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Emergy evaluation using the calculation software SCALE: Case study, added value and potential improvements

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HIGHLIGHTS

• Three emergy-based methods are applied to four potable water production plants.
• SCALE applies the emergy algebra on life cycle inventory datasets.
• SCALE provides more comprehensive and accurate information about man-made inputs.
• However, its results do not yet include human labor and ecosystem services.
• SCALE can be effectively used for emergy evaluation of human activities.

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ABSTRACT

This paper reports the emergy-based evaluation (EME) of the ecological performance of four water treatment plants (WTPs) using three different approaches. The results obtained using the emergy calculation software SCALE (EME_{SCALE}) are compared with those achieved through a conventional emergy evaluation procedure (EME_{CONV}), as well as through the application of the Solar Energy Demand (SED) method. SCALE's results are based on a detailed representation of the chain of technological processes provided by the lifecycle inventory database ecoinvent®. They benefit from a higher level of details in the description of the technological network as compared to the ones calculated with a conventional EME and, unlike the SED results, are computed according to the emergy algebra rules. The analysis delves into the quantitative comparison of unit emergy values (UEVs) for individual technospheric inputs provided by each method, demonstrating the added value of SCALE to enhance reproducibility, accurateness and completeness of an EME. However, SCALE cannot presently include non-technospheric inputs in emergy accounting, like e.g. human labor and ecosystem services. Moreover, SCALE is limited by the approach used to build the dataset of UEVs for natural resources. Recommendations on the scope and accuracy of SCALE-based emergy accounting are suggested for further steps in software development, as well as preliminary quantitative methods to account for ecosystem services and human labor.

1. Introduction

Emergy evaluation (EME), unlike most of the other environmental assessment tools, adopts a nature-centered viewpoint, focusing on the resources used up by a human system (an activity, a territory) and considering it as embedded within its natural environment. Emergy is defined as the *direct and indirect energy of one kind to produce a product, resource or service* (Odum, 1996) and measured in solar emergy Joules (solar emjoule or sej). Since the concept originates from systems ecology, the EME of a human activity emphasizes more on calculating the emergy value of locally-available natural resources. Given the complexity of their production chain, the characterization in emergy terms of man-made resources produced elsewhere and used up by the activity (e.g. human labor and commodities) suffers from a low level of accuracy. Despite the valuable paradigm shift emergy brings about, further efforts are needed to make it a more popular tool for environmental sustainability (Cleveland et al., 2000; Hau and Bakshi, 2004; Månsson and McGlade, 1993).

In contrast, other approaches such as Life Cycle Assessment (LCA) (European Commission, 2010; ISO, 2006) have a user-oriented or utilitarian perspective and evaluate the environmental consequences of materials and energy flows taken from and emitted to the natural environment by human activities. For example, the impact on resources

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with the Life Cycle Impact Assessment (LCIA) method ReCiPe (Goedkoop et al., 2009) is based on the notion of functional utility of the resource for the user and its rate of depletion; other methods such as CExD (Bösch et al., 2007) and CEENE (Dewulf et al., 2007) assess the thermodynamic equivalent of the maximum work that is possible to extract from the resource, i.e. its exergy. These human-centered approaches, although consistent with the underlying rationale of a lifecycle perspective, could not be successfully applied to renewable resources and many Ecosystem Services (ES), which, by definition, are not stock-limited (i.e. they do not 'get depleted') but are flow-limited (i.e. are regenerated at a limited pace).

EME takes a donor-side approach oriented to consider the natural mechanisms that form the resources. Hence, it is complementary to LCIA methods and somehow advantageous in providing an overall characterization of renewable resources as well as non-renewable ones and ES. EME shares many similarities with the broader LCA framework: it has been demonstrated that the two approaches are complementary and can be combined (Brown et al., 2012; Ingwersen, 2011; Raugei et al., 2014; Rugani and Benetto, 2012; Rugani et al., 2012a; Zhang et al., 2010b). By integrating emergy within LCA (Ingwersen, 2011; Raugei et al., 2014; Rugani, 2010), it was shown that emergy could provide a complementary indicator for resources, as '*a unified measure of the provision of environmental support, and an indication of the work of the environment that would be needed to replace what is consumed*' (Raugei et al., 2014).

EME could also benefit from the detailed description of the network of industrial and agricultural processes and the exchanges of energy and materials among them (the so-called technosphere) that LCA practitioners use to build the Life Cycle Inventory (LCI) of the functional unit under study. The LCI represents the cumulated amount of elementary flows (resources and emissions) exchanged between the technosphere and the natural environment. An important step toward the combination of the LCI database ecoinvent® (Ecoinvent, 2010) and EME was carried out throughout the development of the Solar Energy Demand (SED) method (Rugani et al., 2011). In SED, the Solar Energy Factors (SEFs) of natural resources, derived from the emergy concept, are applied as characterization factors to LCI results.

The main challenge for integrating LCA into EME is, however, rooted in the specific features underlying the emergy algebra, which hamper the direct use of LCI databases. While LCA adopts allocation rules among co-products of a multi-output process following a logic of *conservation* (of mass, energy, etc., where the environmental burden is shared among the co-products), emergy algebra relies on a logic of *memorization* (Rugani et al., 2012a), as described by four algebra rules (Brown and Herendeen, 1996). Two of them are particularly relevant for the discussion in this paper: rule #2 (co-products from a multi-output process have the total emergy assigned to each pathway) and rule #4 (emergy cannot be counted twice within a system: emergy in feedback loops cannot be double-counted, and co-products, when reunited, cannot be added to equal a sum greater than the emergy source from which they were derived). Marvuglia et al. (2013a, 2013b) developed an algorithm to apply the four rules of emergy algebra to large networks of interconnected processes, which was implemented in the software SCALE using the ecoinvent® database and the SEF dataset (Rugani et al., 2011). SCALE is therefore the first tool using an LCI database for automatic emergy calculation in compliance with the emergy algebra rules.

The aim of this paper is to present the first fully comparative case study performed with SCALE, in which we analyze the results obtained through: i) 'conventional' EME (hereafter EME_{CONV}), meaning the application of the emergy accounting framework as usually performed in the literature (see e.g. Bastianoni et al., 2009; Brown and Ulgiati, 2002; Cavalett et al., 2006; Pulselli et al., 2008; Vassallo et al., 2007); ii) the SED method (Rugani et al., 2011), using the ecoinvent® database but not fulfilling the algebra rules and iii) SCALE (EME_{SCALE}), where both the ecoinvent® database and the algebra rules are included. Four water treatment plants (WTPs) are considered as test bed cases for the comparison. The three methods are described and compared from a conceptual point of view in Section 2.1. The case studies and their system boundaries are presented in Section 2.2. A quantitative comparison of the results (Section 3.1) is followed by the analysis of the contribution of each technospheric input according to the three methods (Sections 3.2 and 3.3) and of the differences in interpretation (Section 3.4). Some limitations remaining in using SCALE are finally discussed in Section 3.5.

2. Materials and methods

The three methods share a common framework (Fig. 1): the man-made products and natural resources inputs to the studied system are inventoried and then converted into emergy per unit output (sej/m^3 potable water), using unit emergy values (UEVs, defined as the emergy value of a product or resource per unit of a corresponding physical quantity e.g. mass, energy, volume) and SED or SEF of products or resources, respectively. The resulting figure is the UEV or SED of the system's output. However, the conceptual differences between the methods (Section 2.1) involve alternative calculation of UEVs and SED for each input.

