Quantifying the Emergy of Resources: Challenges for a Bottom-up Approach

Benedetto Rugani, Enrico Benetto, Damien Arbault, Ligia Tiruta-Barna, Antonino Marvuglia

ABSTRACT

The baseline allows for a top-down scaling of the global Emergy budget to systems at regional and local levels, assuming that the geobiosphere generates energy flows and resources as co-products of the same annual cycles. Undoubtedly, the baseline is one of the best findings H.T. Odum provided with a uniform, holistic and flexible method for the evaluation of the ‘energy of one kind necessary to produce resources and products’. Nevertheless, its use has been reputed to be source of inaccuracy for downstream Emergy results of technological productions and it has undergone a number of criticisms. Though we acknowledge the usefulness of the baseline and its extensive adoption by the most of the Emergy practitioners, we suggest a preliminary redesigning of the framework behind the resource-UEVs calculation with the baseline. The goal is to use a ‘bottom-up’ approach. Accordingly, the Emergy values of the three primary sources (sun, tides, geo-heat) should not be summed, but the Exergy (as available energy) of each source be separately assigned to the corresponding resource production compartment (i.e. the natural processes involved) which are connected by exchanges of natural products (the equivalent of the commodities for the technosphere). These compartments can be framed into two matrix systems: 1) the matrix $\beta (3 \times m)$, where the three independent Exergy flows are assigned to $m$ natural processes (e.g. water evaporation, net primary production, soil formation, coalification), and 2) the square matrix $\alpha (m \times m)$, where the same $m$ natural processes produce corresponding $m$ natural products (e.g. rain, wood, land, coal). The UEV of these natural products (ecosystem goods and services) can be obtained by inverting and scaling the two related matrices. We do recognize that the sun, tidal and geo-heat sources show different contributions in terms of magnitude and along representative time and space conditions. These are factors essentially neglected by the balance equations used to account for the baseline. The main challenge to tackle for the development of the bottom-up approach is certainly the extensive collection of reliable data able to approximately describe the network of geobiosphere processes. A feature of this bottom-up framework is that UEVs would be vectors no more calculated in sel/unit but instead including the memory of the amounts of Exergy provided by the three separated sources (sun, tides and geo-heat) to the complex network of processes from which the unit of resource (e.g. 1 kg of soil formed,…) is directly and indirectly generated.

INTRODUCTION

The Unit Emergy Value (UEV) represents the Emergy required to produce directly and indirectly one unit of good or service. It represents somehow a binding equivalence term at the foundation of an Emergy analysis, since UEVs are usually collected from the literature (very often ‘not peer-reviewed’) to be multiplied by the inventoried inputs of a considered product. This allows to eventually
calculating a new UEV of product, which then becomes again part of the literature. However, this (only apparently virtuous) process has generated thousands of UEVs during the past decades that have been (and still are) used by Emergy analysts without any sort of standardization process, spreading around many uncertainties about the quality and reliability of an Emergy analysis. This is valid both for ecological (i.e. goods and services generated by the ecosystems) and anthropic (i.e. goods and services produced by the economic/technological processes) systems, the former being always included in the latter. As a consequence, an accurate and consistent quantification of the UEVs of natural resources would be recommended to avoid a possible perpetuation of errors downstream in the chain ‘resources-human products’. While the attention is usually focused on the quality of man-made products’ UEV, what makes an Emergy evaluation consistent is instead a significant degree of accuracy, when not of representativeness, embodied in the resource-UEVs, which can be regarded as the first sources of uncertainty for Emergy evaluation analysis.

In the Emergy community, a large effort has been spent to provide a uniform approach and to increase UEVs robustness. For example, the recent National Environmental Accounting Database (NEAD; Sweeney et al., 2007) addresses a global formalization for Emergy analyses of countries. However, this framework includes sets of aggregated and unclear data and results are therefore only useful for comparisons at national scale (Sweeney et al., 2007). To some extent, attempts to increase consistency of UEVs with characterization of uncertainty have been provided (Ingwersen, 2010; Li et al., 2011), though not specifically addressed to the primary sources of error (i.e. resource-UEVs).

