Evaluating natural resources use for potable water production

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Abstract Several assessment methods have been proposed to evaluate the use of natural resources in the life cycle of industrial processes. However, these methods are not adapted to all kinds of resources (especially to renewable resources) and can lead to very different results. This study performed a comparison of methods for the case of potable water treatment, considering both the construction and operation phases of the plant. The results show that the contribution of the construction phase is less important than the operation, although being not negligible. A paradigm shift toward a nature centred viewpoint is suggested a step forward to proper consideration of renewable and non renewable resources and related research challenges are outlined.

1 Methods to assess natural resources use: state of the art

1.1 Life cycle impact assessment (LCIA) approaches

Existing Life Cycle Impact Assessment (LCIA) approaches show clear shortfalls in the evaluation of natural resource use, i.e. in quantifying the value of natural resources which support production activities in the Technosphere. To begin with, the main focus of the Area of Protection (AoP) "Resources" is on the depletion of natural resources, mainly fossil and mineral. The AoP is built on the notion of scarcity of resources, therefore clearly adopts an anthropocentric viewpoint. Higher is the abundance of a resource lower is its value up to valueless. Targeted resources are the ones which are intentionally requested by production activities (via market mechanisms) and are scarce. The value of resources is therefore limited to the function they provide to production systems (see e.g. notion of "resource functionality" in [1]). In practice, operational approaches do not strictly follow the AoP definition and are usually grouped in three categories (see [2] for a short presentation of methods and further references): 1) approaches evaluating an intrinsic property of resources, namely the Cumulated Exergy Demand - CexD (a.k.a. Industrial Cumulated Exergy Demand); CExD represents the potential work that resources could provide as compared to a reference state (baseline) which is the standard environment. As it is, CExD (and slightly modified methods, like CEENE) represents the exergetic cost of a product, but does not assess scarcity and therefore is not recommended in LCA. 2) Methods based on the "use to availability ratio" (e.g. EDIP) or "use to availability - current rate of extraction ratio" (e.g. CML2001), which are fully compliant to the AoP Resources but still subject to large uncertainty, e.g. because of the estimation of reserves. 3) Methods evaluating the (marginal) consequences of resource use, i.e. the marginal additional effort (in energy - MJ or monetary - $ unit) the mankind will have to provide in the future to extract the same quantity of resources which is currently extracted in the product system investigated (and therefore is getting scarcer). Marginal effort is calculated by identifying the marginal technology and estimating the (cost or energy) difference to extract resources as compared to the current (conventional) technology. Methods like ReCiPe and Stepwise provide such endpoint values for a wide range of resources but are based on very different assumptions, regarding e.g. future technological developments and discounting ratios. Finally, they usually end up in very different evaluation of natural resource use. The uncertainty on such estimation is quite high as well.

1.2 Consideration of water and renewable resources

Potentially (locally) scarce resources, like water, are mostly ignored by the aforementioned methods. While plethora of methodological developments are ongoing to assess the effects of water use to the other areas of protection (Ecosystem quality and Human health), few attempts have been (and are being) done to evaluate water within the AoP Resources. The reason is that water depletion is very site specific, i.e. there is no global market for water, as e.g. for fossil resources. Within the method category group 1) CExD consider the same characterization factors (50 MJ/m^3 or 0.05 MJ/kg) for all the water resources, irrespective of the type of source (from river, lake, ground etc). Basically, average water properties are considered and chemical exergy is then calculated. In group 3), [3] calculated endpoint characterization factors of consumptive[1] water use per watershed for the entire world. First, water stress, defined by the ratio (WTA) of total annual freshwater withdrawals to hydrological availability, is calculated per watershed. Afterwards fractions of freshwater consumptive use that contribute to depletion ($F_{depletion}$) are calculated for each watershed and further aggregated using total annual withdrawal within the watershed as a weighting factor to obtain an average $F_{depletion}$ per country. Finally, the surplus energy is calculated by considering the actual consumptive water use of the studied system, multiplied by the average $F_{depletion}$ of the country of consumption times the surplus required by desalination of seawater (11 MJ/m^3), considered as a backup technology to compensate for water resource depletion.