2.1. Methodological principles

EME_{CONV} has recently been applied to the case studies used in this paper (Arbault et al., 2013a). When applied to a local activity, EME_{CONV} calculates the unit emergy value (UEV_{CONV}) of the output by accounting for all resources needed by the activity to be operational. These resources are natural, locally available (R and N, for renewables and non-renewables, respectively), or man-made (so-called 'feedback inputs', F). F inputs include materials and energy transformed into useful goods within the technosphere, and non-material services and labor. The underlying philosophy of the emergy approach is to assess the role of natural resources in supporting human systems (activities, economies, territories). Therefore, EME_{CONV} gives a particular importance on depicting natural mechanisms responsible for the formation of R and N resources. Oppositely, the usual practice is to use simplified representations of the F inputs, for instance by attributing them the UEV of the corresponding natural resource (e.g. the UEV of limestone for lime product). When their contribution is assumed to be important, the transformation steps are roughly estimated (e.g. production of an electricity mix: Brown and Ulgiati, 2002; soda and chlorine production: Campbell and Ohrt, 2009). In contrast, labor and services are usually estimated using the national average of the emergy value of one working-hour or one monetary unit (Odum, 1996).

The SED method (Rugani, 2010; Rugani et al., 2011) uses the rationale underlying the ecoinvent® database, which consists in calculating the cumulated amount of each resource (in the corresponding physical unit), ultimately consumed in the technosphere to provide the studied functional unit. The set of SEFs is then used to convert each amount of

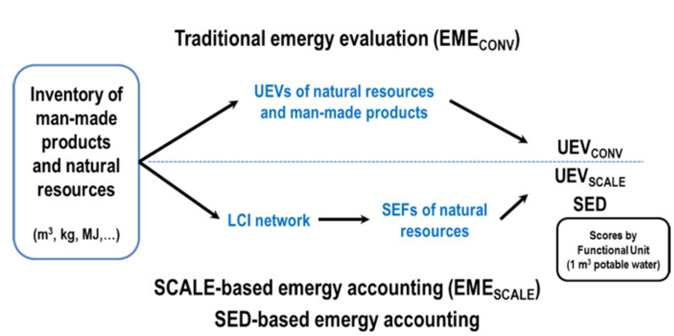

Fig. 1. General framework for the application of EME_{CONV}, EME_{SCALE} and SED.

resource into a solar-energy equivalent. The development of this method was a remarkable attempt toward matching the set of 200+ elementary resources listed in ecoinvent® and their solar-energy equivalents. However, the method cannot be considered as a rigorous application of the emergy concept: SED applies allocation rules typically used in LCA, which are not compatible with the specific emergy algebra. It can be thus considered as an effort toward integrating an emergy-like indicator into LCA, rather than embedding LCI datasets into emergy evaluation.

EME_{SCALE} also uses the detailed representation of the technosphere provided by ecoinvent® (in principle, other LCI databases could also be used), and the SEF dataset as UEVs of natural resources. However, as opposed to the SED method, it calculates the emergy of the system's output by rigorously applying the emergy algebra to the detailed network of technological processes. The software SCALE requires a preliminary modification of allocation values originally set in the ecoinvent® multi-output processes (see supporting information of Marvuglia et al., 2013a, for details). Then it applies a backtracking algorithm to trace flows of energy and materials within the modified network and to avoid double-counting.

According to the rules of emergy algebra, the output emergy value is lower than (or equal to) the total emergy value of inputs, provided that the exact set of inventory data and SEFs is used. The difference depends on the number of feedback loops in the network of processes. An important consequence is that the level of details in the representation of processes influences the resulting emergy value of outputs (Tiruta-Barna and Benetto, 2013). To avoid infinite calculation time, a threshold (named *minflow*) on the value of the flow tracked by SCALE must be set by the user (hereafter called Minflow). A high threshold value (e.g. 0.1 Msej) would lead to the omission of important feedback loops, while a low threshold value (say lower than 1E−6 Msej) would increase computation time drastically with a negligible loss of information (named *emergy lost* in Marvuglia et al., 2013a). Supplementary information SI1 discusses the influence of threshold value selection.

The conceptual differences between EME_{CONV}, EME_{SCALE} and SED are translated into different mathematical assumptions that support the calculation steps. In EME_{SCALE}, all resources used up by a multi-output process of the technosphere (e.g. salted water electrolysis, crop cultivation) are allocated to all co-products; in other terms, each co-product is considered to require the full use of all incoming resources. Consequently, specific algebra rules are necessary to avoid double counting in feedback loops included in the considered network of interconnected processes. The differences between EME_{CONV} and EME_{SCALE} lie in the accuracy for calculating technospheric inputs and the scope of the resources considered. In EME_{CONV}, all forms of resources shall be taken into account: F inputs also include non-material, man-made resources such as labor and services or information. The point of the traditional accounting technique is to provide a holistic but rather simplified description of the functioning of a system and the external drivers feeding it. Therefore, it has a limited accuracy and often scarce reproducibility. In SED, the rationale for co-products differs: the resources consumed by the multi-output process are allocated among the co-products on the basis of their material or energy content. SED adopts a user-side viewpoint (the same as in LCA), in which the environmental burden is shared among all users of co-products.

2.2. Description of the case studies

The characteristics of the four WTPs investigated in this paper are comprehensively described in Igos et al. (2013) (Sites 1 and 2) and Igos et al. (in press) (Sites A and B). Sites 1 and 2 are located in the Paris area and the raw water input comes from the Seine River. Sites A and B are new plants located in Brittany, using raw water from local streams. It is worth mentioning that water streams in Brittany are more polluted than the Seine River, and require a heavier treatment process, which explains why the UEV of output potable water from Sites A and B is higher than the UEV of potable water produced in Sites 1 and 2 (Arbault et al., 2013a).

The data used for the present study focus on the UEVs of inputs from technosphere, i.e. energy, chemicals and services. Each piece of data presented below is the input required for the production of 1 m^3 of potable water and is extensively discussed in Arbault et al. (2013a). Technospheric inputs were modeled with products available in the ecoinvent® v2.2 database. Since there is no feedback loop or co-production in the WTPs, they can be considered as a single process in the calculations without violating the emergy algebra. All the calculations were done using the 9.26 E24 sej/yr baseline (Campbell, 2001), which represents the sum of annual independent emergy inputs to the geobiosphere from solar radiation, tidal energy and geothermal heat (Odum, 1996).

3. Results and discussion

3.1. Quantitative comparison

Table 1 compares the contribution of technospheric inputs in sej for EME_{CONV}, EME_{SCALE} and SED for the four case studies investigated. EME_{SCALE} results were calculated with a *minflow* equal to 1E−6 Msej. In our case studies EME_{SCALE} provides higher results than EME_{CONV} because the UEVs of technospheric inputs used in both methods are different (see Section 3.2).

The three methods provide slightly different rankings of UEVs among the case studies. For Sites 1 and 2, the UEVs are systematically lower than for the other sites, but EME_{CONV} shows lower emergy value of technospheric inputs for Site 2 than for Site 1, while the two other methods yield the inverse ranking. Nevertheless, the order of magnitude is comparable for the three methods. In particular, the SED method provides results 20–30% lower than EME_{SCALE}, while EME_{CONV} delivers results 40–60% lower than EME_{SCALE}. Site 1 is an exception, for which EME_{CONV} is higher than SED and only 13% lower than EME_{SCALE}. Interestingly, Site 1 has a higher consumption of electricity than the other sites and a lower consumption of chemicals (see Arbault et al., 2013a).

Results of SED are useful for comparative purposes, although they do not have the same meaning as the emergy value of technospheric inputs (see Section 2.1). As SCALE also uses SEFs, comparing results from EME_{SCALE} and SED helps investigating the influence of emergy algebra vs. LCA-like allocation on the results. To this aim, the contribution of each individual technospheric input within the four case studies is analyzed in the following section.

3.2. Contribution analysis

Contribution analysis investigates the relative importance, in sej, of each technospheric input (among purchased energy, chemical reagents and external services such as waste disposal and product transportation) to the system's output (1 m^3 of potable water). Fig. 2 shows that the three methods provide comparable results for electricity, which is the major input (in emergy terms) to Site 1.