Conventionally, resource-UEVs are quantified starting from the value of the global Empower, solar annual or planetary ‘baseline’ (hereafter just baseline) (Odum, 1996). The baseline allows for a top-down scaling of the global Emergy budget to systems at regional and local levels, assuming that the geobiosphere generates energy flows and resources as co-products of the same annual cycles. Undoubtedly, the baseline is one of the best findings H.T. Odum provided with a uniform, holistic and flexible method for the evaluation of the ‘energy of one kind necessary to produce resources and products’. Nevertheless, its use has been reputed to be source of inaccuracy for downstream Emergy results of technological productions (Campbell et al., 2005) and it has undergone a number of direct and indirect criticisms (Mansson and McGlade, 1993; Cleveland et al., 2000; Hau and Bakshi, 2004; Gasparatos et al., 2009; Sciubba, 2010).

Though we acknowledge the usefulness of the baseline and its extensive adoption by most of the Emergy practitioners, our contribution aims at suggesting an alternative framework for resource-UEVs calculation avoiding the use of the baseline. More specifically, the goal is to use a bottom-up approach (based on matrix algebra formulation), opposite to the top-down perspective represented by the baseline.

**PERSPECTIVES WITH THE BASELINE**

In the Emergy literature, a large number of UEVs of natural resources is available, such as for water flows and storages (Buenfil, 2001), renewable energy resources such as wind or geothermal heat, biomass resources, soil erosion, different kinds of minerals and fossil fuels (Odum, 1996; Odum, 2000). A summary of resource flow UEVs has been provided by Brown and colleagues (Brown and Cohen, 2008; Brown and Ulgiati, 2009). Recently, UEVs have been calculated for a large number of metal ore resources (Cohen et al., 2007). Besides this, the calculation for fossil resources of gas, crude oil, and coal has been also upgraded (Brown et al., 2011).

As introduced above, the calculation of resource-UEVs is rooted on the baseline concept (Odum, 1996; Odum, 2000; Campbell, 2000; Brown and Ulgiati, 2010). It states that resource storages and flows are co-products of the same global Emergy budget (i.e. baseline) that drives all geobiosphere processes. In general, the UEV of a given resource (e.g. mineral, water, biomass) is quantified through the following equations:
where the UEV of resource \( i \) is in \( \text{seJ/g, seJ/m}^3, \text{seJ/J, etc.} \), \( S \) represents the baseline (e.g. \( 15.20 \times 10^24 \text{ seJ/yr; Brown and Ulgiati, 2010} \)), \( F \) the flow of resource \( i \) (in \( \text{g/yr, m}^3/\text{yr, J/yr, etc.} \)), \( \Delta T \) the resource-turnover time in years and \( Q \) the storage (or global capacity) of the resource \( i \) (in \( \text{g, m}^3, \text{J, etc.} \)). The baseline is the sum of solar radiation Emergy, tides Emergy, and geothermal heat Emergy. Its final value thus depends on the degree to which these three independent inputs conceptually interact to generate resources. Additionally, the baseline could change if a new energy source is added to the inputs (Campbell et al., 2005). For example, if all those three inputs interact to produce the sedimentary cycle of the Earth and the geopotential energy of the world oceans, the \( 15.83 \times 10^24 \text{ seJ/yr} \) baseline (Odum, 2000) is the result of the equivalences determined. In contrast, if solar energy and the Earth’s deep heat interact to produce the sedimentary cycle, and gravitational attraction and solar energy interact to produce the geopotential energy of the world oceans, the \( 9.26 \times 10^24 \text{ seJ/yr} \) baseline results (Campbell et al., 2000). However, discussing on the different characteristics behind the available baselines, whose selection is arbitrarily left to the user (which is an aspect that sounds as a limitation toward a standardization of the Emergy method), is out of the aims of this paper. The focus here is rather on the intrinsic meaning and worth behind the baseline concept itself.

