+21	1.31E+23	1.20E+23	8.26E+22	8.26E+22	2.27E+20	6.18E+20	**1.31E+23**
Tropical & Subtropical Coniferous Forest	6.25E+21	6.14E+21	3.13E+19	3.75E+22	2.71E+22	1.83E+22	1.83E+22	3.64E+18	8.25E+17	**3.75E+22**
Temperate Broadleaf & Mixed Forests	7.37E+22	7.86E+22	2.77E+22	6.44E+23	3.80E+23	2.62E+23	2.53E+23	8.67E+21	3.04E+21	**6.44E+23**
Temperate Conifer Forests	2.55E+22	3.29E+22	1.92E+21	1.78E+23	1.18E+23	7.17E+22	7.13E+22	4.48E+20	1.84E+20	**1.78E+23**
Boreal Forests/Taiga	6.79E+22	8.53E+22	6.77E+21	5.37E+23	2.64E+23	1.90E+23	1.77E+23	1.37E+22	6.21E+21	**5.37E+23**
Tropical & Subtropical Grasslands, Savannas & Shrublands	1.78E+23	1.28E+23	7.94E+21	9.06E+23	6.33E+23	5.16E+23	4.77E+23	3.97E+22	1.42E+22	**9.06E+23**
Temperate Grasslands, Savannas & Shrublands	6.48E+22	6.22E+22	4.28E+21	3.51E+23	1.55E+23	1.28E+23	1.25E+23	3.21E+21	2.00E+22	**3.51E+23**
Flooded Grasslands & Savannas	8.11E+21	6.52E+21	2.87E+20	5.46E+22	2.66E+22	2.38E+22	2.10E+22	2.73E+21	6.18E+20	**5.46E+22**
Montane Grasslands & Shrublands	4.28E+22	3.77E+22	4.13E+18	2.34E+23	8.40E+22	6.30E+22	6.28E+22	1.71E+20	1.03E+21	**2.34E+23**
Tundra	4.57E+22	8.22E+22	3.52E+22	7.32E+23	1.35E+23	6.28E+22	6.10E+22	1.81E+21	1.29E+21	**7.32E+23**
Mediterranean Forests, Woodlands & Scrub	2.47E+22	2.57E+22	2.11E+20	1.31E+23	5.29E+22	4.05E+22	4.04E+22	9.27E+19	6.04E+20	**1.31E+23**
Deserts & Xeric Shrublands	2.42E+23	1.99E+23	4.90E+21	8.85E+23	1.72E+23	1.43E+23	1.32E+23	1.10E+22	2.83E+21	**8.85E+23**
Mangroves	2.43E+21	2.34E+21	5.05E+21	1.17E+22	1.87E+22	8.93E+21	8.92E+21	1.22E+19	6.72E+21	**1.17E+22**
River	2.32E+22	2.04E+22	1.45E+20	1.01E+23	9.36E+22	1.86E+23	6.35E+22	1.23E+23	2.82E+23	**2.82E+23**
Lake	6.55E+21	5.68E+21	0.00E+00	7.62E+21	2.04E+22	1.68E+22	1.51E+22	1.69E+21	3.82E+20	**1.68E+22**
Rock & Ice	5.69E+22	8.32E+22	1.65E+21	9.75E+23	7.71E+22	7.81E+21	7.72E+21	9.02E+19	2.04E+19	**9.75E+23**
Terrestrial Sub total	1.04E+24	1.01E+24	1.15E+23	6.51E+24	3.73E+24	2.69E+24	2.41E+24	2.80E+23	3.83E+23	**6.97E+24**
Estuary	2.24E+21	2.52E+21	5.52E+21	1.11E+22	1.23E+22	3.58E+24	5.51E+21	3.58E+24	5.40E+23	**3.58E+24**
Ocean	2.69E+24	3.65E+24	3.47E+24	5.48E+24	8.25E+24	1.33E+24	1.32E+24	2.04E+21	4.69E+22	**9.81E+24**
Total	3.73E+24	4.66E+24	3.60E+24	1.20E+25	1.20E+25	7.60E+24	3.74E+24	3.86E+24	9.71E+23	**2.04E+25**

(b)

Transformities	1	4900	30900	520	22500		22600	21300	3220	
EMERGY Table (rain UEV=22500 sej/J)										
Biome Type	Solar	Geothermal	Tidal	Wind	Rain Chem	Water Chemical sej/yr	AET Chem	Runoff Chem	Runoff Geo	MAX BIOME
Tropical & Subtropical Moist Broadleaf Forests	1.48E+23	1.31E+23	1.75E+22	6.00E+23	4.35E+24	2.63E+24	2.56E+24	7.35E+22	4.32E+22	**2.63E+24**
Tropical & Subtropical Dry Broadleaf Forest	2.46E+22	2.21E+22	1.74E+21	1.31E+23	3.84E+23	2.67E+23	2.66E+23	2.27E+20	6.18E+20	**2.67E+23**
Tropical & Subtropical Coniferous Forest	6.25E+21	6.14E+21	3.13E+19	3.75E+22	8.70E+22	5.91E+22	5.91E+22	3.64E+18	8.25E+17	**5.91E+22**
Temperate Broadleaf & Mixed Forests	7.37E+22	7.86E+22	2.77E+22	6.44E+23	1.22E+24	8.26E+23	8.17E+23	8.67E+21	3.04E+21	**8.26E+23**
Temperate Conifer Forests	2.55E+22	3.29E+22	1.92E+21	1.78E+23	3.80E+23	2.30E+23	2.30E+23	4.48E+20	1.84E+20	**2.30E+23**
Boreal Forests/Taiga	6.79E+22	8.53E+22	6.77E+21	5.37E+23	8.47E+23	5.83E+23	5.70E+23	1.37E+22	6.21E+21	**5.83E+23**
Tropical & Subtropical Grasslands, Savannas & Shrublands	1.78E+23	1.28E+23	7.94E+21	9.06E+23	2.03E+24	1.58E+24	1.54E+24	3.97E+22	1.42E+22	**1.58E+24**
Temperate Grasslands, Savannas & Shrublands	6.48E+22	6.22E+22	4.28E+21	3.51E+23	4.99E+23	4.05E+23	4.02E+23	3.21E+21	2.00E+22	**4.05E+23**
Flooded Grasslands & Savannas	8.11E+21	6.52E+21	2.87E+20	5.46E+22	8.52E+22	7.06E+22	6.79E+22	2.73E+21	6.18E+20	**7.06E+22**
Montane Grasslands & Shrublands	4.28E+22	3.77E+22	4.13E+18	2.34E+23	2.70E+23	2.03E+23	2.02E+23	1.71E+20	1.03E+21	**2.34E+23**
Tundra	4.57E+22	8.22E+22	3.52E+22	7.32E+23	4.33E+23	1.98E+23	1.97E+23	1.81E+21	1.29E+21	**7.32E+23**
Mediterranean Forests, Woodlands & Scrub	2.47E+22	2.57E+22	2.11E+20	1.31E+23	1.70E+23	1.30E+23	1.30E+23	9.27E+19	6.04E+20	**1.31E+23**
Deserts & Xeric Shrublands	2.42E+23	1.99E+23	4.90E+21	8.85E+23	5.52E+23	4.37E+23	4.26E+23	1.10E+22	2.83E+21	**8.85E+23**
Mangroves	2.43E+21	2.34E+21	5.05E+21	1.17E+22	6.01E+22	2.88E+22	2.88E+22	1.22E+19	6.72E+21	**2.88E+22**
River	2.32E+22	2.04E+22	1.45E+20	1.01E+23	3.00E+23	3.27E+23	2.05E+23	1.23E+23	2.82E+23	**3.27E+23**
Lake	6.55E+21	5.68E+21	0.00E+00	7.62E+21	6.54E+22	5.03E+22	4.86E+22	1.69E+21	3.82E+20	**5.03E+22**
Rock & Ice	5.69E+22	8.32E+22	1.65E+21	9.75E+23	2.48E+23	2.50E+22	2.49E+22	9.02E+19	2.04E+19	**9.75E+23**
Terrestrial Sub total	1.04E+24	1.01E+24	1.15E+23	6.51E+24	1.20E+25	8.05E+24	7.77E+24	2.80E+23	3.83E+23	**1.00E+25**
Estuary	2.24E+21	2.52E+21	5.52E+21	1.11E+22	0.00E+00	3.59E+24	1.78E+22	3.58E+24	5.40E+23	**3.59E+24**
Ocean	2.69E+24	3.65E+24	3.47E+24	5.48E+24	0.00E+00	1.46E+22	1.26E+22	2.04E+21	4.69E+22	**9.81E+24**
Total	3.73E+24	4.66E+24	3.60E+24	1.20E+25	1.20E+25	1.17E+25	7.80E+24	3.86E+24	9.71E+23	**2.34E+25**

Figure 3 Global hydrologic cycle (a) flows in km³ y⁻¹ from Bengtsson (2010) and (b) in Gibbs energy.

5.0 Renewable Tertiary Earth Emergy Flows

Global available energies of tertiary flows are driven indirectly by the primary flows, but directly by splits of the biosphere's secondary energies. Tertiary flows include ocean currents, the available energy in breaking waves on shorelines of continents as well as chemical and geopotential energy of rivers. The following summarizes methods of computing tertiary flows. Calculations are included in the Renewable Earth Flows worksheet of EmCFdb.

5.1   Ocean Currents

Surface ocean currents[2] are largely wind driven. Accordingly, we can calculate an average ocean current transformity as the emergy input from wind divided by the amount of energy dissipated (Equation **Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.**6). Emergy input from the wind is calculated as the surface wind energy dissipated over the ocean (1.1 E22 J/yr) (Lee and Brown, 2019) multiplied by its transformity (520 sej/J) (Section 4.1) and is equal to 5.5 E24 sej/yr. The amount of energy dissipated by surface ocean currents is obtained from Wang and Huang (2004a), who estimate total energy input to the Ekman layer of 3 TW (9.5 E19 J/yr). We assume that this total energy input is equally balanced by dissipative drag forces in the Ekman layer (i.e., steady state) and is thus equivalent to total energy dissipation. The resulting transformity is 58,000 sej/J.

$$\tau_{currents} = \frac{Em_{wind}}{E_{currents}} = \frac{5.5 \ E24 \ \frac{seJ}{yr}}{9.5E19 \ \frac{J}{yr}} = 58,000 \ sej/J \qquad (6)$$

5.2   Waves

Ocean waves are created as the result of wind dissipation over the ocean surface. The transformity of ocean waves is therefore calculated as this wind dissipation rate over the energy dissipated by the waves themselves through turbulence or frictional drag with the ocean bottom (Equation 7). The driving emergy is the same as that driving surface ocean currents (5.5 E24 sej/yr) while global wave energy dissipation is assumed equivalent to the amount of energy transferred to waves from wind (i.e., steady state is assumed). The amount of energy transferred to waves from wind is estimated as 68 TW, or 2.2 E21 J/yr (Rascale et al., 2008).