Table 1
Comparison of the unit emergy value (i.e. total emergy of technospheric inputs by functional unit – 1 m^3 potable water – excluding direct and indirect labor and freshwater resource) calculated for the 4 case studies of water treatment plants using EME_{CONV}, EME_{SCALE} and SED (baseline: 9.26 E24 sej/yr; Campbell, 2001).

Technospheric inputs (E12 sej/m^3)	Site 1	Site 2	Site A	Site B
EME_{CONV}	0.37	0.29	0.51	0.56
EME_{SCALE}	0.43	0.47	1.25	1.14
SED	0.31	0.32	0.92	0.92

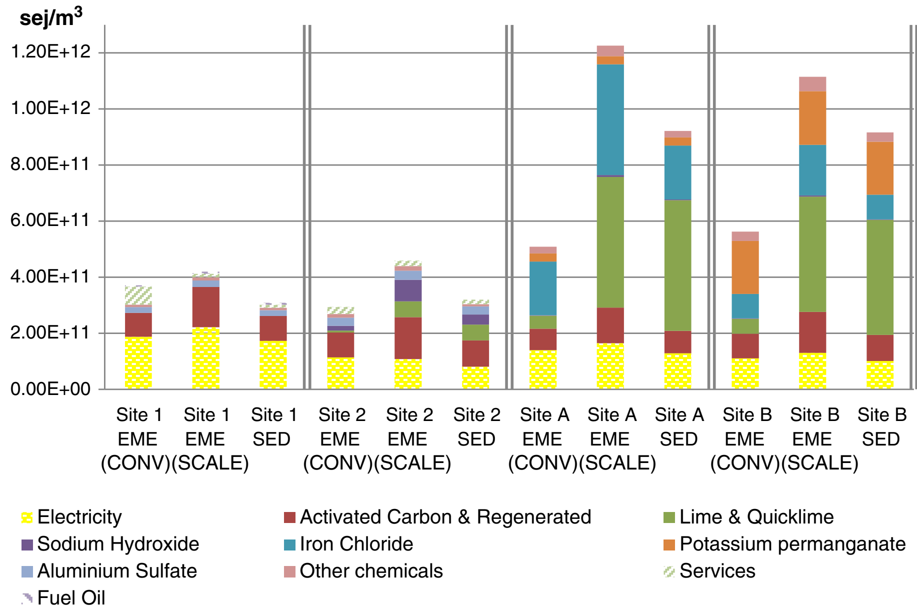

Fig. 2. Contribution of technospheric inputs across the 4 case studies by analyzing the three emergy-based methods.

The main chemical products (in sej/m^3) used by the plants are activated carbon, lime, sodium hydroxide, iron chloride, potassium permanganate and aluminum sulfate. However, the emergy value of their contribution varies across the methods employed. Fig. 3 compares the ratio UEV_{SCALE}/UEV_{CONV} of the products for which an UEV_{CONV} was found in literature (see SI2).

Lime and quicklime have a much higher UEV with SCALE. This has a major influence on the diverging results presented in Table 1 and Fig. 2, in particular with regard to Sites A and B. This can be (only partly) explained by the UEV of the main natural resources used for each compound to calculate the UEV_{CONV} and its SEF (used to calculate its UEV_{SCALE}): UEV_{CONV} of limestone is 9.81 E11 sej/kg (Campbell and Ohrt, 2009), while the SEF of calcite is 5.5 E12 sej/kg, i.e. 5.6 times higher (Rugani et al., 2011). Both data, however, were retrieved from two different documents of the same author (respectively: Odum, 1996 and Odum, 2000); this highlights the need for a single and consistent dataset of natural resources' UEV. The relative differences between the UEV_{SCALE} and UEV_{CONV} of lime and quicklime, and sodium

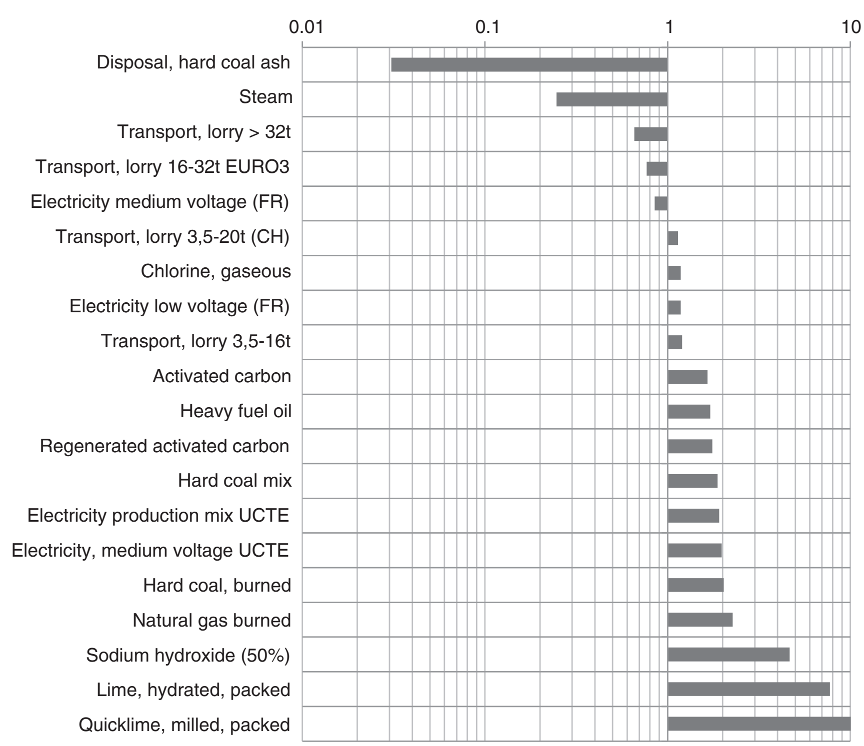

Fig. 3. Ratio UEV_{SCALE}/UEV_{CONV} (unitless) for selected technospheric inputs (log scale).

hydroxide, also explain why EME_{CONV} provides a lower emergy value of technospheric inputs for Site 1 than for Site 2, while EME_{SCALE} provides opposite results.

Disposal of hard coal ash (which simulates the destruction of exhausted activated carbon) and steam (used in the production and regeneration of activated carbon) has a much lower UEV with SCALE. Since the service 'disposal, hard coal ash' is used only in Site 1 (see Arbault et al., 2013a), and its UEV_{CONV} is much larger than its UEV_{SCALE} and SED (see Fig. 3 and Table S1), the resulting contribution of 'Services' is more important for Site 1 evaluated with EME_{CONV} than with the other methods, in contrast to the other sites (see Fig. 2). To a lesser extent, SCALE provides higher UEVs for sodium hydroxide, electricity from the European grid (UCTE), natural gas, coal, and activated carbon. UEV_{SCALE} and UEV_{CONV} present less significant differences for the other products. UEV_{CONV} of coal and natural gas is rather close to their SEF: concerning coal, $UEV_{CONV} = 1.15$ E12 sej/kg (Odum, 1996, assuming 29.3 E6 J/kg coal) and SEF = 1.42 E12 sej/kg (Rugani et al., 2011); for natural gas, $UEV_{CONV} = 4.35$ E10 sej/MJ (Bastianoni et al., 2005) and SEF = 3.67 E10 sej/MJ (Rugani et al., 2011, assuming 40 MJ/m^3). The UEV_{CONV} of mineral NaCl is equal to its SEF (9.81 E11 sej/kg, Odum, 1996).

Rather than discussing which value is most adequate to use as SEF for these resources, the focus here is on analyzing the differences in the results provided by the three methods. In the aforementioned cases, the differences concerning coal, gas and sodium hydroxide can be only explained by the additional technospheric inputs used up to transform the primary resource into a refined material, which are accounted for in the UEV_{SCALE}, but not in the UEV_{CONV}.

