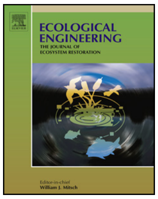
Ecological Engineering 60 (2013) 172–182

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng



Emergy evaluation of water treatment processes

Damien Arbault[a,b], Benedetto Rugani[a], Ligia Tiruta-Barna[b,*], Enrico Benetto[a]

[a] Public Research Centre Henri Tudor (CRPHT)/Resource Centre for Environmental Technologies (CRTE), 6A, avenue des Hauts-Fourneaux, L-4362 Esch-sur-Alzette, Luxembourg
[b] Université de Toulouse INSA, UPS, INP, LISBP, INRA UMR792, CNRS UMR5504, 135 av. de Rangueil, 31077 Toulouse, France

ARTICLE INFO

Article history:
Received 16 February 2013
Received in revised form 21 June 2013
Accepted 6 July 2013

Keywords:
Ecological performance
Emergy evaluation
Life cycle assessment (LCA)
Unit emergy value (UEV)
Water treatment

ABSTRACT

The emergy evaluation (EmE) method is acknowledged to be a holistic approach to account for the primary (solar) energy that generates the renewable and non-renewable resource flows used up by human activities. This paper examines its application and robustness, using four water treatment plants (WTPs) as case studies. We obtained an average unit emergy value for potable water of 1.06 (±0.15) E12 sej/m^3, which is in accordance with existing literature. Chemicals and electricity were the most important man-made inputs; infrastructure, when accounted for, had a significant but lesser contribution. The application of several emergy-based indicators allowed comparing the ecological performance of water production with other types of resource extraction. These indices showed that WTPs are rather blind to economic markets and they exerted a low pressure on local non-renewable resources. A critical analysis of current EmE procedure highlighted the relative low accuracy of the method compared to Life-Cycle Assessment (LCA), when man-made inputs are predominant, as well as the complementary goals and scopes of the two methods. Methodological improvements in the classification and treatment of the emergy associated with man-made inputs are necessary to make EmE indicators more straightforward and robust.

1. Introduction

Society as a whole is far from relying on natural resources in a sustainable way. Individuals and businesses must share the collective effort to reduce the pressure on resources. Appropriate tools and indicators are therefore needed to assess that pressure and provide decision-makers with an estimate of the distance-to-target between the current condition of stress and a more sustainable relationship with the natural environment (Moldan et al., 2012).

Among the available environmental assessment tools, emergy evaluation (EmE) is a resource-oriented method that compares all resources on the basis of the solar-driven natural processes that contributed to their formation (Odum, 1996). The EmE associated with an activity or a territory embraces a holistic picture of the studied human system embedded within a surrounding natural and economic environment and the global Earth system. It highlights the need for an activity to adjust to the local and global ecosystems that support it, instead of focusing on the local and relative efficiency of technological processes.

The cumulative direct and indirect solar energy used up by natural systems to form a resource contributes to its emergy value, expressed in solar emjoules (sej; i.e. equivalents of solar energy). The Transformity of a resource is the ratio of emergy value to its available energy content (or exergy), expressed in sej/J. Specific emergy of a resource or a product is defined as its emergy value per unit mass (sej/g), while the more general term unit emergy value (UEV) is typically used when the denominator involves also other relevant physical units (e.g. volume). Average UEVs have been estimated for a wide variety of natural resources, including fossil fuels, mineral ores and renewable resources (Brown and Bardi, 2001; Odum, 1996, 2000; Odum et al., 2000).

The emergy value associated with a natural resource accounts for the direct and indirect goods and services provided by the geobiosphere only. Concerning man-made products, each transformation step in their life cycle requires additional inputs, which are either natural resources already transformed by upstream human activities, or direct human interventions through labor and services (L&S). L&S are also fueled by extracted and imported natural (renewable and non-renewable) resources. Accordingly, EmE enables accounting for the various forms of energy, materials and services ultimately consumed by a human activity with the sej unit. To assist decision-making, emergy-based indicators (Brown and Ulgiati, 1997; Odum, 1996; Ridolfi and Bastianoni, 2008; Ulgiati and Brown, 1998) aggregate EmE results into metrics that aim at describing the integration of the production system within its surrounding human and natural environment (section 2.2).

---

[*] Corresponding author. Tel.: +33 (0)5 61 55 97 88; fax: +33 (0)5 61 55 97 60.
E-mail address: ligia.barna@insa-toulouse.fr (L. Tiruta-Barna).

0925-8574/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ecoleng.2013.07.046

EmE has been applied during the last 30 years to coupled natural-human systems of various types and sizes. The emergy evaluation of nations (e.g. Brown and McClanahan, 1996; Chen and Chen, 2006; Pereira and Ortega, 2012; Siche et al., 2008), states, provinces (e.g. Liu et al., 2008; Pulselli et al., 2008; Zhao et al., 2005) and regions (e.g. Campbell and Garmestani, 2012) inform us on the local natural (and imported) resources used up to fuel these economies. Also, EmE has been applied to analyze the production of various commodities, e.g. in agriculture and farming (Castellini et al., 2006; La Rosa et al., 2008; Lefroy and Rydberg, 2003; Liu et al., 2008; Lu et al., 2009; Ortega et al., 2002; Zhang et al., 2012), forestry (Tilley and Swank, 2003), aquaculture (Lima et al., 2012), energy production (Baral and Bakshi, 2010; Brown and Ulgiati, 2002; Brown et al., 2012; Ciotola et al., 2011; Lapp, 1991; Paoli et al., 2008; Yang et al., 2010), building materials (Brown and Buranakarn, 2003; Buranakarn, 1998; Meillaud et al., 2005; Pulselli et al., 2007), recycling in industry (Giannetti et al., 2013; Mu et al., 2012, 2011), ecological conservation or restoration (Dang and Liu, 2012; Dong et al., 2012; Lu et al., 2007, 2011). EmE results for these analyses (i.e. emergy-based indicators, UEVs and transformities of the products) have been used as benchmarks to assess the ecological performance of water treatment.