In order to account for the Emergy of the three primary sources, a number of balance equations are applied (Campbell, 2000; Brown and Ulgiati, 2010). With regard to the latest calculated baseline value (\( 15.20 \times 10^24 \text{ seJ/yr} \)), for example, the Emergy of 1 unit of tidal energy absorbed and of 1 unit of crustal heat then becomes 72,400 and 20,300 times higher, respectively, than the Emergy of 1 unit of solar energy absorbed (Brown and Ulgiati, 2010). This means that 72,400 and 20,300 joules of solar energy are assumed to make, respectively, 1 joule of tidal energy absorbed and 1 joule of energy from crustal heat sources. The total annual baseline is then composed by 24% of solar Emergy, 54% of tidal Emergy, and 22% of geothermal Emergy. In other words, the direct solar Emergy contribution to the formation of resources, on a yearly basis, represents only around \( 1/4 \) of the total driving force, while the highest contribution is provided by tidal Emergy. As previously mentioned, rather than overtly confuting the baseline concept, Emergy developers and analysts have only provided a number of baseline values where components (i.e. sun, tide, geo) are weighted differently (Odum, 1996; Odum, 2000; Campbell, 2000; Brown and Ulgiati, 2010). Out of the Emergy community, however, some critiques to the baseline concept have raised. For example, Sciubba identified several uncertainty issues behind the Emergy calculation of those three primary inputs to the geobiosphere, highlighting the potential ability of Exergy to compute the real ‘cost’ of each component to the biosphere (Sciubba and Ulgiati, 2005; Sciubba, 2010). Since UEVs are calculated through a sort of pyramidal process starting from the baseline, it is not surprising finding inconsistencies in Emergy results, in particular when comparing systems that use different baselines at different times and spatial scale (Campbell et al., 2005). Therefore, the baseline itself plays a major role for Emergy accounting. Its use affects the calculation of UEVs, which are based on crude assumptions and whose derived Emergy results are rather seldom reproducible (Hau and Bakshi, 2004; Sciubba, 2010), and cannot be validated a posteriori. In Emergy, the choice of baseline may hide mistakes in UEVs estimations, making the results of hundreds of Emergy studies hardly comparable (Campbell et al., 2005; Sciubba, 2010). Moreover, the effect of using the baseline has further relevant impacts downstream in the resource-UEVs calculation. First, spatial and temporal variability is not included within the UEV models, which are assumed at steady-state conditions for a reference (undefined) year of natural resource production and without specific downscaling properties to regional boundaries, i.e. the UEVs are representative of ‘average’ global conditions. As a consequence, the Emergy value of resources that have a meaningful dependence from the regional scale, such as water or biotic resources, cannot be representative of the different local conditions around the globe. Second, the Emergy accounting procedure usually models the Emergy associated with local resources (e.g. rain, sun) in such a manner that the Emergy input to a
system does not fully contribute to the system development but instead a fraction is usually exported (Campbell et al., 2005). In this regard, we argue that only the equivalent (solar) exergy that was actually needed to generate a given resource should be accounted for to give a more consistent evaluation of how much available energy is embodied in the UEV. Finally, by using the baseline, the notion of ‘history’ of resource formation (i.e. the accounting for solar inputs over geological time scales; Hau and Bakshi, 2004), as apparently stems from the definition of Emergy as the available energy of one kind used up directly and indirectly to generate resources and products (Odum, 1996), seems to be missing. This is particularly true for most of the resources whose turnover time is greater than one year, those which are usually considered as non-renewable, i.e. minerals, metal ores, top soil, groundwater, etc. Indeed, assigning with a top-down perspective a global production value (i.e. the baseline) to the annual flow of the resource (see Eq.1), does neither mean assessing how much available energy is memorized within the ‘life cycle’ chain upstream that resource, nor even being able to approximate the environmental work required to replace it in the future. The assumption that all the different resource flows, at global scale, are co-products of the same annual contribution of solar Emergy (i.e. the baseline) makes the UEVs different solely because of the relative amounts of the resource flows on the globe. As a result, the lower the amount of resource flow (which of course depends on the ratio between stock and turnover time, see Eq.2) the higher the UEV, but without any link to the actual effort invested by Nature in generating that flow, which remains eventually unknown.