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[2] Ocean currents consist of surface currents, which are primarily wind driven, and deep currents, which are primarily driven by differences in temperature and salinity (also referred to as thermohaline circulation). The calculation of ocean current transformity only refers to the surface currents.

$$\tau_{waves} = \frac{Em_{wind}}{E_{waves}} = \frac{5.5\ E24\ \frac{seJ}{yr}}{2.2\ E21\ \frac{J}{yr}} = 2{,}600\ sej/J \qquad (7)$$

When ocean waves reach shore, the driving wind emergy is dissipated on the shore. Therefore, the EmCF value above cannot be used when the EmCF is used in terrestrial activities. The annual wave energy transmitted to surface zone turbulence is believed to be 2.4 TW (equivalent to 7.57E19 J/yr). The EmCF of wave power on the shore is the ratio of the ocean wind emergy to the energy dissipated on the shore which is much larger than the wave in the ocean Eq. Error! R eference source not found.:

$$ECF_{waves\ on\ shore} = {5.49\ E24\ sej/yr}/{7.57E19\ J/yr} = 72400\ sej/J \qquad (8)$$

5.3   Continental runoff geopotential transformity

Average annual global river discharge $m_g = 3.73\ E19\ g/yr$ (Dai et al., 2009) runs off land whose average elevation is $h = 797m$ (Eakins and Sharman, 2013). The geopotential energy dissipated by this runoff is given as $E_g = m_g gh = 2.9\ E20\ J/yr$, where g = gravitational constant. The mass of yearly continental precipitation which drives continental runoff is $m_r = 1.13\ E20\ g/yr$ (Adler et al., 2003). The emergy of continental rainfall is 1.13 E20 g/yr * 4.72 J/g * 22,500 sej/J = 1.2 E25 sej/yr, which is the GEB (see 4.2. Precipitation above). The EmCF of geopotential energy dissipated by continental runoff is the emergy of terrestrial rain divided by E_g as follows in Equation 9:

$$\tau_{r,g} = \frac{\Delta G_r \tau_r m_r}{E_g} = \frac{12.0\ E24\ \frac{sej}{yr}}{2.9\ E20\ \frac{J}{yr}} = 41{,}180\ sej/J \qquad (9)$$

5.4   Continental runoff chemical exergy

Dissipation of the chemical exergy of terrestrial precipitation also drives the formation of chemical exergy in continental runoff. This means that the emergy of runoff chemical exergy is a co-product with the emergy of runoff geopotential exergy, both of which are produced from terrestrial precipitation's chemical exergy. Global average chemical exergy in runoff is found using Equation 10, substituting TDS of $S = 100\ ppm$ (Milliman and Farnsworth, 2011; table 2.9).

$$\Delta G_d = \frac{RT}{w} \ln \left(\frac{10^6 - S}{10^6 - S_0} \right) = 4.71 \, J/g \qquad (10)$$

The EmCF of chemical exergy of runoff is the emergy of terrestrial precipitation (1.2 E25 sej/yr, which is the GEB (see 4.2. Precipitation above)) divided by the chemical exergy of runoff (3.7 E19 g/yr * 4.71 J/g = 1.8 E20 J/yr) (Equation 11).

$$\tau_{r,c} = \frac{\Delta G_r \tau_r m_r}{E_c} = \frac{12.0 \, E24 \, \dfrac{sej}{yr}}{1.8 \, \text{E}20 \, \dfrac{J}{yr}} = 68{,}300 \, sej/J \qquad (11)$$

6.0 Water EmCFs

Figure 4 is a summary systems diagram of the global water cycle showing aggregated global storages of surface and ground water as well as ice. Specific emergy ε of each global water storage i (at its global average purity, denoted $\bar{\varepsilon}$) is the ratio of driving emergy, Em, to the quotient of mass m and turnover time t (Equation 12). The driving emergy for all flows and storage in hydrological cycle such as rain, vapor, glaciers, ground ice, and ocean, is the GEB ($Em = 12.0 \, E24 \, sej/yr$) because they utilize high latitude precipitation which originates from global transpiration and evaporation from marine and terrestrial waters at global scale.

$$\bar{\varepsilon}_i = \frac{Em}{\left(m_i / t_i \right)} \qquad (12)$$
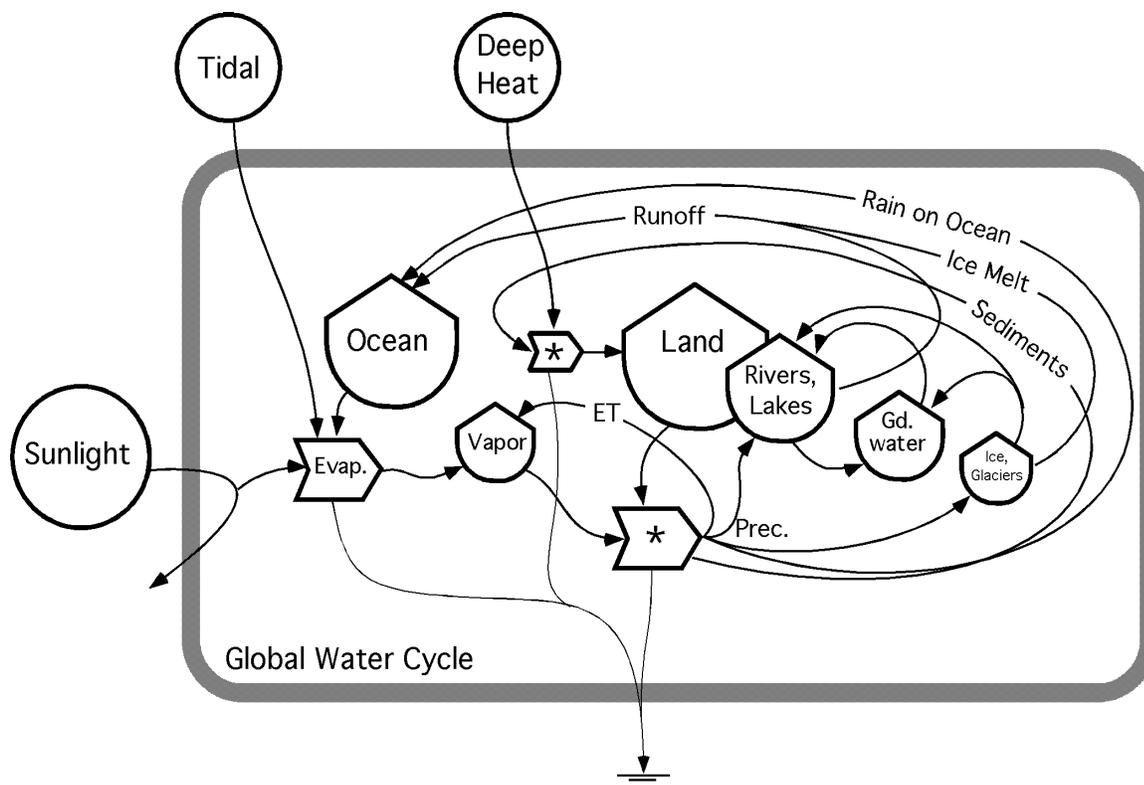
Figure 4 The global water cycle showing the hierarchical circulation of water driven by the tripartite and the main storages of water. ET = evapotranspiration, Evap = evaporation, Prec. = precipitation, and Gd water = ground water

6.1   Scaling Water EmCFs by Purity and Turnover Time

The chemical transformity for freshwater varies by purity according to its Gibb's free energy ΔG, also called mixing exergy. The Gibbs free energy equation is given below (Equation 13), where $s_0 = 35,000\ ppm$ salt ionized molecules in the oceans, R is the gas constant, $T = 287.25K$ is surface temperature (http://www.ncdc.noaa.gov/sotc/global/2013/10), w is water's molecular weight, and c_i is the concentration of water molecules in freshwater storage i.

$$\Delta G_i = -\frac{RT}{w} \ln\left({c_i}/{965,000}\right) \tag{13}$$

As water cycles through the geobiosphere, it changes phase from *liquid* saline water *to* comparatively pure atmospheric *vapor*. This results in a bimodal distribution of water's purity with local maxima around seawater 35 ppt TDS and vapor with 10 ppm TDS. The average transformity of a freshwater body i is the ratio of its average specific emergy $\bar{\varepsilon}_i$ to its Gibb's free energy (Equation 14). Global average TDS, transformity, and specific emergy are given for several major freshwater storages in the EmCFdb Water worksheet.

$$\bar{\tau}_i = \frac{\bar{\varepsilon}_i}{\Delta \bar{G}_i} \qquad (14)$$

As terrestrial precipitation accumulates dissolved solids in route to seawater, its mixing exergy or Gibbs free energy decreases (Figure 5) according to Equation 15.

$$\tau_i = \bar{\tau}_i \left(\frac{\Delta G_i}{\Delta \bar{G}_i}\right) \qquad (15)$$

The specific emergy of a water storage can be back calculated from its transformity (Equation 15) using Equation 16.

$$\varepsilon_i = \tau_i \Delta G_i \qquad (16)$$

Equation 15 is an enrichment ratio that approaches zero as water approaches seawater purity (Figure 5). In the EmCFdb, 'Surface water' and 'Water of unknown origin' are assigned the minimum value of surface water resources, which are found for rivers/streams, to avoid unreasonable over-accounting.
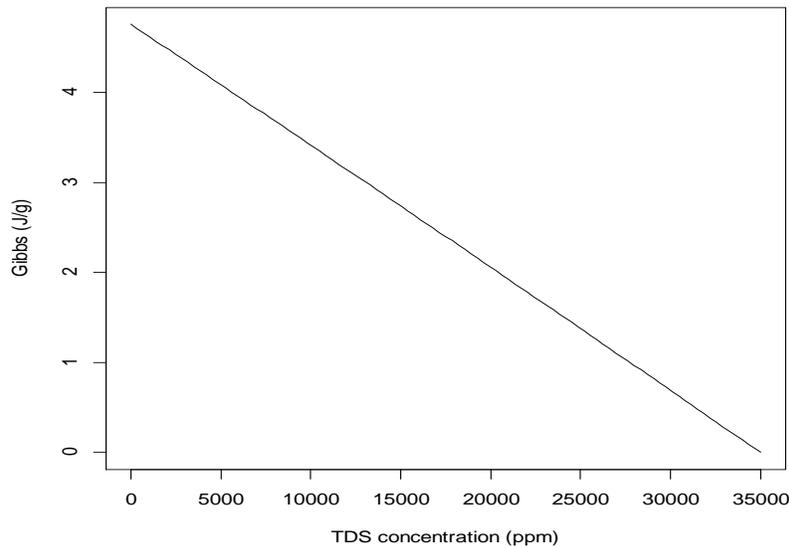

Figure 5 Gibbs energy of freshwater with varying TDS concentration at T = 287.25 K.

7.0 Crustal mineral EmCFs

7.1 Singular Minerals

Individual crustal minerals and metals (hereafter collectively referred to as minerals) have different uses within the geobiosphere and technosphere based on their chemical composition. They

can only be effectively utilized, however, when available at biologically or economically sufficient concentrations. Although the mechanisms for generating these two types of qualities – chemical and concentration exergy – are different, we assume both are co-products of the GEB. For example, following the original elemental endowment of the Earth, billions of years of physical, chemical and biological processes have resulted in the formation of unique chemical properties of crustal minerals. The same processes are responsible for their non-uniform distribution. Accordingly, we assume the GEB is responsible for a mineral's chemical composition and its distribution. Mineral and metals interact with sediment within the larger crustal cycle (

Figure 6)

We calculate singular mineral EmCFs using an adapted version of the methods of De Vilbiss and Brown (2015), where the chemical specific emergy of mineral k ($\varepsilon_{k,ch}$) and the concentration specific emergy of mineral k ($\varepsilon_{k,c}$) are calculated separately. Both $\varepsilon_{k,ch}$ and $\varepsilon_{k,c}$ are calculated using Equation 17, where individual mineral specific emergies (sej/g) are the product of mineral exergy (b_k in J/g) and average crustal transformity ($\bar{\tau}_{crust}$ in sej/J). If $\bar{\tau}_{crust}$ is thought of as a global emergy budget divided by a global exergy budget, the implication of this approach is that the GEB is allocated to individual minerals as a split, where each allocation is made on the basis of the individual mineral's exergy.

$$\varepsilon_k = b_k \bar{\tau}_{crust} \tag{17}$$

To calculate $\bar{\tau}_{crust}$ we first calculate average crustal specific emergy, $\bar{\varepsilon}_{crust}$, which represents the amount of emergy used to generate a gram of crustal material. Average crustal specific emergy is the ratio of the GEB to average crustal flux, where the crustal flux $\dot{m}_{crust}$ is given by the ratio of the crustal mass (2.17 E25 g, Peterson and Depaolo, 2007) and the average age of the crust (2.5 E9 yr, Taylor and McLennan, 1995; Veizer and Jansen, 1985): $\dot{m}_{crust} = (2.171E + 25g) / (2.5E + 09yr) = 8.68\,E15\,g/yr$.

The average specific emergy of crust is as follows in Equation 18:

$$\bar{\varepsilon}_{crust} = \frac{GEB}{\dot{m}_{crust}} = \frac{12.0\,E24\,\frac{sej}{yr}}{8.68\,E15\,\frac{g}{yr}} = 1.38\,E + 09\,sej/g \tag{18}$$

Next, we must calculate the average specific formation exergy of a gram of crustal material. Note we only use Gibbs formation energy, rather than standard chemical exergy, for this calculation. Standard chemical exergy is calculated as the sum of an element or compound's Gibbs formation energy (also called Gibbs free energy of formation, or Gibbs energy) and chemical exergy (Valero, 2008; Valero et al., 2012), the former representing the interactions between mineral constituents and the latter representing the presence of the matter itself relative to a background environment. Because we can only account for the emergy associated with

planetary evolution (i.e., the GEB) and not planetary generation, we only account for matter evolution and not matter generation.