All the other methods propose a common evaluation unit (e.g. marginal cost or MJ energy) for a wide range of natural resources, in order to compare their relative importance and then to aggregate all the results into a single score which should describe the total magnitude of resource use. For group 1), the problem of substitutability of resources arises [4]. Aggregation implies the assumption that resources are substitutable, which does not hold true for renewable and non renewable CExDs. From the standpoint of including water resources, and more generally locally scarce or renewable resources, this problem becomes even more severe, because of the different originating processes of renewable and non renewable.

1.3 Paradigm shift: nature centred viewpoint

Accounting for more and more renewable resources which are significantly supporting human production activities is urgent in today's assessments, and goes clearly beyond the current LCIA framework. The outcomes of the Millennium Assessment [5] showed that ecosystem services (not only ecosystem quality!) are being degraded by human activities. Ecosystem services are intimately related to natural resources, which could be seen as sort of "outputs" of natural processes which are actively supporting human activities despite they are not explicitly

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[1] Consumptive use (water consumption) represents freshwater withdrawals which are evaporated, incorporated in products and waste, transferred into different watersheds, or disposed into the sea after usage

required (through market mechanisms) by production processes. Therefore the value ecosystem services (via natural resources) provide in supporting human activities shall be accounted for in the environmental assessments. This value has nothing to do with the notion of scarcity or utility for mankind, but is instead related to the efforts put into place by natural processes to make natural resources available at a given level of quality.

The value of natural resources, combined with a quality differentiation, has therefore to be quantified from a nature-centred viewpoint. To this aim, alternative approaches based on the concept of Emergy have recently emerged. Emergy is defined as the content of equivalent solar energy (MJse) required by every kind of natural resource (at a given quality state), i.e. the equivalent solar energy that was used by natural processes to make that resource available. Basically emergy quantifies the energy flows behind natural resources and ecosystem services which are typically not considered in conventional life cycle approaches, whose inventory boundaries are defined at the entrance of resources into the Technosphere. When calculating the solar energy equivalence for obtaining a unit exergy, the method informs about the quality of resources. This represents a major change of paradigm with respect to LCA: emergy provides the value of natural resources in terms of the effort spent by natural processes to make them available, which is fully complementary to the LCA perspective based on scarcity and human utility (Fig. 1).

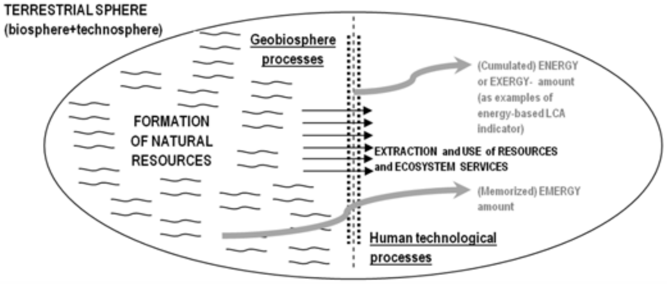

Fig. 1. Paradigm shift from human-centred to nature-centred evaluation perspective.