The quantitative comparison of UEVs retrieved from literature and those computed using SCALE can only partly explain the differences in the results of EME_{SCALE} and EME_{CONV} showed in Table 1. The remaining difference involves technospheric inputs for which $UEVs_{CONV}$ were not available in literature and were thus assimilated to their SED (see Table S1). SEDs and $UEVs_{SCALE}$ are based on exactly the same network data upstream: their difference is only due to the application of respectively LCA-like allocation factors and algebra rules for UEV calculation. Fig. 4 shows the relative changes when applying the two algebra approaches (of *conservation* in SED and of *memorization* in SCALE): the circle markers show the virtual UEV of each input, when rule #2 of emergy algebra is applied but not rule #4. These values have no physical meaning, they are assigned a value of 100% in order to investigate separately the influence of the additional application of rule #4 (square markers) to provide the final $UEVs_{SCALE}$. Triangle markers represent the relative difference due to the application of LCA-like allocation instead of rule #2, leading to SED. The comparison between the data points marked with circles and those marked with triangles indicates the influence of the allocation rule #2, all other aspects being equal.

Fig. 4 shows that SEDs are systematically lower than UEV_{SCALE}: the use of LCA-like allocation criteria in SED thus provides a significant underestimation of the real emergy value of man-made products. Chemicals derived from sodium chloride (sodium hypochlorite, iron chloride, sodium hydroxide, hydrochloric acid, chlorine) present some of the highest differences between SED and UEV_{SCALE}, which explain the variations observed in Fig. 2. This means that the allocation rule for these processes plays a very important role: LCA-like allocation (reflected in SED results) is equivalent to accounting (in terms of environmental burdens) only for the anion chloride (Cl^-) to produce chlorine, disregarding the fact that resources in Cl^- and cation sodium (Na^+) cannot be produced independently. Such reasoning makes sense only from the user-side point of view, when it is assumed that the Na^+ will be used by another technospheric process and thus the burden can be shared. In contrast, from a 'donor-side' perspective, both ions are necessary to form the crystal NaCl, which is then used up in its entirety by downstream users: each downstream user should take into account the whole burden even though he/she would need only the Na or Cl part of the crystal. This is the rationale of rule #2 in emergy algebra. Rule #4 pinpoints that double-counting should be taken care of when both users of Na^+ and of Cl^- combine their products.

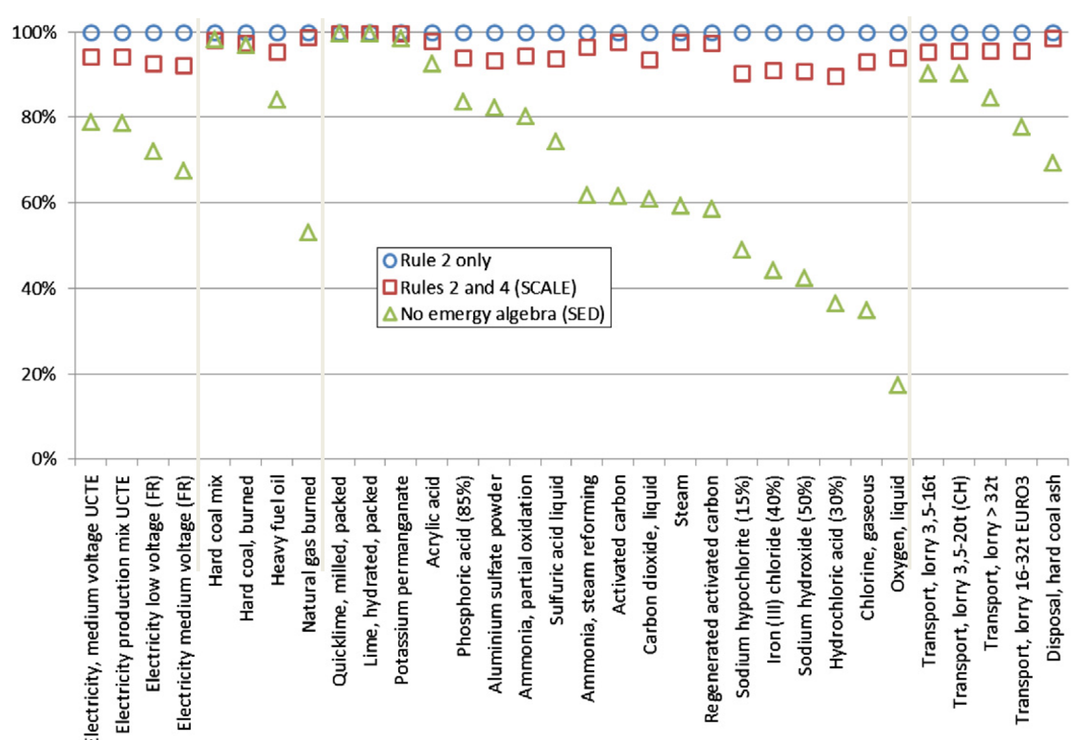

Fig. 4. Relative influence of emergy quantification procedure on the final UEVs of technospheric inputs due to 1) 'LCA-type' allocation rule instead of emergy algebra rule #2 (only): triangle vs. circle markers; 2) influence of the application of emergy algebra rule #4 after rule #2 (square vs. circle markers).

Similarly, the SED of liquid oxygen represents roughly 20% of the UEV_{SCALE} value, because it is produced from air liquefaction, with liquid nitrogen and liquid hydrogen as co-products, with allocation factors in ecoinvent® assimilated to the air composition. The differences found for fuel oil and natural gas are also explained by the fact that they are co-products of multi-output processes (i.e. considered as being extracted from the same oil reservoir). The differences for activated carbon and road transportation can be explained by those found for natural gas and fuel oil.

3.3. Gravity analysis

Another interesting feature of SCALE and SED is the decomposition of outputs into resource categories, as illustrated in Fig. 5.

The classification in resource categories is not possible in EME_{CONV}, unless a detailed decomposition of resource contribution was carried out for each technospheric input. SCALE provides higher results (1.05–1.65 times higher) for fossil, metal, mineral and water resources, similar results for nuclear and renewable energy resources and much higher results regarding land resources (17–32 times higher). Agriculture operations are often multi-output processes (e.g. grain and straw out of wheat production), which explains the high difference. Since these items only indirectly enter the composition of chemicals and processed energy, the selected case studies do not highlight such difference. Gravity analysis of technospheric inputs, per resource category, is detailed in SI3. For instance, in Fig. S2, the ratio SED/INPUT (i.e. UEVs calculated with rule #2 only) shows the influence of allocation rules (LCA-like vs. emergy rule #2), per resource category. Relative differences are the highest for land resources, for a large majority of the studied products; however, the absolute contribution of land resource to the UEV_{SCALE} (and SED) of technospheric inputs is marginal (the main contributors are fossil, metal and mineral resources). Excluding land resources, the highest relative differences between SED and INPUT concern liquid oxygen (78–87% difference) and chlorine-based compounds (Cl_2: 56–72%; HCl: 55–72%; $FeCl_3$: 50–58%; NaOH: 47–66%; NaOCl: 43–54%). For each of these products, the ratio is similar among the resource types. For the other products, the difference sometimes reaches values higher than 40% (see e.g. electricity, regenerated activated carbon, ammonia via steam reforming, steam, natural gas) but only for one or two resource types. This decomposition highlights again the potentially high influence of the allocation rules, all other aspects being equivalents. In a multi-output process like salt water electrolysis to retrieve sodium hydroxide and chlorine compounds, allocation in LCA is based on mass (here: 46% chlorine, 52% sodium hydroxide, 1% hydrogen), which reflects the figures mentioned above.