The average crustal Gibbs energy is calculated by summing the Gibbs energy of each crustal mineral ($\Delta G_{f,k}^0$) (Valero et al., 2012) on the basis of that mineral's molar concentration within an average gram of crust using Equation 19:

$$\Delta \bar{G}_{f,crust}^0 = \sum_k -c_k \Delta G_{f,k}^0 = 1.17\ E4\ J/g_{crust} \tag{19}$$

where c_k is the molar concentration of mineral k (mol_mineral/g_crust) and $\Delta G_{f,k}^0$ is the Gibbs energy of mineral k (J/mol_mineral). The average Gibbs transformity of a gram of crust can then be calculated using Equation 20:

$$\bar{\tau}_{crust} = \frac{\bar{\varepsilon}_{crust}}{\Delta \bar{G}_{f,crust}^0} = 1.19\ E5\ sej/J \tag{20}$$

Chemical specific emergy of each mineral can then be calculated as the product of its Gibbs energy ($\Delta G_{f,k}^0$ in J/g_mineral) and $\bar{\tau}_{crust}$ following the format of Equation 17.

Concentration specific emergy uses a similar approach but replaces Gibbs energy with the mixing energy required to produce minable concentrations. Mixing energy is calculated as the difference between free energy at mine concentration and free energy at average crustal concentration, following the method of De Vilbiss and Brown, 2015.

Free energy for each mineral (ΔG_k) makes use of molar fraction x and standard Gibbs energy $\Delta G_{f,k}^0$ (Valero et al., 2012), where $T_0 = 298.15K$ (Equation 21). Please note this standard temperature was used by Valero et al., (2012) to compute mineral free energy. In the future it may be appropriate to redo their entire data set using the standard temperature referenced elsewhere in this document ($T = 287.25K$)

$$\Delta G_k = x_k (\Delta G_{f,k}^0 + RT_0 lnx_k) \tag{21}$$

Molar fraction (Equation 22) uses molarity a (mol/g) for mineral k at mine concentrations c in (g/g) and molarity of average crust $\bar{\alpha}$, given that average molar mass of the crust is 155.2 g/mol (Valero et al., 2012).

$$x_{k,c} = \frac{a_{k,c}}{(a_{k,c} + \bar{\alpha})} \tag{21}$$

Mineral mixing exergy, b, expresses the difference in free energy between mine concentration c and average crustal concentration (Equation 23). This is the work available due to geobiospheric concentration above background concentrations.

$$b = \Delta G_{k,c} - \Delta \bar{G}_k = RTln \, {}^{x_{k,c}}\!/_{\bar{x}_k} \qquad\qquad (23)$$

The product of mineral mixing exergy (b in J/g) and average crustal transformity ($\bar{\tau}_{crust}$, in sej/J) is a mineral's concentration specific emergy at mine conditions.

Following co-product algebra, each mineral's final specific emergy is calculated using the greater value of its chemical specific emergy and concentration specific emergy, to avoid double-counting. There are 316 singular minerals included in EmCFdb under Singular Minerals worksheet.

As pointed out in De Vilbiss and Brown (2015), negative concentration exergy refers the mineral concentration is below average. However, a negative transformity is not allowed. Due to this issue, De Vilbiss (2013) used concentration energy rather than concentration exergy to link crustal mass quality with energy quality. There is no thermodynamic method in the literature to link crustal specific emergy with its transformity. In this library, only specific emergy (no transformity) is reported because many mineral uses are mass-based.
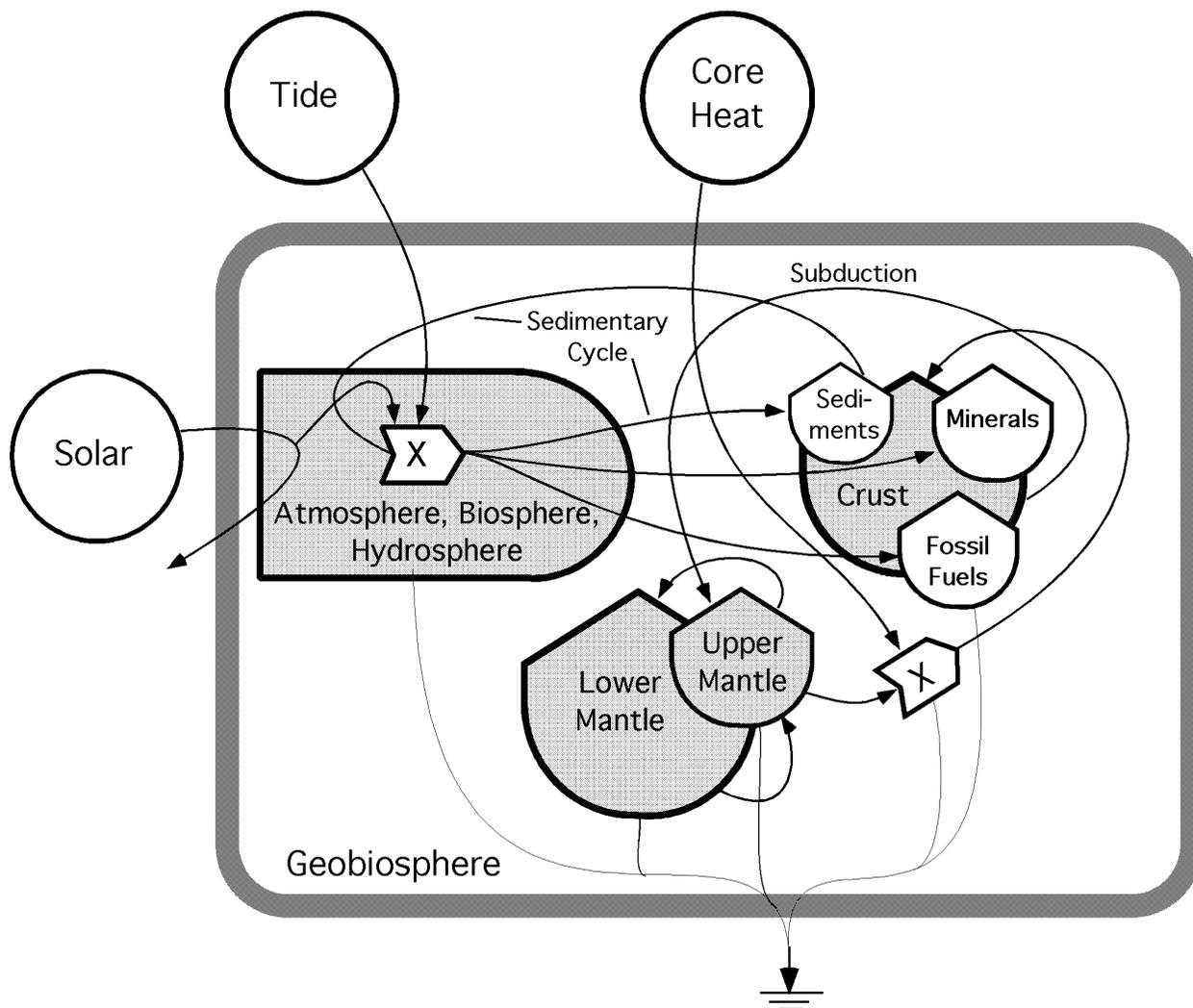
Figure 6 Diagram of the geobiosphere showing the crustal cycle of sediments interconnected with a much longer cycle of the upper mantle. The productive processes of the atmosphere, biosphere, and hydrosphere contribute to the cycling of sediments, minerals and the fossil fuels.

7.2   Mixed Minerals

For mixed minerals, or minerals that are not pure element minerals, element mass ratio is used. A suitable parent mineral is used for the element. In some cases, multiple minerals are used (see Multiple minerals worksheet of EmCFdb) and a weighted average taken. The element EmCF is the ratio of the parent mineral EmCF by the mass fraction f of the desired element within it. For example, in a lead deposit with $c_{Pb} = 0.03 g/g$, lead's EmCF is $\varepsilon_{Pb} = \frac{\varepsilon_{PbS,0.0346}}{f_{Pb}} = 3.39E +$ 08 sej/g where $f_{Pb} = 0.87 g/g$ is the mass fraction of lead in galena (PbS), and $0.0346 = c_{PbS} = c_{Pb}/f = mineral\ grade$. The specific emergy of the element is always greater than the

specific emergy of the parent mineral unless the mineral is a pure element, in which case the specific emergy of the element and of the parent mineral are identical.

7.3   Multiple Minerals

Some element EmCFs are the weighted average of multiple minerals according to their average crustal abundance (Multiple minerals worksheet in the EmCFdb). These elements have multiple important parent minerals (Valero, 2008). The weighted average of multiple minerals was the chosen method because of the importance of several minerals in the ore extraction process. To choose only one parent mineral could potentially bias the EmCF of the desired element, as each mineral would have a different EmCF. Major multiple minerals evaluated (aluminum, iron, nickel, silver, uranium, magnesium, manganese, titanium, cerium, lanthanum, phosphorus, smectite) are calculated under Multiple Minerals worksheet.

7.4   Aggregate rock EmCFs

Aggregates like shale, sand, basalt, calcite, granite/gravel, perlite, bentonite and pumice are agglomerated minerals held together mechanically, not chemically. Almost all the constituent minerals of these aggregates are known, mostly from DeWulf et al. (2007). The EmCFs for aggregates are the sum of EmCFs for all n constituent minerals (Equation 24) and are given in the Aggregate minerals worksheet in the EmCFdb.

$$\varepsilon_{agglomerate} = \sum_{k=1}^{n} \varepsilon_{k,c} \tag{24}$$

LCA items named 'Aggregate, natural' and 'Rock, unspecified' are assigned the minimum EmCF from all other aggregate rock types to avoid unnecessary overestimation of their emergy.

7.5   Minerals in seawater

The oceans are the repository for many minerals eroded from the continents. Wind and runoff-based erosion carries minerals to the oceans where they either settle to the bottom or stay suspended as dissolved ions. These dissolved ions generally exist as salts and give seawater its characteristic salinity. Dissolved ions may be taken up by biological processes, splashed into the atmosphere to form aerosols, or precipitated out of the water column to join the bottom sediments. Aerosol minerals precipitate out of the atmosphere, mostly on to the marine surface, but some are transported through precipitation on to the continents where rivers again may transport them to the seas. Ocean sediments may be stirred up through waves, tides, or ocean current actions such as in upwelling zones. On longer time scales sediments may be subducted at plate margins. Over Wilson cycle time scales ocean floor sediments are swallowed during supercontinent formation. Subducted sediments mostly find their way back into continental crust as sedimentary rocks because the seafloor spreads away from its interiors. As rivers erode the

continents, the underlying crust is exposed to the surface hydrologic and sedimentary processes once again through the sedimentary cycle.

We compute the EmCF of seawater ions ε_O as the ratio of the GEB to the annual flux φ of seawater minerals i (Equation 25).

$$\varepsilon_O = \frac{GEB}{\sum_{i=1}^{n} \varphi_i} \tag{25}$$

In this way seawater ions are a co-product to all other global emergy flows. We further split the GEB among each seawater ion ($n = 48$) for which residence times, and thus annual fluxes, could be found (Equation 26).

$$\varepsilon_{O,i} = \frac{GEB/n}{\varphi_i} \tag{26}$$

Sarmiento and Gruber (2006) provide the data for 47 ions. However, iodine was not included in their data. The residence of ocean iodine was computed from seawater iodine abundance (Muramatsu et al., 2004), and river iodine flux rate from the continents (Fuge and Johnson, 1986). River iodine flux is not precisely known. The range of values $(0.5 - 20 \ \mu g/L)$ given by Fuge and Johnson (1986) falls within the newer data ranges in Snyder and Fehn (2004). This latter paper however is far from globally comprehensive. We use a value of $2 \ \mu g/L$ as a modest pre-industrial value.