The emergy framework presents however known limitations, in terms of transparency of calculations and data availability. Work is in progress to overcome these limitations. A couple of attempts to implement emergy-based approach indicators into life cycle database have already been done [6,7]. In [7] the indicator of Solar Energy Demand (SED) has been developed within Ecoinvent database (v2.2), and is implemented as a single score LCIA indicator. SED represents the total solar energy required to sustain production systems, as it is for emergy. In general, the higher is the SED, the higher the use of resources of a production system. SEFs are the Solar-Energy Factors applied to accumulated Ecoinvent resources to characterize the SED impact (SEFs in MJse/kg, MJse/Nm^3, MJse/m^3, MJse/m^{2}yr, MJse/MJ). The SEF is calculated by allocating the emergy baseline 9.26E18 MJse/yr [8] according to the annual flow of a given resource (e.g. kg/yr), estimated by multiplying the stored quantity by its turnover time [9]. The baseline represents the annual budget of energy that flows in the geobiosphere, i.e. sum of energy in sun, tide, and crustal heat. A SEF can be calculated for each resource (land, water, mineral, energy carrier, and so forth) of the Earth, by assuming the baseline as 'free' energy that feeds and sustains each of the resource flows.

2 Objective of this study

This study aimed at applying and testing the methods of natural resource evaluation to the specific case of potable water production against two objectives: 1) evaluate the relative contribution of (renewable and non renewable) resources, with special focus on water resources; 2) assess the significance of the resource use for infrastructure as compared to the resource use in the operation phase. There is a common denominator between the type of studied system (potable water production) and the two objectives: the consistent accounting of resources in general, and more specifically renewable resources. Infrastructures are often claimed to be negligible, whereas there is no formal proof of this claim and the proper consideration of conventional resources (e.g. sand, gravels) and of additional renewable resources could provide new insights.

3 Case study: potable water production

3.1 Water treatment plant description

The studied treatment process is representative of European conditions, including common but modern operations. Water comes from river source, contains average of 11 mg/L total organic carbon and 24 NTU turbidity. Two pump stations are used on site for resource extraction and treated water distribution. The treatment line is depicted in Fig. 2. After pumping, water is ozoned to oxidize organic matter and limit coagulant consumption during settling. Ozone is produced on plant by an ozonizer. Pre-mineralization is achieved to increase alkalinity and regulate pH. Lime and carbon dioxide are injected. Coagulation with iron chloride, combined with flotation, eliminates suspended matter. Bubbles, injected under pressure, adhere to suspended matter which is trained to the surface. Water loss during this step is between 1.5% and 2% of raw water. Oxidation by potassium permanganate limits organic carbon and other ozonation by-products development. Another step of mineralization is realized with lime addition in order to stimulate biological activity. Then, water settles in a reactor by adsorption on Powdered Active Carbon (PAC). Micro pollutants, as pesticides, and residual organic matter are targeted here. Ultra-filtration is a barrier for bacteria, viruses and protozoa Giardia and Cryptosporidium. Washing water is recycled, as for sand filtration. Before distribution, water is subjected to disinfection with bleach and pH adjustment thanks to soda. For this plant, detailed (attributional) LCA for construction (infrastructure and equipments) and for operation were performed.

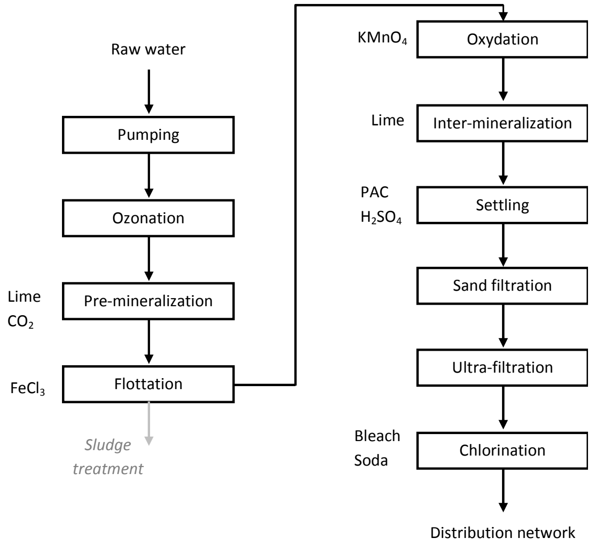

Fig.2: Operation flowchart for potable water production.