3.4. Differences in interpretation

The investigation carried out so far has highlighted two main points. Firstly, the higher level of detail achieved with SCALE as compared to traditional emergy evaluation. Processes involved in the transformation of the primary raw material into a useful product (for downstream users) are taken into account in a more detailed and homogeneous manner, thanks to the use of the ecoinvent® database. Secondly, the higher resolution of the UEV of man-made products (e.g. chemicals, refined fuels and types of electricity) as compared to state-of-the-art UEV datasets (Sweeney et al., 2007). This is particularly important for the evaluation of industrial systems, in which local natural inputs are marginal compared to technospheric ones (Arbault et al., 2013a). Such enhancement may also have significant consequences on emergy-based indicators, such as the percentage of renewability and the emergy yield ratio (Brown and Ulgiati, 1997; Odum, 1996; Ridolfi and Bastianoni, 2008), but this type of analysis is outside this paper's scope. SCALE, however, does not provide a full emergy accounting: it only gives a higher level of detail on technospheric inputs.

The mathematical differences sketched up among the 3 methods and illustrated in Sections 3.2 and 3.3 can be translated in textual form, to shed light on the added values brought from SCALE to emergy accounting:

1. *The UEV of potable water derived from conventional EME is the cumulated solar energy used up directly and indirectly by natural and human systems to deliver 1 m^3 of potable water.*
2. *The UEV of potable water derived from SCALE is the cumulated solar energy used up by natural systems to form the natural resources that are used up, directly and indirectly via the supporting technosphere, to deliver 1 m^3 of potable water.*
3. *The SED of potable water is the sum of solar-energy equivalents of resources consumed by the portion of the technosphere allocated to the delivery of 1 m^3 of potable water.*

Fig. 6 illustrates the conceptual difference between EME_{CONV} and EME_{SCALE} for the case study of water treatment plants.

While SCALE includes a much more detailed description of the technospheric processes, EME_{CONV} encompasses a larger scope of man-made contributions by including the emergy value of direct and indirect labor. The third sentence shows that SED adopts a user-side point of view: resources are allocated among users, while EME (via emergy algebra) attributes the whole value of the resources to each user.

Applied to the present case studies, each method emphasizes the large contribution of chemical reagents in the use of resources. By assuming that the lower the output's emergy value, the better (according to the

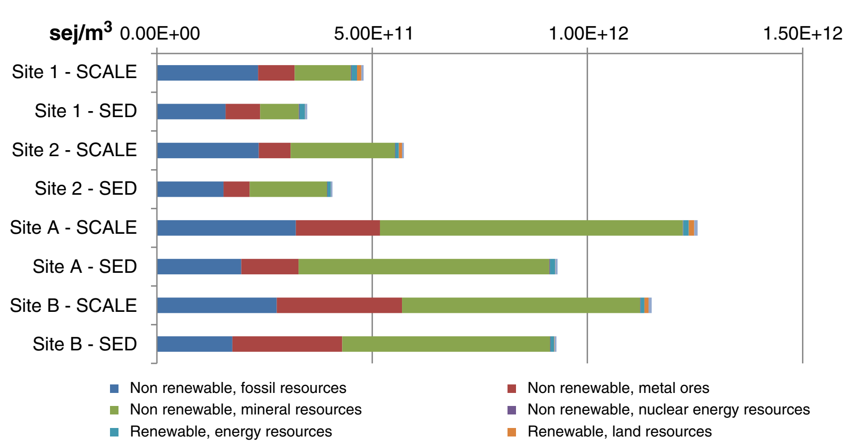

Fig. 5. Decomposition per resource category of technospheric inputs in the EME_{SCALE} and the SED of the 4 case studies.

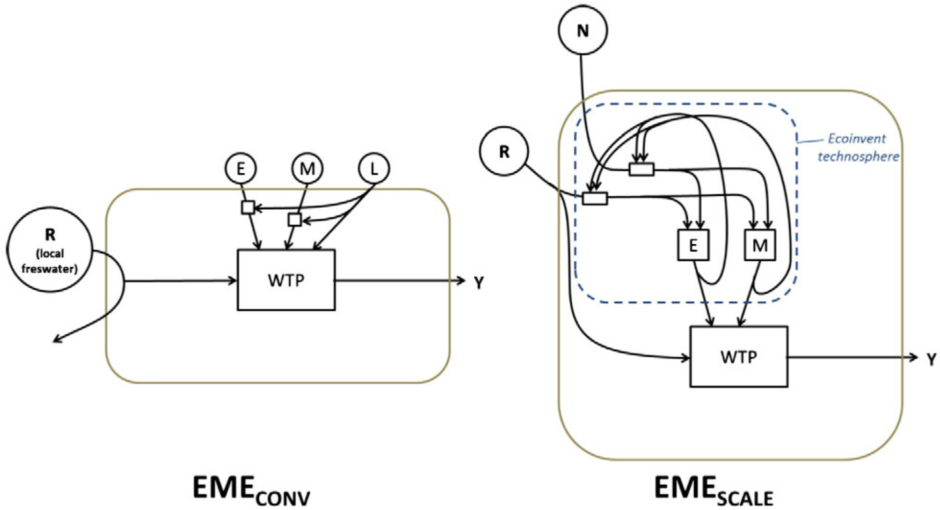

Fig. 6. Graphical comparison between traditional EME (left) and SCALE (right, including information retrieved from ecoinvent®, dotted-blue box). E = Energy products (fuels, electricity …); L = Labor (incl. services and non-material inputs); M = Materials (chemicals, infrastructure …); N = Non-renewable resources; R = Renewable resources; Y: Activity's output (Yield); WTP = Water treatment plant.

conventional directionality adopted to interpret the emergy values, see Arbault et al., 2013b), the final generic recommendation from all the methods is to monitor and possibly reduce the amount of chemicals consumed in the treatment plant. However, whereas the SED method implicitly suggests favoring chemical processes that provide more co-products, the emergy-based accounting methods recommend selecting only those processes that provide a similar amount of chemical reagents, but using up natural resources that are more 'easily' delivered by natural processes (i.e. that require less direct and indirect solar energy to be produced).

Despite the valuable leap forward it brings to emergy evaluation, SCALE has also some limitations in terms of scope, as listed and illustrated in Section 3.5.

3.5. Limits of SCALE

The correct application of SCALE to the technosphere depends on a good resolution and comprehensiveness of the database representing the network of industrial processes that compose the technosphere. The ecoinvent® database, used in this study, remains perfectible, as illustrated in Section 3.5.1. Moreover, it covers only a limited portion of the man-made contributions to the coupled human–natural system under study. While Table 2 shows the comparison of scopes between EME$_{CONV}$, EME$_{SCALE}$, SED and LCA (ReCiPe method, Goedkoop et al., 2009), Fig. 7 emphasizes the identified missing elements in SCALE-based emergy accounting, which are further discussed in Sections 3.5.2 to 3.5.6.

3.5.1. Algebra issues specific to ecoinvent®

Rule#2 of emergy algebra entails a revision of the allocation criteria, which involves a preliminary change of allocation factors in the ecoinvent® database (see Materials and methods section). In the latter, most of the processes are modeled by adopting a 'gate-to-gate' perspective, i.e. each transformation step of the chain of processes is modeled separately. This is convenient, for example, when a process is involved in various production chains. It also allows a flexible, customizable allocation procedure when multi-output processes are present in the life cycle and the changes required by rule#2. However, a few processes are modeled from a "cradle-to-gate" perspective, i.e. in an aggregated form. An overview of the 2000+ processes involved in the modeling of our case studies shows that around 50 of them (2.5%) are actually modeled in an aggregated form, where only the cumulated environmental interventions throughout the whole 'cradle-to-gate' lifecycle (i.e. from nature to the production plant output) are visible. Twenty-one of them are related to basic organic chemical reagents (e.g. benzene, toluene, esters, polyols), which form the basis of organic chemistry and are likely to form other compounds directly used in the plant such as polymers; 16 of them are plastics (PVC, HDPE, PP), which represent a significant part of e.g. material assets. If the concerned production chains generate co-products, emergy algebra would be inapplicable to them, because allocation rules are already embedded in the available dataset and cannot be modified manually. In order to correctly apply the emergy algebra, one possibility is to ask data providers to use SCALE by themselves and publish aggregated results, per resource category, assuming that there is no feedback loop from downstream systems that use polymers and the petroleum industry. This would be

Table 2
Comparison of scope between EME$_{CONV}$, EME$_{SCALE}$, SED and ReCiPe method (LCA).