Because of this, rain has an energetic potential relative to runoff (assumed TDS of 100 ppm) and seawater and cellular interstitial fluid, both of which have a solute concentration of around 35,000 ppm.

When accounting for seawater at average concentration of 35,000 ppm, the chemical potential is zero because ocean is the solute concentration reference. However, where concentrations vary, e.g., uranium harvesting, transformities may be calculated using the exergy values of Szargut et al. (2005) for seawater ions. These transformities are limited to 16 of the 48 computed seawater mineral EmCFs as exergy values for all seawater ions are not yet available (Table 1 of the Ocean ions worksheet in the EmCFdb). Scaling specific emergy of seawater ions would follow the same process as used for crustal minerals. Currently we utilize a weighted average EmCF calculation, identical to our method for aggregate mineral EmCF calculations, for mineral compounds in seawater (i.e., $CaCl_2$ and $NaCl$). These computations are in Table 2 of the Ocean ions worksheet in the EmCFdb.

8.0 Atmospheric gases

Typically, EmCFs are computed for steady-state systems, which means production will equal respiration in the biosphere. For example, CO_2 fixed in NPP is released in organic matter decay.

For this reason, atmospheric gases have never had EmCFs, except for water vapor. With no previous method to refer to, we develop a first attempt at computing EmCFs for atmospheric gases. To be consistent in algebra principles, this first attempt uses the same framework as that used for crustal minerals, where atmospheric gases are treated as a co-product of the GEB and the specific emergy of each gas is allocated as a function of its exergy.

The GEB drives atmospheric material exchange within the geobiosphere. The average specific emergy of the atmosphere ($\bar{\varepsilon}_A$) is the ratio of the GEB to annual mass flux of the atmosphere (Equation 27), where t_i is the turnover time and m is total mass of gas i in the atmosphere.

$$\bar{\varepsilon}_A = \frac{GEB}{\sum_{i=1}^{n} t_i / m_i} \tag{27}$$

Average transformity $\bar{\tau}$ of an atmospheric gas, i, is the ratio of average atmospheric specific emergy (2.0 E4 sej/g) to its chemical exergy β_{ch} from Szargut et al. (2005) (Equation 28).

$$\bar{\tau}_i = \frac{\bar{\varepsilon}_A}{\beta_{ch,i}} \tag{28}$$

Like in the mineral EmCF method, after specifying an above average concentration c, the specific emergy ε of each gas i is the product of the average atmospheric transformity and its mixing exergy b (Equation 29). Mixing exergy is the difference in chemical exergy of a molecule in its concentrated conditions relative to average conditions (Equation 29),

$$\varepsilon_{i,c} = \frac{\bar{\tau}_i \cdot b}{w} = \frac{\bar{\tau}_i \cdot RTln(\frac{c_2}{c_1})}{w} \tag{29}$$

where w is the gas molar mass (g/mol). Gases with below average concentrations have a chemical EmCF of zero. The EmCFs of some atmospheric gases are given in the Atmospheric Gases worksheet of the EmCFdb.

9.0 Land, Biomass and Soil EmCFs

9.1 Land Occupation

The classifications titled "land occupation" in the Ecoinvent and GABI databases are not geographically specific, allowing allocation of a representative quantity of Earth emergy to a particular analysis area. It has been suggested to characterize the land use impacts based on net primary production loss as a proxy (Taelman et al., 2016). As a means of improving on former practice, which used a global average areal empower intensity, 19 specific biome/ecosystem types have been characterized based on the work of Lee (2019) and Lee and Brown (2019) and included in the EmCFdb (Land, Biomass, & Soil worksheet of the EmCFdb). In this way the land occupied classification has been expanded and now includes the 19 most common global

terrestrial biome/ecosystem types. The driving emergy of each biome type was used to compute aerial empower intensities (AEI), which is emergy per time per area expressed as sej m^{-2} yr^{-1}. Figure 7 is a generalized biome/ecosystem diagram. The AEI is used to compute the EmCF of gross primary production (GPP), net primary production (NPP), biomass and soil carbon.

Land EmCFs, while based on the concept of AEI, are computed slightly differently than in the past. Here we reconsider how emergy algebra is used to characterize AEI. The fourth rule of emergy algebra (Section 2.1 Emergy Algebra) states that co-generated outputs, when recombined as inputs, cannot sum to more emergy than the input emergy from which they are derived (Brown and Herendeen, 1996). While the GEB are all independent emergy flows, secondary Earth emergy flows are co-products of the GEB.
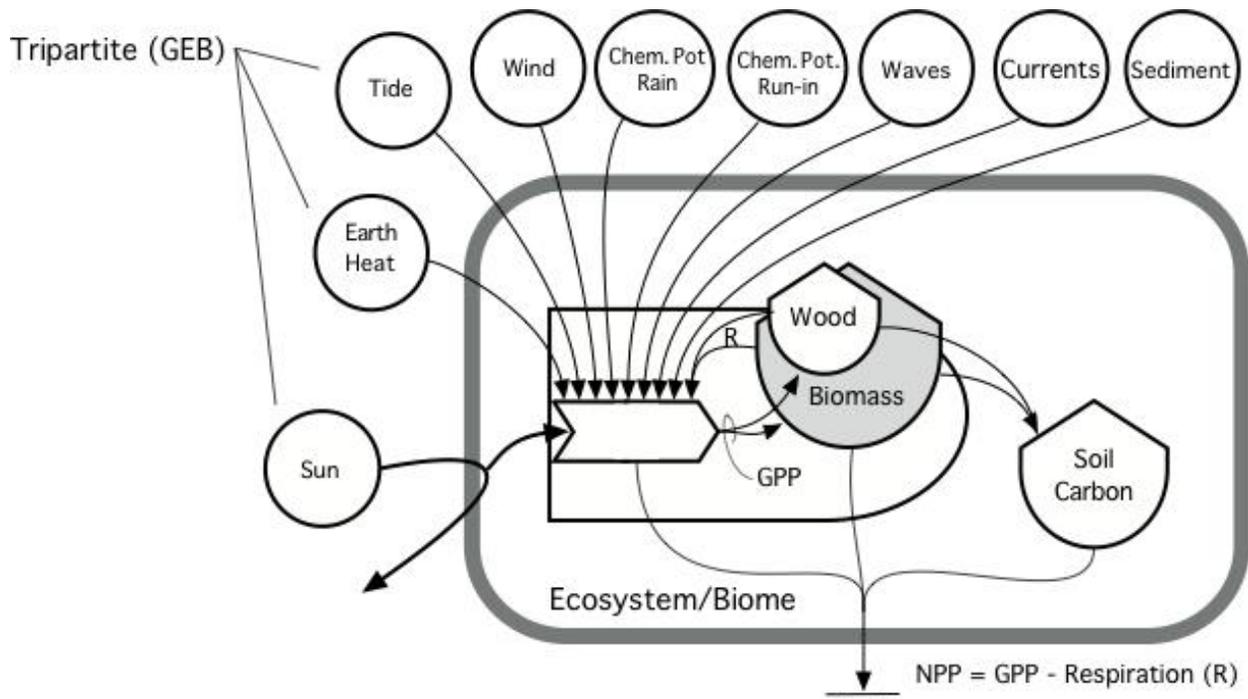
Figure 7 Generic ecosystem/biome showing the inputs of emergy driving gross primary production (GPP) and net primary production (NPP) as the difference between GPP and respiration (R). The storages of wood, biomass and soil carbon are all products of primary production. Note that we compute separate EmCFs for biomass, wood and soil carbon because they are on very different time scales.

AEI computation in past evaluations was customarily taken as the largest of the renewable input emergy. That is, the max of emergy from sun, tide, geothermal, rain, wind, etc. regardless of whether they were primary flows (the GEB), secondary, or tertiary flows (Odum, 1996). Evaluations were done in this way to avoid double-counting input emergy because it was reasoned that all renewable inputs were co-products of the geobiosphere tripartite. To some extent this is true, but only for the secondary and tertiary renewable sources. The global tripartite are separate sources and can be added, because emergy inflows of each one is independent and their equivalencies are not transformations of each other, i.e., they are

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independent. Whereas the emergy of the global tripartite can be added, the emergy of their "products" cannot, because each of them "embodies" a fraction of the tripartite baseline. For this reason, we suggest a new computational procedure to assign emergy sources to landscape systems. This new method sums the tripartite sources and compares this value with the largest of the secondary and tertiary sources (Equation 30). Areal empower intensity of each ecosystem/biome type is taken as the largest of these two flows.

$$AEI = \max \left[\sum (sun, tide, deep\ heat), secondary\ emergies, tertiary\ emergies \right] \quad \textbf{(30)}$$

Table 2 in the Land, Biomass and Soil worksheet of the EmCFdb lists the major Earth biomes, their area, and their AEI.

It should be noted that the classifications of 'Occupation, unspecified area' and 'Occupation, cultivated lands' use the world terrestrial average AEI of 1.14E11 sej m^{-2} yr^{-1} (Land, Biomass & Soil worksheet).

9.2 Land Transformation/Volume Occupied

'Land transformation' and 'volume occupied' have been assigned zero emergy in the EmCFdb. Instead, we suggest that if lands are transformed from natural forests, swamps, etc., the biomass or soil organic carbon (see below) lost as a result of land clearing be accounted as elementary flows. The same rational is applied to volume occupied.

9.3 NPP and Biomass

EmCFs for NPP and biomass are calculated by major biome using data compiled by Lee (2019). Biomass EmCFs are based on biomass standing mass (in grams of carbon, or gC) and turnover time which were compiled by Lee (2019) from various literature sources (Whittaker and Likens, 1975; Olson et al., 1985; Gibbs, 2006). Biomass EmCFs are calculated using Equation 31.

$$EmCF_{biomass}\left(\frac{sej}{g}\right) = \frac{Emergy\ Input\ \left(\frac{sej}{yr}\right) \times turnover\ time(yr)}{biomass\ (g)} \quad \textbf{(31)}$$

NPP EmCFs are calculated in a similar manner from data compiled by Lee (2019) from NASA's Terra/MODISNPP product (MOD17A3) (Zhao et al., 2005) using Equation 32.

$$EmCF_{NPP}\left(\frac{sej}{g}\right) = \frac{Emergy\ Input\ \left(\frac{sej}{yr}\right) \times turnover\ time(yr)}{NPP(gC)} \quad \textbf{(32)}$$

No EmCF was assigned to biomass from cultivated lands as this is a product of a human activity. Analyses for land areas where the biome is unknown should use the world average terrestrial AEI and biomass specific emergy (5.62 E14 sej/ha/yr and 5.18 E8 sej/gC, respectively; Tables 2 and 3, Land, Biomass & Soil worksheet of the EmCFdb). The average transformity and specific emergy are weighted averages based on areas of terrestrial biomes.

9.4 Soil organic carbon

EmCFs are included for soil organic carbon by biome type (see Table 4 – Land, Biomass & Soil worksheet of the EmCFdb). The AEI of a biome drives its NPP *and* soil carbon genesis. NPP and soil carbon are co-products of biome areal empower, albeit with different time scales. Soil carbon EmCFs utilize soil turnover time, storage quantity, and AEI for each biome following Equation 33:

$$ECF_{C\ org} = \frac{AEI\ \times\ replacement\ time}{energy\ or\ mass\ of\ storage} \qquad \textbf{(33)}$$

While the organic carbon and biomass for cultivated lands are not considered elementary flows because they are under the influence of anthropogenic inputs (i.e., fertilizer, labor, etc.), we have included an EmCF for soil carbon in cultivated lands. For the time being, the AEI for cultivated lands is estimated as the world terrestrial average AEI. Raich and Schlesinger (1992; table 3) provide the average global quantity and residence time of soil C in cultivated lands. Its EmCF is found in the same way as other soil C.

We have assigned an EmCF to "Soil, unspecified" by assuming it to be 5% organic carbon and 95% mineral soil (Lee and Brown, 2021). The emergy of the organic portion was taken as the smallest of the biome soil carbon EmCFs (grassland) while the emergy of the mineral portion was assumed to be that of shale rock (see discussion of Inorganic Matter below).

9.5 Soil minerals

There are three EmCFs for inorganic soil constituents; inorganic matter in soil, unspecified; nitrogen (N) in soil; and sulfur (S8) in soil. Methods for their computation are given next.