**MATRIX-BASED FORMULATION**

**Background from life cycle assessment**

Relevant studies demonstrate the feasibility of using matrix systems to represent the main biosphere connections to assess resources and, more in general, ecosystem goods and services (Costanza et al., 1997; Patterson, 2002). Proposals to integrate natural geologic features into ecosystem matrices were also formulated (Hughes, 1995). A framework of interlinked chains to define (in matrix form) environmental processes and combine them with economic processes has been defined by Heijungs (Heijungs, 2001). Finally, using matrix algebra to calculate UEVs is not a novel topic even in the Emergy literature (Collins and Odum, 2000; Brown and Cohen, 2008; Li et al., 2010; Patterson, 2012, 2013; Tiruta-Barna and Benetto, 2013). Nevertheless, in this study the main link to a new matrix-based formulation for UEVs comes from a similarity with the life cycle inventory principles.

Life Cycle Assessment (LCA) represents one of the most accepted and used tool for the environmental impact evaluation of goods and services (Curran, 2006; European Commission, 2010). The ecoinvent® database (Ecoinvent database, 2012) is the largest framework worldwide aiming to provide Life Cycle Inventory (LCI) models for thousands of products (i.e. of energy generation, materials and agri-food production, infrastructure and transportation), which can be used as the background system to build LCAs. Ecoinvent follows the matrix inversion method for the solution of the inventory problem (Heijungs and Suh, 2002). To shortly recall it, this method determines the LCI related to a specific product by solving a system of linear equations using matrix algebra. More specifically, the system \( \mathbf{A} \cdot \mathbf{s} = \mathbf{f} \) has to be solved (see Figure 1), where the technology matrix \( \mathbf{A} \) includes the flows within the economic system (i.e. it describes the technosphere); the vector \( \mathbf{f} \), called *final demand vector* or *external demand vector* (or simply *functional unit vector*), is an exogenously defined set of economic flows whose amount is imposed by the LCA analyst; the solution vector \( \mathbf{s} \) is called *scaling vector* (Heijungs and Suh, 2002).

As illustrated in Figure 1, the inventory vector \( \mathbf{g} \) (i.e. the vector of the environmental flows associated with the reference flow under consideration) can be obtained as \( \mathbf{g} = \mathbf{B} \cdot \mathbf{s} \), where \( \mathbf{B} \) (i.e. *environmental intervention matrix*) includes the resources consumption and pollutant emissions. This computation thus aims at obtaining the scaling factors (i.e. the elements of \( \mathbf{s} \)) that can be used to scale all the unit processes in the system such that their linear combination obtained using those scaling factors exactly produces the desired reference flow (i.e. the functional unit). The vector \( \mathbf{g} \) is commonly
Figure 1. Simplified life cycle inventory scheme in a matrix-based framework.

used afterwards in LCA to calculate impacts, within the so called Life Cycle Impact Assessment (LCIA) step. In this case, the scaled resources included in \( g \) are simply multiplied by corresponding characterization factors that identify a specific category of impact, e.g. metal resource depletion\(^1\).

In the context of this paper, the principles behind the LCA matrix-based formulation are adopted as illustrated in the next section. This method provides several advantages, among which:

- the full transparency of the system;
- the possibility to deal with complex processes’ networks;
- the high comprehensiveness of the life-cycle models, which can be representative of average regional and/or technological conditions;
- the system boundary flexibility, which allows the incorporation of any kind of resource and emission flow within the models of goods and services production.

**Bottom-up based Unit Emergy Values**

The proposed alternative UEVs framework uses a bottom-up perspective, as opposed to the top-down approach currently adopted in the baseline concept (Figure 2). The bottom-up procedure explicitly acknowledges that the three primary sources contribute differently in time, power and space to generate resources, factors neglected when using the baseline but necessarily relevant to estimate the previous environmental work. Moreover, the bottom-up seems to be a more systematic approach than the one presented in Bastianoni et al. (2007), where the authors started from the output and went backwards using ‘partial efficiencies’ (i.e. the amount of an input necessary to obtain a unit product).