Scope	EME$_{CONV}$	EME$_{SCALE}$	SED	ReCiPe (LCA)
Value of resources (donor-side perspective, i.e. solar-energy embodied in primary natural resources)	✓	✓	✓	✗
Ecosystem services	Partly*	✗	✗	✗
Local resources	✓	✗	✗	✗
Human labor	✓	✗	✗	✗
Level of details in man-made inputs	Low	High	High	High
Impacts of pollution	Partly*	✗	✗	✓
Impacts of resource depletion	Partly*	✗	✗	✓

* Different approaches are currently under development in the emergy community (see Sections 3.5.4 and 3.5.6). These aspects are not systematically included in emergy evaluations, as commented in Arbault et al. (2013b).

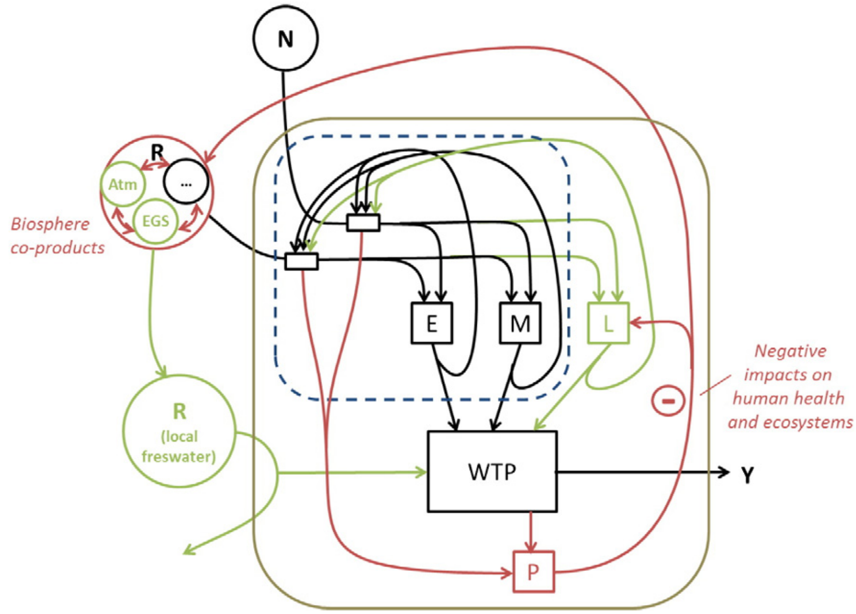

Fig. 7. Missing elements in SCALE-based emergy accounting. Green shapes refer to the inventory of flows; red shapes refer to the impact assessment; dashed-blue box refers to the ecoinvent® database. Atm = Atmospheric resources; E = Energy products (fuels, electricity …); EGS = Ecosystem goods and services; L = Labor (incl. services and non-material inputs); M = Materials (chemicals, infrastructure …); P = Pollutants released; R = Renewable resources; WTP = Water treatment plant.

a prerequisite for an integral, correct application of emergy algebra in SCALE.

3.5.2. Human labor, services and economic inputs

In the ecoinvent® database, several components necessary to run industrial and agricultural activities, such as human labor, management of economic assets e.g. banking activities, and of social welfare, e.g. education, healthcare, and public administration, are omitted. These aspects may have important contributions to the overall environmental impacts of an activity. For instance, Rugani et al. (2012b) demonstrated that human labor may increase by 10–15% the overall environmental impacts of LCIA profiles.

EME_{CONV} accounts for the non-material inputs from the anthroposphere, by translating their economic cost in emergy terms. The emergy value of the economic cost of a man-made good is complementary to the emergy value of the resources used up: it is a proxy of the total direct and indirect human labor and services necessary to its production. There is thus no risk of double-counting in using complementarily SCALE along with economic data, as long as human labor and services are not included in ecoinvent®. Non-material, economic costs in our case studies are detailed in Arbault et al. (2013a), and have an emergy value of 6.4 E10 (Site 1) to 2.6 E11 (Site B) sej per m^3 of potable water produced, which represents 2–6% of the results found for man-made goods in the present case studies.

However, this estimation should not be summed up with results provided by SCALE, since the level of details used to calculate them is not consistent with that of the description of the technosphere provided by ecoinvent®. According to Tiruta-Barna and Benetto (2013), values calculated from a different level of detail of the network of processes cannot be added without creating a bias in emergy accounting. This inclusion of non-material, man-made inputs into EME_{SCALE} should rely on a process-based decomposition of indirect costs, whose resolution matches the level of details found in ecoinvent®. A potential way forward is to consider new process categories in ecoinvent® to represent several types of human labor (Rugani et al., 2012b) and public service providers, as illustrated in Fig. 7. However, it would require updating the whole database.

3.5.3. Atmospheric resources

Atmospheric resources are seldom inventoried as inputs in ecoinvent® (only CO_2, Xenon, Krypton and Helium), as these resources are not directly solicited by human activities but freely available. This omission might compromise SCALE's results. For instance, atmospheric nitrogen is a major component in the production of ammonia and most fertilizers used worldwide. Assuming that 0.82 kg of atmospheric N_2 (UEV 2.28 E13 sej/kg, from Campbell et al., 2014) is consumed for the production of 1 kg ammonia, the potential additional contribution of nitrogen to ammonia (1.87 E13 sej/kg, see SI2) is 4.4 times higher than the UEV_{SCALE} of ammonia 'from partial oxidation' (4.06 E12 sej/kg, including 2.46 E10 sej/kg from renewable resources; see SI2). This example demonstrates that atmospheric resources should not be systematically omitted. Similarly, chemical oxidation is a very common reaction in industrial processes, and is often made with atmospheric oxygen. However, it could be claimed that the volume of airborne resources used up in industrial processes is negligible as compared to the oxygen consumption by living organisms including human bodies, nitrogen fixation by plants, and air flowing through factories useful e.g. for ventilation. Natural processes do not affect the overall balance between the production and the consumption of airborne resources, contrary to chemical reactions in industry for which there is a net consumption, potentially affecting the natural equilibrium of oxygen and nitrogen cycles and their supporting ecosystem services. Indeed, the nature-centered viewpoint of emergy can evaluate the regeneration capacities of atmospheric oxygen and nitrogen (along with carbon, water, sulfur) by global processes, which are so-called supporting ecosystem services (Watanabe and Ortega, 2011) and are important natural inputs to the technosphere. The SEF dataset (and hence SCALE) also disregards atmospheric resources and other renewable resources such as solar radiation, biomass and soil carbon, by attributing a SEF equal to zero, in order to avoid double-counting. Further discussion on such shortcomings and potential advances is provided in SI4.