9.5.1 Inorganic matter
Using the method of Odum (1996; pg. 47) inorganic soil material was assumed to be derived from shale rock, where half the rock is lost during soil formation. Thus, the EmCF for inorganic matter in soils is equal to the EmCF of shale multiplied by 2 (because half is lost during soil formation).

9.5.2 Soil Nitrogen
Soil nitrogen is mostly controlled by biologically driven processes (Berner, 2006). The EmCF for 'Nitrogen in ground' refers to both organic and inorganic soil N. Watanabe and Ortega

(2011) used a static steady-state N cycle to compute a nitrogen UEV. We use their data to compute the EmCF (Equation 34) as the ratio of the GEB to the terrestrial soil N flux $m_N = (190 + 140 + 29.4)\, E9\ kg/yr$ (the sum of organic and inorganic N; Figure 5 in Watanabe and Ortega, 2011).

$$EmCF_{soil\ N} = \frac{GEB}{m_N} = 3.34\ E13\ sej/kg \qquad (34)$$

9.5.3 Sulfur

Sulfur is not included in the minerals section because no ore grade could be found for mined sulfur. It is predominately produced as a by-product of the refining process of other materials (primarily oil and natural gas and secondarily as a by-product of ferrous and non-ferrous metal smelting). Soil sulfur was, however, included as a soil resource. We use the mineral sulfur (S8) and assume soil content of 0.5% to yield the soil sulfur EmCF (Lee and Brown, 2021). This concentration and EmCF is easily changed in the EmCFdb should better data become available.

10.0 Wood

Wood EmCF is the ratio of AEI to annualized net wood production for various forested ecosystems (see Wood worksheet of the EmCFdb). It should be noted that wood and biomass have different EmCFs. Biomass EmCFs are derived from net community production, which is greater than the net production of wood. The flows and storages in the database are elementary flows, which means how nature does the work to produce them. This is not the same as the timber production from modern timbe industry with added inputs. It should also be noted that the evaluations for wood use different AEI values than biome biomass and soil carbon (Land, Biomass and Soil worksheet of the EmCFdb) because the data for wood harvest is from specific forests whose inputs may be different from aggregated global biomes.

Wood is the marketable lumber produced by forests of different types. Wood grown in commercial forests would have non-renewable emergy inputs in addition to the wood elementary flow added as part of the commercial operation. For wood to be an elementary flow we only account for renewable emergy inputs. Wood EmCFs differ from biomass EmCFs in that biomass EmCFs are used to account for the emergy of biomass lost in land clearing processes.

The EmCFdb contains several types of wood including wood from specific biomes:
  Wood, dry, temperate forests
  Wood, dry, boreal forest
  Wood, dry, tropical lowland forest
  Wood, dry, swamps
  Wood, dry, unspecified

Each of these wood types is assigned a different EmCF based on productivity of the forest ecosystem from which it is harvested. Usually, rainfall is the defining emergy input to these wood producing systems except for swamps, temperate forest, and wetland, in which organic matter deposition, and run-in, characterize the AEI respectively. The "unspecified" classification uses the minimum wood EmCF to minimize over-estimation.

In addition to the wood types above, the EmCF contains two general wood types:
> Hardwood, dry, unspecified, and
> Softwood, dry, unspecified

The unspecified hardwood uses the EmCF computed for hardwood harvested from southern mixed hardwood forest in US, whereas the unspecified softwood uses the EmCF computed for pine from a Florida Pine Flatwood.

11.0 Fossil fuels

Brown et al. (2011) applied novel concepts to the emergy calculation of coal, oil, and natural gas such as:

- Estimating the emergy of NPP in past geologic eras
- Carbon preservation factors at major transformation stages in fossil fuel genesis, and
- Geothermal heat absorbed to transform buried organic carbon into fossil fuels

Preservation factors are the proportion of carbon that survives each transformation step (i.e., peat formation, digenesis, etc.). Preservation factors are inherently uncertain because their time scales are too long to directly observe.

Estimation of global NPP from past geologic eons based on oxygen isotope records is potentially another major source of uncertainty for at least two reasons. First, the GEB of the past 500 Ma or so was assumed to be equal to today's GEB. Second, the emergy driving terrestrial and marine NPP was topologically split from the GEB according to the present-day ratio of land to sea surface area.

Brown et al. (2011) implemented a Monte Carlo simulation to include the uncertainties of preservation factors for what was essentially modeled as a two (coal) or three (natural gas and petroleum) tiered transformation process from NPP to crude fossil fuel. Our following explanations discuss modifications applied to their method but without the use of Monte Carlo simulation. The resulting values are within 5% of the reported values which, when considering the inherent uncertainty, seems not to necessitate further sensitivity analysis.

11.1 Peat

Peat is partially decayed organic matter generally formed in wetlands where anoxic conditions slow decomposition.

Figure 8 is a summary diagram of the formation of coal, where peat is the first step in the process. The EmCF of Peat utilizes the EmCF of flooded grasslands and savannas soil C. Assuming C composes 50% of peat's mass (Brown et al., 2011), and that the units of peat in LCA databases are kg of peat, rather than only its carbon content, peat's EmCF is found as follows (Equation 35).

$$EmCF\ Peat = \frac{flooded\ grasslands\ and\ savannas\ soil\ C\ EmCF}{50\%\ C\ in\ Peat\ organic\ material} = \frac{2.30\ E12\frac{sej}{kg}}{0.50\frac{kgC}{kgPeat}} \quad \textbf{(35)}$$

$$= 4.61\ E12\ sej/kg$$

Once buried deep enough, geothermal heat cooks peat into coal. The initial accumulation of organic matter in ecosystems is a biological function driven by surface inputs, such as rain, wind, and sunlight.

11.2 Coal

The pre-historic terrestrial NPP calculated in Brown et al. (2011) was used in the EmCFdb to calculate fossil fuel EmCFs. Methods differ, however, in regard to geothermal contributions to the coalification process.

As shown in

Figure 8, we divide the coal resource into two groups determined by carbon concentration. These are anthracite/bituminous (A/B) and sub-bituminous/lignite (SB/L). Geothermal exergy at earth's surface is a function of Carnot efficiency C where T_R is reservoir temperature and T_S is source temperature in Kelvin Equation 36.

$$C = 1 - \frac{T_R}{T_S} \quad \textbf{(36)}$$

Coalification for A/B and SB/L occurs at $T_S = 237.5$ and $97.5\ °C$ respectively (Brown et al., 2011) and Earth's surface temperature is $T_R = 14.1\ °C$. The Carnot efficiency of deep earth heat contributions are $C_{A/B} = 43.7\%$ and $C_{SB/L} = 22.5\%$. These are 82% and 181% larger than what is used in Brown et al. (2011). Deep heat exergy of coalification is the product of the Carnot efficiency of coalification with the quantity of deep earth heat F and the mass fraction of organic carbon at the temperature depth in the lithosphere m_C (Equation 37).

$$E_{DH} = C_i F m_C \quad \textbf{(37)}$$

We update the emergy of deep heat contribution to the coalification process using the deep heat flow and deep heat SER from Brown et al., (2016), which is 9.52 E20 J/yr and 4,900 seJ/J, respectively.
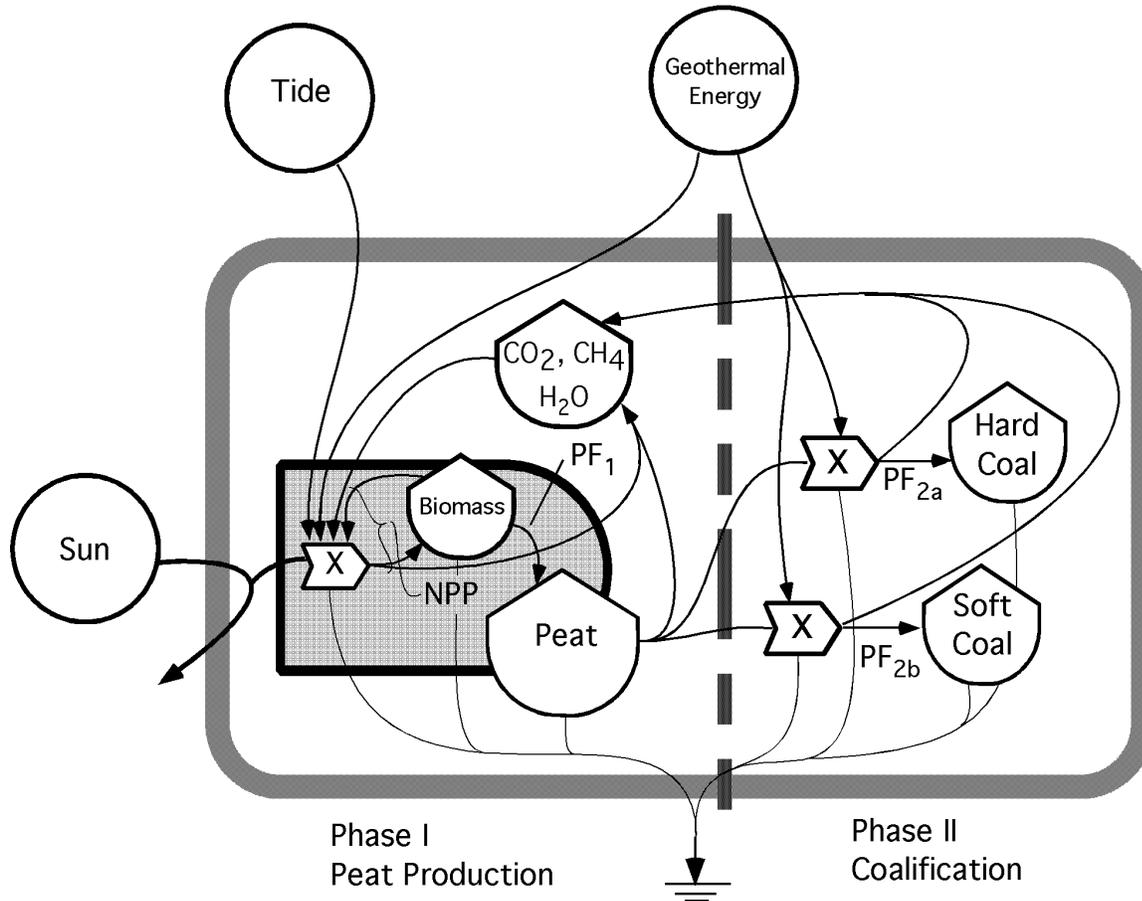
Figure 8 The two phases of coal formation. Phase I: peat production is dominated by ecological processes that are driven by solar, tidal, and geothermal energies of the geobiosphere. Phase II: coalification is driven by geothermal energy. PF$_{1-2}$ are preservation factors (fraction of carbon that is 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.

We only consider the carbon portion of organic matter because that is where the principal amount of chemical exergy is stored in the resulting fossil fuel. The mass fraction of carbon receiving deep heat exergy in the lithosphere is the average of initial carbon m_I to final carbon m_F divided by the mass of the lithosphere $m_L = 2.17\ E25\ g$ (Equation 38).

$$m_C = \frac{\frac{m_I + m_F}{2}}{m_L} \qquad (38)$$

In Brown et al. (2011) m_I is the total of carbon in buried organic matter. However, coalification is the transition from peat to coal, not from organic matter to coal. We make $m_I = carbon\ in\ peat$ and $m_F = carbon\ in\ coal$. We assume buried peat has the same density as the surrounding lithosphere. Our $m_C = 1\ E - 8\ g/g$ crust, reduced from the $2\ E - 7\ g/g$ reported in Brown et al. (2011).

In summary, two steps are performed to account for the emergy of coal, namely calculation of the emergy of past NPP that is buried as peat, and calculation of the emergy required for coalification of peat into coal. In this evaluation, the first step is identical to Brown et al. (2011) whereas the latter has been recalculated to contribute between 0.04 and 0.08% to the EmCF of coal, less than the former 13.7% contribution (calculated from data in their paper).