In the new framework, UEVs calculation is no longer referred to the baseline (as a sum of sun, tides, and geo-heat Emergencies), but instead the provisions of the three sources are independently quantified among each natural resource storage and flow at a global scale (Figure 2B). For instance, the sunlight required for water evaporation (Hermann, 2006), the tidal energy implied in the productivity of salt marsh ecosystems (Steevera et al., 1976), or the geothermal energy needed for coalification processes (Brown et al., 2011). An effective structure to assign and connect flows (e.g.  

\(^1\)For further details, see European Commission (2010).
the portion of solar radiation that annually feeds the compartment of Net Primary Production, NPP, on land and then to calculate the Emergy associated with average interactions among the resource compartments (e.g. the wood from NPP that is used to produce peat) is provided by the matrix scheme already used in LCI.

As conceptually illustrated in Figure 3a, a square matrix \( \alpha \) (here named resource-sphere) and a rectangular matrix \( \beta \) (here named primary-sphere) are defined. Firstly, the flows of primary energy sources (in MJ/yr), listed in the rows of \( \beta \), are assigned to a given number of ‘natural processes’ listed in the columns of \( \beta \), e.g. \( \approx 2E15 \) MJ\(_{\text{sunlight}}/\text{yr} \) are converted by photosynthesis (Hermann, 2006) to produce \( \approx 6E13 \) kgC/yr of NPP (Field et al., 1998). Then, the same natural processes, now listed in the columns of \( \alpha \), will produce a corresponding number of ‘natural products’, listed in the rows of \( \alpha \). Natural processes and products may be connected differently in \( \alpha \) (e.g. the \( \approx 6E13 \) kgC/yr of NPP can be linked to a production of a given amount of peat as well as of a hardwood resource) to describe the transfer and exchange of the (annual) available energy flows from \( \beta \) to \( \alpha \). Therefore, the primary-sphere in the bottom-up approach corresponds to the biosphere (i.e. Ecoinvent-matrix B) in ecoinvent®, whereas the resource-sphere corresponds to the technosphere (i.e. Ecoinvent-matrix A). In other words, the two matrix systems in Figure 3a and 3b, respectively, become ‘inversely analogous’. Finally, once the two matrices are completed, UEVs of resources (i.e. natural products in \( \alpha \)) can be derived using conventional matrix inversion and scaling techniques, as explained in the previous section, assuming that natural products are the functional units in the ideal ‘life-cycle inventory’ of the geobiosphere.

The main challenge to tackle for the development of the bottom-up approach is the collection of reliable data that could approximate the geobiosphere complexity and the environmental work. The bottom-up based UEVs for non-renewable resources, such as fossil fuels, minerals, metal ores, and groundwater reserves should include the information related to past solar radiation, tidal energy (if not negligible) and geothermal heat available energies that were required to generate them along with the corresponding geological ages of formation. Reliable assumptions on how to average turnover times and to report data on a yearly basis must be defined. The flow of energy that supports ecosystems (mostly solar radiation on yearly basis) should be properly assigned to renewable resources such as biomass (e.g. net amount of solar exergy converted to plant organic matter through photosynthesis), or surface waters according to the solar energy required for the different water cycle processes (Hermann, 2006). In previous studies, Emergy scholars have already re-calculated fossil resource UEVs, e.g. for gas and oil (Bastianoni et al., 2005), using a sort of bottom-up approach. Those new UEVs consider the biogeochemical efficiency of the natural and geological steps of oil formation. To this respect, the solar energy contribution required for photosynthesis of the biomass, which later formed oil and gas resources, is directly taken into account providing a relevant contribution to the final UEV (Bastianoni et al., 2005). Nevertheless, that proposal failed to consider important additional parameters, e.g. the

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*Figure 2. Top-down vs Bottom-up approach; LCI=Life Cycle Inventory (of a good or service).*
Figure 3. (a) Model of bottom-up approach for the alternative calculation of Unit Emergy Values (UEVs) of resources and (b) life cycle products. The entire ‘geo-bio-techno-sphere’ is represented.

contribution of geothermal ‘treatment’ necessary to convert the buried biomass into kerogen to finally obtain oil and gas (Brown et al., 2011).