3.5.4. Ecosystem services

Other ES not included in ecoinvent® may also provide important inputs to the technosphere (Zhang et al., 2010b). This is the case of

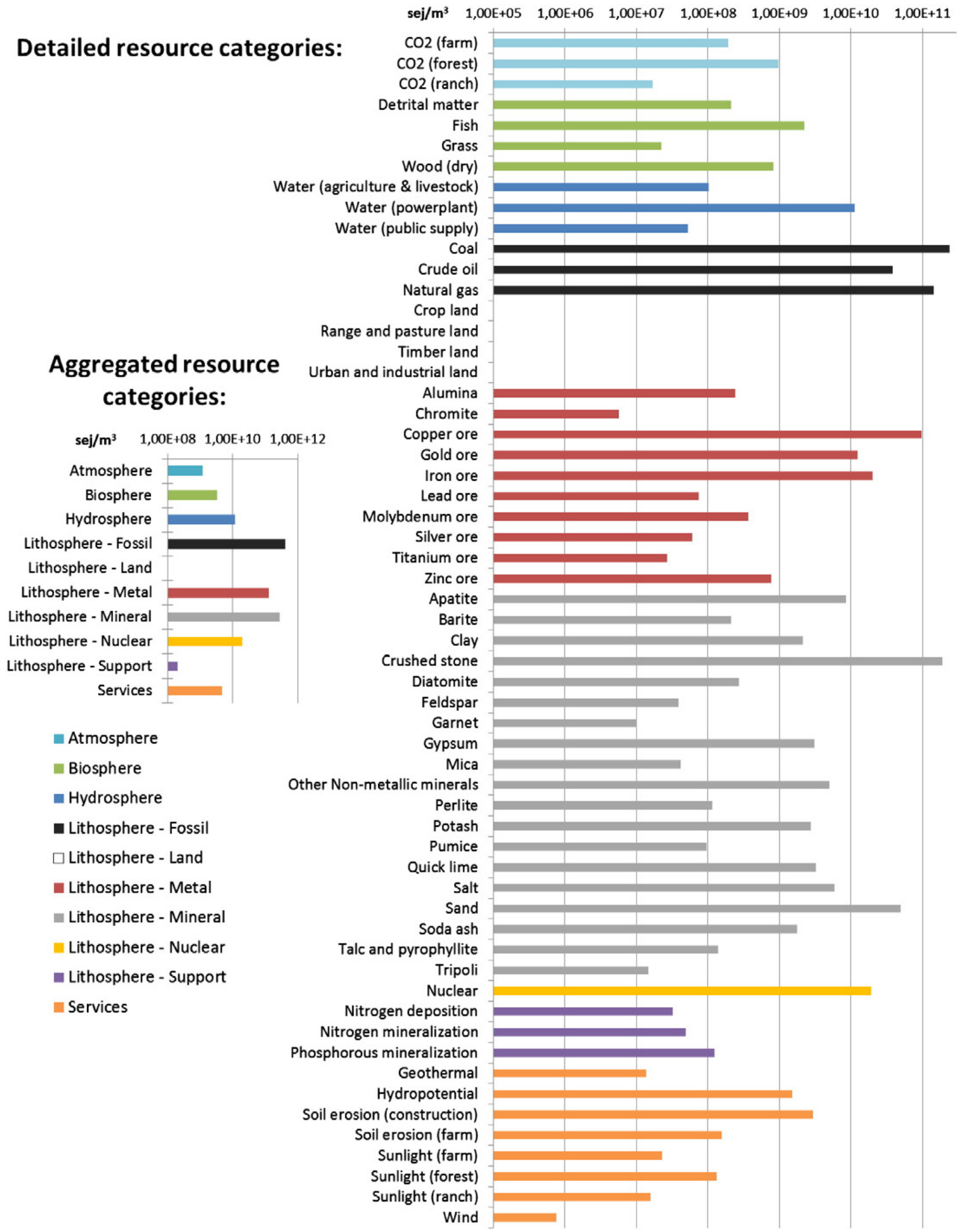

Fig. 8. Additional contribution (in sej/m^3, log scale) of Ecosystem Services to the final UEV of the functional unit (using EcoLCA, Zhang et al., 2010a); left-hand side figure: contributions aggregated into resource and service categories; right-hand side figure: contributions detailed per ES accounted for in EcoLCA. See SI5 for method and calculation details.

some provisioning services (e.g. production of biogenic material), regulating services (e.g. erosion control, CO_2 sequestration) and supporting services (e.g. nitrogen and phosphorous mineralization), which are omitted in ecoinvent®. To estimate their relative importance we applied to the case studies the EcoLCA method developed by Zhang et al. (2010a), available online (www.ecolca.org). EcoLCA uses economic data of the 1997 US Input–Output table to calculate the direct and indirect contribution of a selection of ES to the generation of 1$ of output value by each industrial sector. This model converts the economic value of each input of the studied system into an emergy value using economic Input–Output tables. The application of this model to our case studies suffers from three important limitations: 1) the economic structure of France (and the price of goods) differs from that of the US; 2) Input–Output tables are suitable for macro-economic studies but not for one single plant; 3) the system described in this tool has a different scale and resolution from the technosphere as described in ecoinvent®: their results should not be mixed (Tiruta-Barna and Benetto, 2013). For these reasons, the results of EcoLCA shall not be used for the final interpretation of SCALE results but only for the purpose of obtaining a first estimation of the potential relative contribution of ES that are not yet reported in ecoinvent®. The emergy value of the economic sector "potable water production" obtained from EcoLCA is 8.70 E11 sej/m^3 (see SI5 for details on calculation and the underlying method). This result is in line with the results yielded by SCALE for our case studies. Detailed results (Fig. 8) show that the main contributors are lithospheric processes to generate fossil, mineral and metal resources. These resources are also accounted for in SCALE. Although the ranking of these contributors is different, as well as the set of natural resources used up, EcoLCA and SCALE provide similar results for non-renewable resources. This implies, however, that CO_2 sequestration by forests, fish production, water provision for power plants, hydro-potential energy and soil erosion control in construction sites should be investigated more in detail.

Despite being inexact, the application of EcoLCA allowed us in identifying ES which are potentially important inputs to the studied system. It further illustrates the need for complementing LCI databases like ecoinvent® with the contributions of ecosystems and the biosphere to the functioning of the technosphere. Specific considerations related to the calculation of ES based on the application of emergy algebra in SCALE are discussed in SI4.

3.5.5. Local resources

Another limitation of the joint use of SCALE, the SEF dataset and ecoinvent® v2.2 is the lack of geographic information. Emergy evaluation originally intended to place human activity within its direct surrounding natural environment, and therefore required the re-evaluation of the emergy value of local natural resources — while the emergy value of natural resources indirectly used up by the surrounding *human* environment (so-called Feedbacks) are estimated with coarser information.

For example, the SEF of raw freshwater used in SCALE calculations is 3.09 E11 sej/m^3 (adapted from Buenfil, 2001). Arbault et al. (2013a) calculated a specific UEV for local water resources used up in the present case studies of 5.40 (Site 1), 5.76 (Site 2), 3.93 (Site A) and 4.33 (Site B) E11 sej/m^3, which are 29% to 86% higher than the SEF value. Consequently, UEVs and emergy-based indicators are likely to change significantly. Another example is the SEF of land occupation, which is constant (i.e. equal to the empower density of the Earth; see Odum, 1996) among the various types of land. This is a typical limitation of the traditional top-down approach, which must be overtaken by future research to obtain more spatially-explicit results from a rigorous application of emergy algebra.

Bottom-up approaches could use Geographic Information System (GIS) tools to retrieve local UEVs, as illustrated by state-of-the-art research e.g. on freshwater and land use (Agostinho et al., 2010; Huang et al., 2007; Mellino et al., 2014). Moreover, the ecoinvent® v3 database provides a convenient structure to include geographical information in the representation of the technosphere (Weidema et al., 2011). In this case, however, it remains questionable whether natural, renewable resources captured at the same location and time should be considered as co-products, since they are likely to have been generated at different geographical locations (e.g. wind, rain) and/or time horizons (e.g. groundwater, biomass).

3.5.6. Pollutants and societal costs: impacts on human health, ecosystems and resources

Emergy evaluation typically focuses on the consumption of natural resources. The impacts of pollution on human health and ecosystems remain unaddressed both in EME_{CONV} and EME_{SCALE}, though several authors suggested quantitative methods to account for them. For instance, it was suggested to quantify the costs of pollution remediation (Paoli et al., 2013), the technological costs to treat it before release (Song et al., 2013; Ulgiati et al., 2007), or the volume and mass of air necessary to dilute airborne pollutants until acceptable concentrations (Mu et al., 2011; Ulgiati and Brown, 2002; Zhang et al., 2011). This approach is close to the concept of grey water in ecological footprint (Chapagain and Hoekstra, 2011) and to the ecological scarcity method in LCA (Frischknecht et al., 2006). Its weakness lays in the definition of 'acceptable' level of pollutants, which is set by an environmental agency and is thus not determined by the analysis of the biophysical mechanisms affected by pollution. Oppositely, the latter are frequently used in LCA. For example, the ReCiPe method (Goedkoop et al., 2009) aggregates impacts into three 'Areas of protection': Human Health (HH), Ecosystem Diversity (ED), and (abiotic) Resource Depletion (RD).