11.3   Oil and natural gas

Conventional reserves of crude oil are usually found in association with natural gas. Similar to coal, the production process can be separated into two distinct phases (Figure 9). 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 (80% vs 20%; Klemme and Ulmishek, 1991). An important distinction occurs during the Oligocene-Miocene era when the production of natural gas is almost entirely from terrestrial sources.
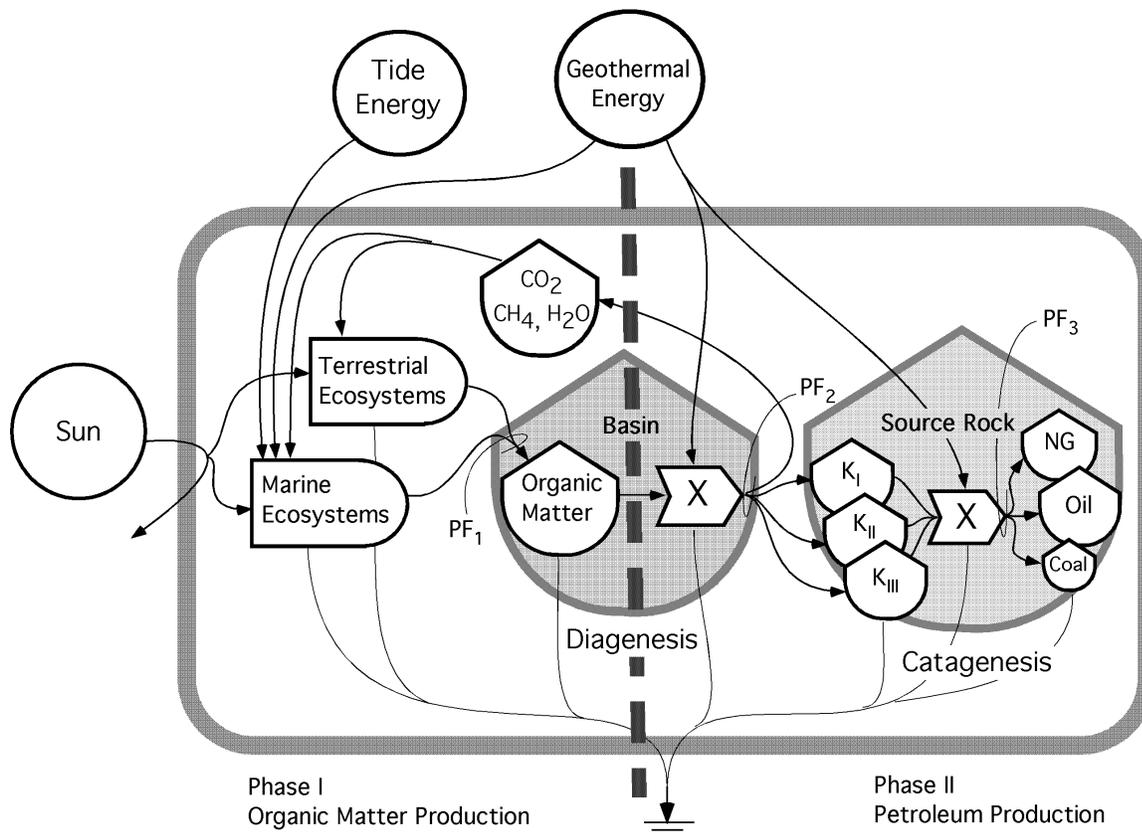
Figure 9 The two phases of petroleum formation. Phase I: organic matter production is dominated by ecological processes driven by solar, tidal, and geothermal energies of the geobiosphere. Phase II: petroleum production is driven by geothermal energy. PF_{1-3} are preservation factors (fraction of carbon 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).

Brown et al. (2011) characterized the emergy of crude oil and natural gas (NG) and computed UEVs by geologic age and then aggregated with a weighted average to represent a single EmCF for global crude oil and another for NG, reporting the UEVs per unit carbon in the fuel (Ibid.). Because approximately 85% of crude oil and natural gas is carbon, the EmCFs of crude oil and NG in Table 2 of Oil & NG worksheet of the EmCFdb are multiplied by the reciprocal of this percentage to reflect the emergy of a mass unit of the crude fuel.

11.4   Helium

Most helium on Earth is a result of radioactive decay, known as alpha decay, and is trapped in the subsurface under conditions that also trap natural gas. Hence the greatest natural concentrations of helium on the planet are found in natural gas, from which most commercial helium is extracted. The concentration varies in a broad range from a few ppm up to about 7%.

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For most uses, helium is extracted by fractional distillation from natural gas, and as such is not an elementary flow but the product of an industrial extraction processes. Until we have a better way of computing the emergy of helium (the result of natural radioactive decay of thorium and uranium) we have assigned helium the EmCF of natural gas.

12.0 Discussion/Future Research

12.1 Global emergy baseline

The planet's sources of exergy (sunlight, gravitational attraction, and deep earth heat) are not constant on geologic timescales (Campbell, 2016). The sun's luminosity increases about 6% per Ga. The Earth grows farther from Moon and Sun as tidal drag transfers Earth's angular momentum to orbital geopotential. Earth heat, both isotopic decay and relict heat, diminish through time. It may be desirable to consider the evolution of the GEB over geologic time, the implications of which would only apply to the crustal minerals and fossil fuels. Other items in the EmCFdb are too young to be affected by a dynamic GEB. GEB is mostly based on long-term average or steady state data. However, the ever-increasing impacts of climate change on global cycles post higher uncertainties which are trickled down in the elementary flows.

12.2 Renewable vs. Non-renewable

EmCFs in the EmCFdb are classified as either renewable or non-renewable; the slowly renewable classification has been removed. The differentiation between the renewable and non-renewable is based on *turnover time*. We have set the cut-off between renewable and non-renewable at a turnover time to be 100 years which is set as a first approximation. For most EmCFs this does not present an issue. However, several flows classified as non-renewable may be considered renewable if they are "harvested" at renewable rates. For instance, 'water, fresh, ground' has a very long turnover (1400 years) yet many groundwater sources have much shorter turnover times and, in some instances, use rate may be considered slow enough that the resource would be renewable. We mention this point only as a precaution, because under most circumstances current use rates of all slowly renewable resources are fast enough to warrant classification as non-renewable.

In emergy accounting, which renewable flows (as well as non-renewable flows) should be chosen is often determined by the purpose of the research. For example, transformity of wave on the ocean surface (for wave energy harvesting), wave energy on the shore (for mangrove or coral reef research), or wave energy in the oceans as a whole (for global studies). Caution should be taken to ensure proper transformity is used for the intended study.

12.3   Biological EmCFs

Soil carbon and biome NPP have EmCFs computed from the same spatial boundaries, with partially overlapping temporal boundaries. This constitutes a definite co-production of at least some part of the EmCFs for both. LCA software does not have the ability to apply emergy algebra, pertinent to combining co-products. As such, future improvement to the EmCFdb should provide EmCFs that can be added without concern for double-counting. The solution may be in dynamic EmCF calculations, currently being explored. For now, both NPP and soil carbon EmCFs come from static (tabular) calculations.

Soil organic matter currently does not have an EmCF, but rather is approximated by the EmCF of soil carbon. Other components of organic material (i.e., Nitrogen, Potassium, Phosphorous, humus, etc.) should be included to represent the true value of soil fertility. Emergy analyses of these nutrient cycles are available only as a global static evaluation (Campbell et al., 2014), which assumes the GEB is embodied on every pathway and in every storage. In essence all nutrient compartments and flows computed in this static evaluation are co-products and should not be added. Development of a dynamic and all-inclusive EmCF calculation is a current topic of research.

12.4   Land occupation EmCFs

Land occupation EmCFs were developed using the areal empower intensities (AEIs) of 17 biome/ecosystems. However, higher resolution EmCFs could be computed by an LCA analyst for individual enterprises using the approach developed by Lee and Brown (2019) and the renewable earth EmCFs of the Renewable Earth emergy flows worksheet of the EmCFdb as inputs to a defined land area in LCA software. Essentially, users can create and input their own case study sites for which they performed an emergy analysis. Or they can perform the emergy evaluation outside the LCA framework and input the resulting AEI to a defined land occupation in the LCA framework. Whichever method is employed it is important not to double-count emergy.

12.5   Minerals

A crustal genesis of 2.5 gallium is much longer, and more dispersed, than the pulsed production of some sediment (e.g., colemanite, borates, etc.). Future research aims to include the faster production of these sediments in a planetary web matrix evaluation.

Precipitate minerals (e.g., trona, halite, etc.) precipitate from drying saline lakes. Many such minerals still lack EmCFs. Where ore grade information could be found, these minerals would have EmCFs calculated as if they were part of the crustal cycle. Future research will characterize the emergy of precipitates according to more localized evaluations.

Indium, gallium, and rhenium EmCF calculations assume them to be diadochic within a Sphalerite (ZnS), bauxite, and molybdenite molecule respectively. The EmCFs for these elements tend to be very high because of their miniscule mass fractions in their parent minerals. Few minerals have best-guess ore grade concentrations (e.g., uranium). The remaining have references.

12.6   Atmospheric gases

The annual mass flux of atmosphere is dominated by water vapor (Schneider et al., 2010). By far the second most fluxed gas is O_2. Thus, the average specific emergy of the atmosphere is approximately that of water vapor. Also, like water vapor, the specific emergy of a unit of gas is scaled according to its mixing exergy. The rising of global temperature and the intensified hydrological cycle may present a different mixture and the associated exergy. The dynamic impacts of climate change to the elementary flows and cascading effects deserve further comprehensive research.

Uncommon atmospheric gases such as fluorocarbons are generally the product of human systems, not the natural geo-biosphere. Thus, they are not elementary flows and their emergy value should be calculated based on the emergy supporting their production process.

12.7   Accounting procedures for land occupation, standing biomass, and lumber harvest

Land occupation refers to the fact that an enterprise occupies a given portion of land. In land occupation, emergy is accounted differently depending on the enterprise. Three general types of enterprise are possible; the first occupies the land, uses the renewable inputs (computed as the land's AEI), and produces something (i.e., agriculture, commercial forestry). The second is occupation by an enterprise for a short period of time to harvest standing resources such as virgin forest wood. The third occupies the land but does not use the renewable inputs directly for its outputs (industry, buildings, parking lot, etc). In the first case where the enterprise produces something that incorporates the renewable inputs on a continuing basis, the renewable AEI of the land is assigned to the product. In the special case where we have computed an EmCF for a product, such as softwood harvested from a continuing silviculture operation ('softwood, dry, unspecified') the wood that is harvested on a continuing basis can either be assigned the emergy of the renewable elementary inputs (the AEI) to the land, if known, or the emergy of the softwood; but not both. To account for both the AEI and the emergy of the wood would be double counting.

In the second case where a short-term occupation results in harvesting a resource, the emergy of the resource is counted, but not the land's renewable AEI.

In the third case, where the enterprise occupies land on a continuing basis but does not utilize the renewable emergy inputs for its products, the AEI of the land is still assigned to the product. To

do otherwise would disagree with the general principle that regardless of what is "seen" as being incorporated in an economic use, the fact that the renewable emergy is inflowing to the process, it is being incorporated. We have given this considerable thought and debate within the research group and are reminded that emergy accounting algebra should be consistent at all scales. So, when accounting for the renewable input to a country, for instance, it is customary to include all the renewable input, regardless of if it falls on areas not occupied by human enterprise. Thus, countries like Canada and Australia, have very large renewable inputs because of the large "uninhabited areas" in each country.

For land occupation that results in the clearing of biomass, the emergy of biomass that had accumulated before the land was occupied (i.e., using the Biomass UEVs on the EmCF Library worksheet) should be accounted as a onetime input to the subsequent land occupation. Biomass EmCFs refer to all biomass (i.e., roots, shoots, leaves, stems, trunks, etc.), which differ from wood EmCFs. Wood EmCFs consider only the quantity of wood, as lumber, produced and are meant to represent elementary inputs.

12.8   Accounting procedures for water

Water has several values, each of which humans exploit at different times and for different purposes. Often, after use, water is returned to the environment with altered quantity and quality, which may affect downstream systems. Accounting for the emergy of inputs and outputs of water to and from enterprises needs to be treated consistently within the LCA framework and is not simple.