The bottom-up approach presented here, further illustrated in Rugani and Benetto (2012), could improve the UEV consistency, since all calculations are based on the same principles and on the same model. However, this requires a huge interdisciplinary cooperation between experts from different fields (e.g. geology, natural sciences, hydrology). Furthermore, it is not yet defined which kind of data collection should be pursued, such as the use of average global data and/or specific data representative of an optimal resource-formation condition. The definition of Emergy (for the bottom-up) as based on (embodied) Exergy or Energy is also still debated (Bastianoni et al., 2005; Sciubba and Ulgiati, 2005; Nielsen and Bastianoni, 2007; Sciubba 2010). According to the second law of thermodynamics, Exergy or available energy is lost or consumed in all processes, which makes Exergy the ultimate limiting resource for the functioning of all systems and a promising property for the joint analysis of industrial and ecological systems (Hau and Bakshi, 2005; Szargut, 2005). Several authors argue that geobiosphere processes are driven by constant Exergy flows that are destroyed when resources are extracted and used (Wall and Gong, 2001; Chen, 2005; Szargut, 2005; Dewulf et al., 2007). Solar radiation and, to a lesser extent, geothermal and tidal exergies are the three independent fluxes of Exergy that are destroyed in or on the Earth along with the various natural transformation processes, such as atmospheric absorption, photosynthesis, evaporation, carbon burial, and others (Hermann, 2006). The Exergy derived from these sources is thus ‘embodied’ in each resource as available energy that can be extracted once the resource is exploited (Dewulf et al., 2007). It is assumed that if the formation time of the resource were included and multiplied by the ‘embodied Exergy content’ of the corresponding unit of resource, then the total ‘memorized’ (i.e. embodied) Exergy of each resource could be accounted for. The ‘bottom-up’ procedure avoids partitioning of the Emergy baseline as well as accounting for the Emergy actually labeled to sustain the processes, i.e. without the exported fraction. This can improve the estimation of individual contributions of sun, tides and geo-heat energies along with the natural processes that produce flows and stocks of resources. Thermodynamic transformations of energy can also be incorporated as biogeochemical processes that provide natural products, as demonstrated in Bastianoni et al. (2005). Therefore, the bottom-up framework can provide a measure of the actual environmental work spent to make available resources at a higher quality than...
the primary solar, tidal, and geothermal heat exergies, as stated by the Emergy theory. Should the complexity of natural cycles and loops within the network processes become excessive for a satisfactory degree of accuracy of UEVs calculation, a solution would be then to aggregate subsystems and attribute to each of them an average or cumulative transformity. As a result, however, UEVs would be no more scalars expressed in seJ/unit but instead vectors that would include the memory of the amounts of Exergy provided by the three independent sources (sun, tides and geo-heat) to the complex network of processes from which the unit of resource (e.g. 1 kg of soil formed,…) is directly and indirectly generated.

Outlook

By using the bottom-up approach, the connection between Emergy and LCA methods becomes clear. According to the principles of LCA, a large number of elementary flows of resources (fossil fuels, minerals, metals, land and water resources, renewable and biomass energy resources, etc.) are included in the LCI models, such as ecoinvent®. As described before, once an LCA case study is built, by inverting and scaling the technological matrix A (see Figure 1 and Figure 3b) the user can obtain the amount and type of resources related to the functional unit. Then, an environmental impact can be calculated for the functional unit by multiplying those resource values by the specific characterization factors of the selected impact category method (e.g. resource depletion indicators, scarcity indicators, etc.).