The focus of this paper is on the production of potable water. Few past studies refer specifically to potable water production plants (e.g. Odum et al., 1987). The first most comprehensive survey is given by Buenfil (2001), who compared different household technologies with tap water from several municipal treatment plants in Florida. Then, Pulselli et al. (2011a) tracked the UEV of freshwater along a water course, from raw resource to water on tap, and Rugani et al. (2011a) compared ancient and modern aqueduct systems in the city of Siena, Italy. A common conclusion of those studies is that man-made inputs at the factory level make a large contribution to the final UEV of tap water. Case studies on contemporary potable water production plants (Buenfil, 2001; Pulselli et al., 2011a) provide ranges of 6.9 E5–6.9 E6 sej/g, and 1.4 E5–1.4 E6 sej/J (adjusted to the 9.44 baseline, as explained in Section 2.4). Potable water is thus a man-made product with a high transformity relative to its specific emergy. Such particularity is due to the low exergy content of water, compared to the other types of man-made goods.

Water Treatment Plants (WTPs) rely on a single local, renewable resource (freshwater), and a diverse set of man-made products and services. Local, non-renewable resources used up are apparently negligible (Rugani et al., 2011a). Such a situation can also be found in various other commodities, such as wind and solar electricity production, and organic farming (see, e.g. Brown et al., 2012; Ciotola et al., 2011; Lu et al., 2009). Therefore, it seems critical to estimate the UEV of raw freshwater consistently. The water cycle (and the use of water in human activities) has been widely studied in EmE: it shapes landscapes and ecosystems, which can be used for many different activities. Freshwater-related EmEs cover a very large spectrum of situations, including dam proposals (Brown and McClanahan, 1996; Kang and Park, 2002), the overview of the Cache river basin (Odum et al., 1998) and water treatment via natural or artificial wetlands (Carey et al., 2011; Cohen and Brown, 2007; Duan et al., 2011; Martin, 2002) reflecting different aims. The most common objective of EmEs related to freshwater is to value this natural asset, i.e. its contribution to a regional or national public welfare (Chen and Chen, 2009; Chen et al., 2009; Lv and Wu, 2009; Tilley and Brown, 2006), its relationship with land occupation (Huang et al., 2007) and ecosystem services (Huang et al., 2011; Odum and Odum, 2000; Watanabe and Ortega, 2011). EmE of the global water cycle was the subject of several studies (e.g. Buenfil, 2001; Campbell, 2003; Campbell et al., 2013; Watanabe and Ortega, 2011). EmE was also proposed for a method to assess the full cost recovery of water management in a watershed (Brown et al., 2010).

The aim of this study was to compare the outcomes of EmE associated with four WTPs located in France, in particular focusing on the UEV of the potable water produced (considering the actual quality level) and on a selection of emergy-based indicators. A particular emphasis was given to man-made inputs that are necessary to run the plant, and the computation of their emergy value. The importance of infrastructure to the overall performance of the WTPs is also investigated. Additionally, results of EmE are compared to Life Cycle Assessment (LCA) results for the same plants (Igos et al., 2013a, 2013b), in order to highlight differences and complementarities of both environmental assessment methods. The final goal of the paper was to provide new UEVs of drinking water quantified in a consistent manner along with a critical analysis of the EmE application, highlighting weak points of the method and including recommendations on how to deal with them.

2. Methodology and data collection

2.1. Energy system diagram

According to the EmE methodology (Odum, 1996), an energy systems diagram of the WTPs is presented in Fig. 1. The left-hand side of the diagram shows the contribution of the surrounding environment in delivering the freshwater from a river. Geothermal heat runs geological processes that shape the landscape. Rainwater collected within the watershed is stored in soil moisture and then either evaporates or converges into streams and rivers.

On the right-hand side, man-made inputs (fuels, electricity, chemicals, infrastructure materials and L&S) are used in the WTP to transform the freshwater into a product (potable water) valuable for humans. The distribution system was excluded from the system boundary, because specific data were not available, the scope of the analysis being the potable water production at the plant.

Man-made inputs are the ‘feedback’ (F) from the larger economy (i.e. purchased resources and human services), while raw freshwater is the only local, renewable input (R). Local, non-renewable resources (N) were not used up in the potable water production systems investigated. Moreover, one could argue that land occupation of the site by the plant may hamper soil regeneration and could be counted as an N input. However, this was considered negligible in most of the studies presenting a similar situation (see the Supplementary Information material, hereafter SI, Table S8). In the present case studies, preliminary calculations showed that this emergy contribution was much smaller than any other input (SI, section S3), and therefore it was disregarded.

The emergy value associated with each input was calculated by weighting its quantity (in physical units) with the corresponding UEV. When several R flows are feeding the system, only the input with the highest emergy value should be counted to avoid double-counting (Odum, 1996) in the case they are all co-products of the same generating processes and are supporting local, natural processes. Only the highest contributor to R can thus be summed with all other (N and F) inputs (which are not co-products of any local process). By definition, the emergy associated with the process outputs is Y (Brown and Ulgiati, 2002; Odum, 1996). When inputs are not co-products, Y is equal to the total emergy value of inputs.