Water is often used as a sink for thermal energy because water has the highest specific heat capacity of any liquid, or as a carrier of by-products from enterprises (Boundless, 2023). The emergy of water's purity (chemical potential relative to sea water) is used by ecosystems and economic enterprises alike. The constituents carried by water are sometimes used, such as when nutrient laden water is discharged to ecosystems; or when toxins carried by water have detrimental effects downstream. Finally, the gravitational potential of elevated water is used as a power source in technological applications like the generation of electricity. Accounting procedures for each of these uses need be addressed carefully and systematically.

12.8.1 Water's thermal capacity
Because cooling water is an input to a process that uses the water's specific heat capacity, density, and thermal conductivity, rather than its chemical exergy, we must account for its "thermal service" rather than its chemical service. The main mechanism for water cooling is convective heat transfer (Boundless, 2023). Cooling water may be recycled through a *recirculating* system or used in a single pass *once-through cooling* (OTC) system. If recirculating systems are open, then they may have evaporative losses. OTC systems generally return most of the water at temperatures significantly above the ambient receiving water body. Water that is not returned might be considered water that is consumed.

Both the input and output of cooling water need be considered within the LCA framework. Unless cooling water is used up (i.e., evaporated) it should not be counted as an input. For example, in a nuclear power plant, make-up water, i.e., which replaced evaporated losses, is counted. Also blow-down water, water mixed with acids to clean the plant structure, should be accounted for by using its chemical potential energy EmCF. The emergy of these waters should be assigned to the product of the process being evaluated, in this case nuclear power. Saltwater used for cooling would have no chemical potential energy and therefore evaporative losses would not be counted.

Water that is returned to a water body at higher temperature provides a heat gradient to the receiving environment. This heat gradient represents an available energy source that can drive geo-biologic work and post potential environmental impacts.

To compute the emergy of the water, rather than assigning the emergy of the thermal process, we suggest computing an EmCF based on the method proposed by Odum (1996, pp32-33) that used an average transformity for heat derived mechanical work, adjusted by Carnot efficiency. Updating this method to the current GEB yields a new equation where C is the Carnot efficiency of the hot water and receiving water body (see Equation 39) and 0.7 is the efficiency of 1000°C power plant relative to average environmental temperature.

$$EmCF_{hot\,water} \; = \; C(42,000 sej/J) \; / \; 0.7$$

<div align="right">(39)</div>

Thus, hot water with a temperature of 297.25 K that is discharged to a river having a temperature of 287.25 K would have an EmCF of 1200 as follows (Equation 40):

$$EmCF \; = \; 0.034(42000 \; sej/J)/0.7 \; = \; 1200 \; sej/J$$

<div align="right">(40)</div>

12.8.2 Water's chemical potential

In the past, water's available potential energy was computed using its purity relative to seawater where purity was measured by total dissolved solids (TDS). This method stems from the fact that living organisms require freshwater to drive cellular osmotic differences for transfer of wastes from cells. For processes that utilize the available energy in water's chemical potential, the emergy of the input water is computed using the methods outlined in Section 6. The total <u>net</u> volume of water used is multiplied by its EmCF and its emergy assigned to a process's output.

Water that is discharged from a process as a by-product may have different TDS from the input water and thus its transformity may be different. For instance, output water that has lower TDS may have a higher transformity or vice versa, and higher TDS would result in a lower transformity. We do not suggest that the other emergy inputs to a process be added to the output water, unless of course, the output water is the main product of the process.

However, water carries other constituents that may be important sources to biological and technological processes alike. The use of TDS as the indicator for chemical purity may not capture these other constituents. Common sense need prevail. If an input or output water contains high levels of some chemical or element, then the emergy of that chemical or element should be computed using the chemical EmCF methods outlined in Section 7. If the computed emergy is larger than the chemical potential of the water, it should be used instead of the emergy of the chemical potential determined using the TDS because mineral emergy is a global co-product of water emergy.

An emergy signature of water that carries several constituents such as carbon, nitrogen, phosphorus, pesticide, etc., can be constructed to illustrate the emergy of the various constituents. However, adding them together to obtain a total emergy of the water should not be done if those constituents originated from the same place in space and time. They may be added together if the constituents are independent of each other (i.e., they were not added to the water as part of the same process). For instance, runoff water from a watershed may have several constituents whose emergy may be evaluated separately to better visualize the potentials of each constituent, but they should not be added together because they result from the same watershed's runoff process. On the other hand, water that has been used in an industrial process may receive inputs of chemicals manufactured in a different place in both space and time than the constituents that originated in the watershed. In this case, the emergy of the separate constituents could be added.

12.8.3 Water's geo-potential
The emergy of the available geo-potential energy in water is related to the height difference between the inlet and outlet of the process. Thus, computing the emergy of water input to a hydroelectric dam is the volume of water multiplied by the geo-potential of the height difference between inlet and outlet times the EmCF of global water geo-potential. Assuming there is no change in quality or quantity there is no need to compute the emergy of the water outflow from the dam. Not captured by this analysis is the potential alteration of the pulsing regime of a river due to the dam, nor the potential change in temperature (colder) of the discharge water taken from deep reservoirs. For this, calculating the emergy of the chemical change and temperature change, and comparing with the geo-potential change may be considered. The only the largest emergy value of these three exergy descriptors is accounted, as they are all global co-products.

13.0 Conclusions

This report and the associated EmCFdb provides equations, data, and rational, for the emergy characterization of several kinds of elementary flows for inclusion in LCA. EmCFdb also provides consistent elementary flows for emergy accounting. Primarily resources are considered, as the emergy method is most developed in accounting for inputs rather than outputs

or emissions. These resources span natural energies (e.g., wind), land area occupation (e.g., biomes), biologic stocks (e.g., soil carbon, biomass, lumber) for several biome varieties, various kinds of freshwater on a global average basis, many crustal minerals and rocks, some soil properties (e.g., nitrogen), major air constituents, and fossil fuels. These efforts build on several prior studies which greatly assisted the aggregation of such information into a common framework (e.g., Rugani et al., 2011; Sweeney et al., 2006; the emergy Folios, etc.). The library is expected to be useful for quantifying environmental support in LCA studies. The report and the associated EmCFdb are also living documents and database as new data, calculations and methods become available and incorporate into the newer versions.

Among these elementary EmCFs are a few novel calculations. These include updated natural renewable energies, areal empower of biomes (which effects all biological EmCFs), mineral EmCFs with varying concentration, and fossil fuel EmCFs. The details of these calculations are available in the accompanying Excel workbook with the filename EmCF database for LCA.

14.0 Quality Assurance

The EmCF database and this report were prepared under the ORD Quality Assurance Project Plans: S-17059-QP-1-1 for "Emergy Research Support for Supply Chains", G-STD-0030219-QP-1-0 and K-WID-0030219 for "Secondary Data Analysis Emergy Research Support for Task 1b", G-WSD-0031214-QP-1-0 for "Resource Recovery from Municipal Wastewater", G-WSD-0032048-QP-1-0 for "The Development of Smart Water Management Evaluation Database and Emergy Accounting for the "City of Tomorrow" Analysis", K-WID-0018946 for "Emergy Research Support".

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Table A-1   Summary of EmCFs for LCA Elementary Flows

Flow	Type	Units	sej/unit
Renewable Earth Emergy Flows			
Solar energy	Raw renewables	MJ	1.00E+06
Geothermal energy (deep heat)	Raw renewables	MJ	4.90E+09
Tide	Raw renewables	MJ	3.09E+10
Wind energy	Raw renewables	MJ	5.20E+08
Wave energy in the oceans as a whole	Raw renewables	MJ	5.20E+08
Wave energy on the shore	Raw renewables	MJ	7.24E+10
Rain (chemical potential)	Raw renewables	MJ	2.25E+10
Runoff geopotential energy	Raw renewables	MJ	4.12E+10
Ocean Currents	Raw renewables	MJ	5.80E+10
Water			
Water, fresh, unspecified; ppmTDS	water	m3	1.28E+12
Water, rivers and streams; ppmTDS	water	m3	3.26E+11
Water, fresh, lake; ppmTDS	water	m3	2.24E+12
Water, fresh, wetland; ppmTDS	water	m3	5.22E+12
Water, fresh, surface; ppmTDS	water	m3	1.28E+12
Water, fresh, ground; ppmTDS	water	m3	1.46E+12
Water, fresh, polar ice; ppmTDS	water	m3	4.83E+12
Water, terrestrial rain; ppmTDS	water	m3	1.06E+11
Water, atmospheric vapor; ppmTDS	water	m3	1.95E+10
Water, runoff geopotential	water	MJ	4.12E+10
Minerals			
Aluminum, element mass ratio in Bauxite minerals; {11154517413.4696}; g/g in ground	minerals and metals	g	1.12E+10
Anhydrite; {8106152969.06314}; g/g in ground	minerals and metals	g	8.11E+09
Antimony; {8089969016.13499}; g/g in ground	minerals and metals	g	8.09E+09
Barite; {3141371127.91076}; g/g in ground	minerals and metals	g	3.14E+09

Bauxite; {11154517413.4696}; g/g in ground	minerals and metals	g	1.12E+10
Borax (Kernite); {6607106595.78549}; g/g in ground	minerals and metals	g	6.61E+09
Cadmium in Greenockite; {12064152593.9228}; g/g in ground	minerals and metals	g	1.21E+10
Cerium; {4536488375.32133}; g/g in ground	minerals and metals	g	4.54E+09
Chromium in Chromite; {9394621509.27478}; g/g in ground	minerals and metals	g	9.39E+09
Sodalite, Chrysotile; {1855023786.62126}; g/g in ground	minerals and metals	g	1.86E+09
Cinnabar; {8241006041.0332}; g/g in ground	minerals and metals	g	8.24E+09
Cobalt; {10390040589.3785}; g/g in ground	minerals and metals	g	1.04E+10
Colemanite; {3320337587.04997}; g/g in ground	minerals and metals	g	3.32E+09
Copper in Chalcopyrite; {13069354716.7953}; g/g in ground	minerals and metals	g	1.31E+10
Copper in Chalcopyrite; {13447698596.6545}; g/g in ground	minerals and metals	g	1.34E+10
Copper in Chalcopyrite; {13846682428.9523}; g/g in ground	minerals and metals	g	1.38E+10
Copper in Chalcopyrite; {14780329117.6962}; g/g in ground	minerals and metals	g	1.48E+10
Diatomite	rock and aggregate	g	
Europium; {8258230731.38924}; g/g in ground	minerals and metals	g	8.26E+09
Feldspar; {1598328951.8236}; g/g in ground	minerals and metals	g	1.60E+09
Flourine; {37735915249.4802}; g/g in ground	minerals and metals	g	3.77E+10
Flourine; {44302647816.3473}; g/g in ground	minerals and metals	g	4.43E+10
Fluorspar/Fluorite; {19841711822.2734}; g/g in ground	minerals and metals	g	1.98E+10
Gadolinium; {9918725756.3501}; g/g in ground	minerals and metals	g	9.92E+09
Gallium; {7967512438192.56}; g/g in ground	minerals and metals	g	7.97E+12
Gold; {4700264177.80869}; g/g in ground	minerals and metals	g	4.70E+09
Gold; {4816407585.21258}; g/g in ground	minerals and metals	g	4.82E+09
Gold; {4867930733.65328}; g/g in ground	minerals and metals	g	4.87E+09
Gold; {5149828056.51144}; g/g in ground	minerals and metals	g	5.15E+09
Gold; {5648094158.16104}; g/g in ground	minerals and metals	g	5.65E+09
Gold; {4138047840.01968}; g/g in ground	minerals and metals	g	4.14E+09
Gold; {5956429812.69685}; g/g in ground	minerals and metals	g	5.96E+09
Gold; {5996745125.56752}; g/g in ground	minerals and metals	g	6.00E+09
Gold; {6213682983.82381}; g/g in ground	minerals and metals	g	6.21E+09
Gypsum; {1317975555.53474}; g/g in ground	minerals and metals	g	1.32E+09