In this connection, the set of resources’ UEV of can be proposed as the characterization factors for an Emergy calculation in LCA. In the matrix system of Figure 3a, the set of resources in α should be at least the same (in number and typology) as the set considered in B (Figure 3b), which represents the inventory matrix of a LCI model (e.g. built using ecoinvent® as the background database). Such a linked framework can provide indeed a consistent calculation of the primary energy fluxes throughout the formation of resources that are finally used to drive the technological processes, i.e. a ‘cradle to grave’ perspective of the entire techno-geobiosphere. Moreover, the Emergy allocation rules (see Brown and Herendeen, 1996) and a number of further ecosystem services (many are still currently missing within the system boundaries of LCA; see Zhang et al., 2010) should be included within the geobiosphere network to enrich the bottom-up model and the assessment of resources in LCA. In other words, by first calculating UEVs of resources and then applying (automatically) these values as characterization factors in the LCI model, the user should be able to quantify the final Emergy value of the functional unit in the LCA case study (Figure 2).

CONCLUSIONS

This paper aimed at introducing an alternative framework to calculate UEVs of natural resources in order to overcome some of the shortcomings that characterize the traditional environmental accounting based on Emergy. Accordingly, this framework is based on a bottom-up matrix-based formulation that contrasts to the conventional top-down approach underlined by the baseline, which represents a relevant source of inaccuracy for the quality of the UEVs.

The main advantages of calculating UEVs with a bottom-up perspective are represented by:

a) the compliance with the Emergy concept and algebra: by including all the ‘available energy’ or Exergy data in a matrix-based structure analogous to that built for life cycle inventory models, it is possible to apply the algebra rules of Emergy calculation in automatic and rigorous conditions, following a method recently developed by Marvuglia et al. (2013) (also illustrated by Rugani et al. within this volume);

b) the unique feature of including all the ecosystem goods and services within the same network, where everything is (more or less) connected directly and indirectly to everything else; this may enable in the future creating a broad library of consistent UEVs of resource;

c) as a consequence of the previous points, the absence of constraints to avoid double-counting: contrasting with the use of the baseline, where the analyst must carefully detect possible double-
counting of flows coming from the same source (e.g. rain and wind), these problems disappear by applying the bottom-up perspective. Indeed, the algebra rules for counting flows within the geobiosphere network matrix can be implemented automatically upstream (not by the user; see Marvuglia et al., 2013). As a result, the UEVs may be independently quantified and may already embody (as a memory) the contribution of the rest of the natural products and processes without overburdens;

d) the possibility to update, modify, monitor, calculate uncertainty and treat data in a transparent and comprehensive way, which has been eventually one of the most critical aspects in the Emergy methodology.

Despite these advantages, the method presented here has some drawbacks and is still facing challenging issues. First, the bottom-up framework is at its early stage of development: neither a comprehensive set of data nor a case study has been yet provided to demonstrate its feasibility for future uses by Emergy analysts. Conducting a case study, in particular, will be necessary to validate the model, but this is also a highly time-consuming task, because (at least a proxy of) the geobiosphere dataset must be built for the background analysis (i.e. construction of α and β matrices), whereas the authors have only recently started collecting data. Second, similarly to the conventional top-down approach, the bottom-up model has a static form (i.e. steady-state conditions), while the geobiosphere is inherently a complex and dynamic set of non-linear systems; it has also global boundaries, while the main interest would be to focus on regionalized Emergy values. Finally, it remains an open question how and whether the three primary Exergy sources (i.e. of sun, tides, geo-heat) accounted for within each UEV’s vector should be converted in one equivalence metric, such as the conventional seJ.

This having been said, it is clear that until the work aimed at improving the bottom-up model will have reached a full consensus, we stay behind the use of the conventional top-down approach, recommending the use of the baseline.

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REFERENCES

Campbell, D.E., 2000. A revised solar transformity for tidal energy received by the earth and dissipated globally: implications for Emergy Analysis. In: Emergy Synthesis 1; Brown, M.T. (Ed.); Centre for Environmental Policy, University of Florida, Gainesville, USA.