Impact indicators on HH and/or ED have already been used to calculate the 'emergy investment' necessary to recover the impacts (Liu et al., 2013; Reza et al., in press; Ukidwe and Bakshi, 2004; Zhang et al., 2011). Impacts on Human Health (HH) consider the loss of human life or good health, which affects the good functioning of society. The latter needs more resources to recover such losses. This additional requirement can be attributed to the studied activity, although it does not directly use them up. The unit of impacts on HH is the DALY [disability-adjusted life years], which can be thought of as one lost year of 'healthy' life (WHO, 2013). The annual emergy budget per capita in France is 3.76 E16 sej/cap/yr (Sweeney et al., 2007, year 2000, 9.26 baseline-adjusted). According to the afore-mentioned studies, this figure is supposed to estimate the emergy value of the resources used up for 1 average year of human life in France, although an average year of human life is not necessarily 'healthy'. Nevertheless, an impact of 1 DALY can be seen, as a first proxy, as the net loss for the society equivalent to 3.76 E16 sej. Impacts on Ecosystem Diversity (ED) refer to the loss of biodiversity, which ultimately contributes to the efficient delivery of ES. An impact on ecosystem diversity of 1 species yr means that 1 known species is 'lost' (reversibly) by the biosphere during one year (Goedkoop et al., 2009). Assuming a biodiversity of 2 million known species on Earth (Goedkoop et al., 2009) and a global emergy budget (baseline) of 9.26 E24 sej/yr, the maintenance of 1 average species during 1 year by geobiosphere processes has an emergy value (as a first proxy) of 4.63 E18 sej/(species yr).

Impacts on Resources Depletion (RD) calculated according to the ReCiPe method (Goedkoop et al., 2009) account for the marginal (future) economic cost of resource extraction due to the presently extracted quantities. This can be seen as a (user-side) societal cost. It is thus unaccounted for in EME_{CONV} and EME_{SCALE}, which focus only on the regeneration of resources by natural processes. An impact of 1$ on resource depletion means that the net economic loss for society in the consumption of present resources (equivalently the societal replacement cost of presently-consumed resources) is 1$. This cost must be estimated at the societal level: the emergy value of the additional resources necessary to overcome this loss can be approximated as the local emergy-to-money ratio (1.63 E12 sej/$ for France, Sweeney et al., 2007, year 2000, 9.26 baseline-adjusted).

It is worth mentioning that the rationales presented above suffer from several shortcomings for EME. In the first place, impacts on HH and ED hardly match the rationale of emergy, since they are not based on tracking energy transformation pathways but rather on statistical correlations between these impacts and the quantified amounts of various pollution types (Goedkoop et al., 2009). Secondly, assuming these results can be translated into emergy terms, they still originate from a top-down approach and are thus subjected to possible

Table 3
Estimated contribution of pollution impacts and societal net loss (in emergy terms) to the case studies of water treatment plants. HH: Human health; ED: Ecosystem diversity; RD: Resource depletion. Total sej/m^3 is retrieved from the EME_{CONV} method (Arbault et al., 2013a). It includes technospheric inputs, labor and services, and the local UEV of freshwater. Impacts on HH, ED and RD were retrieved from Igos et al. (2013) and Igos et al. (in press).

Impacts per m^3 of potable water	Site 1	Site 2	Site A	Site B
Total sej/m^3	1.00 E12	9.93 E11	1.16 E12	1.33 E12
HH (DALY)	5.25 E−7	4.52 E−7	7.13 E−7	5.82 E−7
HH (sej/m^3)	1.97 E10	1.70 E10	2.68 E10	2.19 E10
% sej/m^3	*1.97%*	*1.71%*	*2.31%*	*1.65%*
ED (species yr)	1.88 E−9	1.81 E−9	2.88 E−9	2.45 E−9
ED (sej/m^3)	8.70 E9	8.38 E9	1.33 E10	1.13 E10
% sej/m^3	*0.87%*	*0.84%*	*1.15%*	*0.85%*
RD ($)	1.33 E−2	1.18 E−2	1.81 E−2	1.98 E−2
RD (sej/m^3)	2.17 E10	1.92 E10	2.95 E10	3.23 E10
% sej/m^3	*2.17%*	*1.93%*	*2.54%*	*2.43%*

double-counting. Finally, they mix different geographical scales and rely on a very rough level of detail regarding the description of the concerned systems: French national averages for emergy budget per capita and economic production, global average for the generation of species. As previously demonstrated, results of emergy evaluation depend on the level of detail in the description of the network of processes (Tiruta-Barna and Benetto, 2013). Therefore, these results can only be considered as a rough estimation of externalities that remain unaccounted for, both in EME_{CONV} and in EME_{SCALE}.

Table 3 indicates the estimated contribution, in terms of emergy, of these externalities. Despite the fact that they seem marginal, a rigorous emergy accounting framework should not disregard them a priori. It must be highlighted, however, that these aspects are of primary importance for the society and should not be assessed only with the lens of resource accounting; EME does not deliver a single metrics on which decision-makers could rely blindly.

4. Conclusions and outlook

For emergy practitioners, using SCALE provides a pragmatic advantage: technospheric inputs are calculated automatically in compliance with the emergy algebra rules and with a level of details never achieved before. This enhancement is useful for nearly all the case studies related to human activities. The precision of SCALE, however, relies on the comprehensiveness and level of details with which the network of processes is described in the selected representation of the technosphere (i.e. in the used LCI database). Similar to LCA, the selection of the LCI database depends on the location and sector of the studied activity. As mentioned in Marvuglia et al. (2013a), all commercial, process-based LCI datasets can in principle be used with SCALE, even when further enriched with process-specific datasets (such as activated carbon in the present study). Therefore the extent to which certain elements (such as e.g. human labor) are taken into account in SCALE mostly depends on the level of information contained in the used database about these elements. There is no technical limitation in SCALE itself to handle these elements and include them in the assessment. However, it was found that the LCI database applied in this case study relies on aggregate information for the plastic industry, and omits some potentially important elementary flows like airborne resources and ecosystem services. The current version of SCALE does not provide definitive results for emergy evaluation, since inputs such as labor and services and local resources must be calculated separately. Summing up these results computed independently raises issues on the heterogeneity of their levels of detail and spatial–temporal scales used for the calculation. A possible way forward is considering human labor and services as additional technospheric processes. Finally, the limitations identified in the use of SEFs in SCALE have very different origins: 1) the traditional top-down approach employed in their calculation leads to disregarding some resources in the dataset (like atmospheric resources) to avoid double-counting; 2) the current representation of the technosphere (i.e. the ecoinvent® database) is site-generic: the SEF dataset cannot accurately represent local resources with a high spatial variability (e.g. freshwater and land); 3) since EME focuses on material and energy resources, it does not yet conveniently account for pollution impacts and societal costs. Further research is needed to replace a top-down, site-generic, material-resources oriented SEF dataset of natural resources by a bottom-up, spatially-explicit, ecosystem-services oriented dataset. Such improvements are necessary to apply rigorously the emergy algebra. A first step, as proposed by Rugani and Benetto (2012), could be a fully-fledged, bottom-up approach made of a matrix representation of geological and biophysical processes, in which SCALE could be jointly applied.

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Appendix A. Supplementary data

Supporting information. SI includes all details of $UEVs_{CONV}$, $UEVs_{SCALE}$ and SED of technospheric inputs used in this paper, as well as the dataset used in the EcoLCA software. Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.scitotenv.2013.11.087.

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