Indium; {13538306380011.9}; g/g in ground	minerals and metals	g	1.35E+13
Iron, element mass ratio in Taconite minerals; {2971505078.21115}; g/g in ground	minerals and metals	g	2.97E+09
Kaolinite; {1780555283.21744}; g/g in ground	minerals and metals	g	1.78E+09
Kieserite; {10871827429.0439}; g/g in ground	minerals and metals	g	1.09E+10
Lanthanum; {3613580204.43372}; g/g in ground	minerals and metals	g	3.61E+09
Lead; {5653757622.01115}; g/g in ground	minerals and metals	g	5.65E+09
Lithium; {91802594457.6113}; g/g in ground	minerals and metals	g	9.18E+10
Magnesite; {16076069613.2529}; g/g in ground	minerals and metals	g	1.61E+10
Manganese; {10861965153.3119}; g/g in ground	minerals and metals	g	1.09E+10
Molybdenum; {6162171539.22386}; g/g in ground	minerals and metals	g	6.16E+09
Molybdenum; {6162171539.22386}; g/g in ground	minerals and metals	g	6.16E+09
Molybdenum; {6162171539.22386}; g/g in ground	minerals and metals	g	6.16E+09
Molybdenum; {6162171539.22386}; g/g in ground	minerals and metals	g	6.16E+09
Molybdenum; {8459441651.19405}; g/g in ground	minerals and metals	g	8.46E+09
Nickel; {3251652514.27375}; g/g in ground	minerals and metals	g	3.25E+09
Nickel; {10410349468.3075}; g/g in ground	minerals and metals	g	1.04E+10
Olivine; {7391005661.33716}; g/g in ground	minerals and metals	g	7.39E+09
Palladium; {44174239569.9182}; g/g in ground	minerals and metals	g	4.42E+10
Palladium; {49727797426.6012}; g/g in ground	minerals and metals	g	4.97E+10
Phosphorous in Apatite; {10904197381.1782}; g/g in ground	minerals and metals	g	1.09E+10
Phosphorous in Apatite; {9284926368.37059}; g/g in ground	minerals and metals	g	9.28E+09
Platinum; {29392037460.0736}; g/g in ground	minerals and metals	g	2.94E+10
Platinum; {31284616834.929}; g/g in ground	minerals and metals	g	3.13E+10
Rhenium; {26529241518500.6}; g/g in ground	minerals and metals	g	2.65E+13
Rhodium; {5448880475379370}; g/g in ground	minerals and metals	g	5.45E+15
Rhodium; {4540733729482810}; g/g in ground	minerals and metals	g	4.54E+15
Silver; {3886196578.51713}; g/g in ground	minerals and metals	g	3.89E+09
Silver; {2277868851.45669}; g/g in ground	minerals and metals	g	2.28E+09
Silver; {5850753719.55117}; g/g in ground	minerals and metals	g	5.85E+09
Silver; {9653872313.92939}; g/g in ground	minerals and metals	g	9.65E+09
Silver; {3923042474.79215}; g/g in ground	minerals and metals	g	3.92E+09

Silver; {7793346702.14797}; g/g in ground	minerals and metals	g	7.79E+09
Nitratine, Sodium nitrate; {1385029982.75347}; g/g in ground	minerals and metals	g	1.39E+09
Sodium sulphate; {1659826089.45453}; g/g in ground	minerals and metals	g	1.66E+09
Stibnite; {5800507784.56879}; g/g in ground	minerals and metals	g	5.80E+09
Sylvite, Potassium chloride; {20454345149.1348}; g/g in ground	minerals and metals	g	2.05E+10
Talc; {2609164348.88319}; g/g in ground	minerals and metals	g	2.61E+09
Tantalum; {1009316836.69473}; g/g in ground	minerals and metals	g	1.01E+09
Tellurium; {9487199561.82625}; g/g in ground	minerals and metals	g	9.49E+09
Tin, element mass ratio in Cassiterite; {1354225.64406906}; g/g in ground	minerals and metals	g	1.35E+06
TiO2; {5521393395.0084}; g/g in ground	minerals and metals	g	5.52E+09
TiO2; {4607243856.26256}; g/g in ground	minerals and metals	g	4.61E+09
Ulexite; {3479934132.57111}; g/g in ground	minerals and metals	g	3.48E+09
Uranium, weighted element mass ratio; {4363229331.72704}; g g/g in ground		g	4.36E+09
Verminculite; {1121696152.01091}; g/g in ground	minerals and metals	g	1.12E+09
Zinc; {13985065720.4718}, g/g in ground	minerals and metals	g	1.40E+10
Baddeleyite, Zirconia; {14103675060.1262}; g/g in ground	minerals and metals	g	1.41E+10
Aggregates			
Aggregate, natural	rock and aggregate	g	1.62E+09
Basalt	rock and aggregate	g	3.30E+09
Calcite (Limestone)	rock and aggregate	g	5.93E+09
Clay, bentonite	rock and aggregate	g	2.04E+09
Clay, unspecified	rock and aggregate	g	2.04E+09
Dolomite; {5926382251.16802}; in ground	rock and aggregate	g	5.93E+09
Granite	rock and aggregate	g	1.62E+09
Gravel	rock and aggregate	g	1.62E+09
Perlite	rock and aggregate	g	1.65E+09
Pumice	rock and aggregate	g	1.62E+09
Rock, unspecified	rock and aggregate	g	1.62E+09
Sand, quartz	rock and aggregate	g	3.24E+09
Sand, unspecified	rock and aggregate	g	3.24E+09

Shale	rock and aggregate	g	1.63E+09
Ocean Ions			
Sodium chloride; {860115312.840238}; g/g in water	minerals and metals	g	8.60E+08
Bromine; {335606441448.866}; g/g in water	minerals and metals	g	3.36E+11
Calcium chloride; {688402240.085752}; g/g in water	minerals and metals	g	6.88E+08
Iodine; {3352284917399.7}; g/g in water	minerals and metals	g	3.35E+12
Magnesium; {1866432551.66494}; g/g in ground	minerals and metals	g	1.87E+09
Atmospheric Gases			
Air; {20359.4161501681}; g/g in air	air	g	2.04E+04
Carbon dioxide; {14202.5635391691}; g/g in air	air	g	1.42E+04
Methane; {88626.4796174336}; g/g in air	air	g	8.86E+04
Krypton; {10049.1766253686}; g/g in air	air	g	1.00E+04
Nitrogen; {}; g/g in air	air	g	
Oxygen; {4651.95185333505}; g/g in air	air	g	4.65E+03
Xenon; {17560.873018566}; g/g in air	air	g	1.76E+04
Land			
Occupation, Tropical & Subtropical Moist Broadleaf Forests	land	m2*a	2.29E+11
Occupation, Tropical & Subtropical Dry Broadleaf Forest	land	m2*a	1.33E+11
Occupation, Tropical & Subtropical Coniferous Forest	land	m2*a	1.24E+11
Occupation, Temperate Broadleaf & Mixed Forests	land	m2*a	9.80E+10
Occupation, Temperate Conifer Forests	land	m2*a	9.49E+10
Occupation, Boreal Forests/Taiga	land	m2*a	5.76E+10
Occupation, Tropical & Subtropical Grasslands, Savannas & Shrublands	land	m2*a	1.04E+11
Occupation, Temperate Grasslands, Savannas & Shrublands	land	m2*a	5.12E+10
Occupation, Flooded Grasslands & Savannas	land	m2*a	8.77E+10
Occupation, Montane Grasslands & Shrublands	land	m2*a	5.25E+10
Occupation, Tundra	land	m2*a	6.34E+10
Occupation, Mediterranean Forests, Woodlands & Scrub	land	m2*a	5.40E+10
Occupation, Deserts & Xeric Shrublands	land	m2*a	3.26E+10

Occupation, Mangroves	land	m2*a	2.90E+11
Occupation, River	land	m2*a	1.16E+12
Occupation, Lake	land	m2*a	6.61E+10
Occupation, Rock and Ice	land	m2*a	8.81E+10
Occupation, Estuary	land	m2*a	3.80E+13
Occupation, Terrestrial Average	land	m2*a	1.14E+11
Occupation, Cultivated Land	land	m2*a	1.14E+11
Occupation, Unspecified Area	land	m2*a	1.14E+11
Biomass			
Biomass, Tropical & Subtropical Moist Broadleaf Forests		gC	9.76E+08
Biomass, Tropical & Subtropical Dry Broadleaf Forest		gC	8.24E+08
Biomass, Tropical & Subtropical Coniferous Forest		gC	8.76E+08
Biomass, Temperate Broadleaf & Mixed Forests		gC	6.55E+08
Biomass, Temperate Conifer Forests		gC	8.80E+08
Biomass, Boreal Forests/Taiga		gC	8.31E+08
Biomass, Tropical & Subtropical Grasslands, Savannas & Shrublands		gC	1.27E+09
Biomass, Temperate Grasslands, Savannas & Shrublands		gC	1.04E+09
Biomass, Flooded Grasslands & Savannas		gC	1.13E+09
Biomass, Montane Grasslands & Shrublands		gC	2.57E+09
Biomass, Tundra		gC	3.64E+09
Biomass, Mediterranean Forests, Woodlands & Scrub		gC	8.03E+08
Biomass, Deserts & Xeric Shrublands		gC	4.99E+09
Biomass, Mangroves		gC	2.16E+09
Biomass, River		gC	6.94E+10
Biomass, Lake		gC	3.97E+09
Biomass, Rock and Ice		gC	1.21E+11
Biomass, Estuary		gC	1.76E+11
Biomass, Terrestrial Average		gC	1.01E+09

Soil

Soil Carbon, Tropical & Subtropical Moist Broadleaf Forests	biological	gC	7.41E+08
Soil Carbon, Tropical & Subtropical Dry Broadleaf Forest	biological	gC	4.63E+08
Soil Carbon, Tropical & Subtropical Coniferous Forest	biological	gC	3.62E+08
Soil Carbon, Temperate Broadleaf & Mixed Forests	biological	gC	2.19E+08
Soil Carbon, Temperate Conifer Forests	biological	gC	2.03E+08
Soil Carbon, Boreal Forests/Taiga	biological	gC	2.22E+08
Soil Carbon, Tropical & Subtropical Grasslands, Savannas & Shrublands	biological	gC	1.23E+08
Soil Carbon, Temperate Grasslands, Savannas & Shrublands	biological	gC	2.77E+08
Soil Carbon, Flooded Grasslands & Savannas	biological	gC	3.61E+09
Soil Carbon, Montane Grasslands & Shrublands	biological	gC	3.21E+08
Soil Carbon, Tundra	biological	gC	2.38E+09
Soil Carbon, Mediterranean Forests, Woodlands & Scrub	biological	gC	7.92E+07
Soil Carbon, Deserts & Xeric Shrublands	biological	gC	2.15E+08
Soil Carbon, Mangroves	biological	gC	7.58E+09
Soil Carbon, Terrestrial Average	biological	gC	5.69E+08
Soil Carbon, Cultivated Land	biological	gC	1.09E+08
Soil, Unspecified	biological	kg	3.10E+12
Nitrogen {N}, in soil	minerals and metals	kg	3.34E+13
Inorganic matter, in soil, unspecified	biological	kg	3.25E+12
Sulfur; {4947462077382.01}; g/g in soil	minerals and metals	kg	4.95E+12

Wood

Hardwood, dry, unspecified	biological	kg	3.99E+10
Softwood, dry, unspecified	biological	kg	3.16E+10
Wood, dry, unspecified	biological	kg	3.16E+10
Wood, dry, temperate forests	biological	kg	5.44E+11
Wood, dry, boreal forest	biological	kg	2.35E+11
Wood, dry, tropical lowland forest	biological	kg	4.65E+12
Wood, dry, swamps	biological	kg	1.77E+12

Fossil Fuels

Peat	fossil fuel precursor	kg	7.22E+12
Coal, anthracite	fossil fuel	MJ	3.89E+10
Coal, bituminous	fossil fuel	MJ	3.89E+10
Coal, sub-bituminous	fossil fuel	MJ	3.23E+10
Coal, lignite	fossil fuel	MJ	3.23E+10
Gas, natural	fossil fuel	Nm3	5.36E+12
Oil, crude	fossil fuel	m3	5.09E+15
Helium; {7464230827230.45}; g/g in natural gas	minerals and metals	kg	7.46E+12

Radionuclides

Potassium	minerals and metals	MJ	8.20E+09
Thorium	minerals and metals	MJ	4.20E+09
Uranium 235	minerals and metals	MJ	3.90E+09
Uranium 238	minerals and metals	MJ	3.70E+09

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