3.2 Infrastructure and equipments

The life cycle inventory (LCI) of infrastructure and all the equipments (e.g. each pump) was based on: 1) Civil engineering data for basins, reservoirs and buildings, including the quantity of construction materials used (i.e. concrete, reinforced steel, glass fibre) and buildings designs (areas, volumes, types). 2) Equipments used and their mass composition. The main material categories are: steel (different qualities), cupper, PVC, PEHD, polyester, glass, other plastics. 3) Transport operations from the equipment suppliers to the plant. 4) Land occupation. Considering the lifetime of equipments, the LCI was built on a year basis. All necessary background data were taken from Ecoinvent.

3.3 Plant operation

The plant has a yearly production of 8,365,000 m^3 of potable water. Specific electrical consumptions were collected for each unit operation of the treatment plant. Consumption of reagents (Tab.1) was calculated from required concentrations and associated volumes. Datasets for all the reagents were available in Ecoinvent database except for PAC [10] and polymer.

Tab.1: Raw materials used in plant operation

Reagent	Consumption
Iron chloride	1326 t/a
Lime	396 t/a
Carbon dioxide	176 t/a
Potassium permanganate	3 t/a
PAC	42 t/a
Sulphuric acid	2 t/a
Bleach	40 t/a
Soda	24 t/a
Polymer	4.8 t/a

4 Natural resources evaluation results

The R ratio, being the ratio between the impact (damage) results for infrastructure and operation, and the resources which are mainly contributing to the results (gravity analysis) are presented for all the methods investigated. First the methods evaluating "scarcity" are considered in Tab. 2 and Fig. 3; ReCiPe and Stepwise pertain to group 3) and CML2001 and EDIP2003 to group 2).

Tab.2: Ratio R [%] for LCIA evaluating "scarcity"

Methods	Midpoint	Endpoint
ReCiPe	**9**	**9**
Fossil depletion	9	9
Fossil fuels		
Metal depletion	17	16
Manganese, copper, nickel, iron		
Stepwise	**16**	**16**
Non-renewable energy	3	0
Fossil fuels		
Mineral extraction	16	16
Nickel, iron, aluminium, copper, tin		
CML2001		
Depletion of abiotic resources	**9**	-
Fossil fuels		

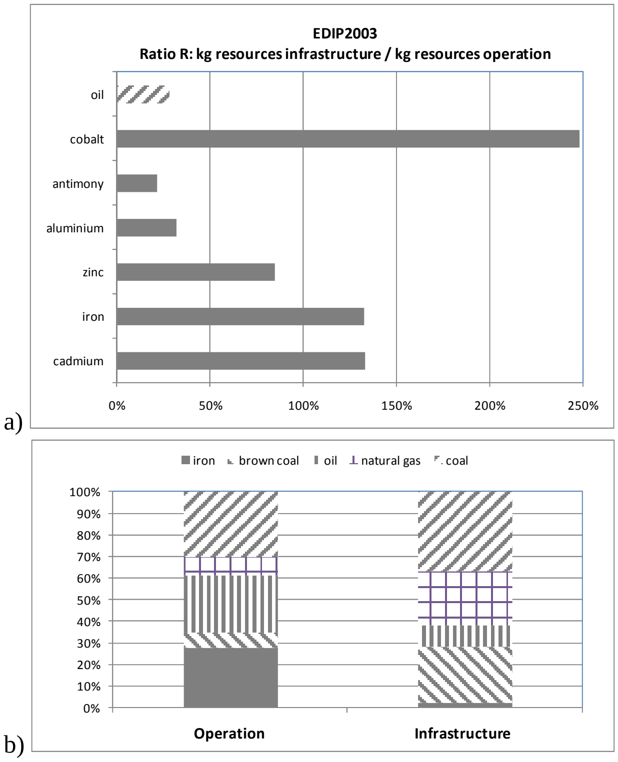

Fig.3: EDIP2003; a) ratio R; b) gravity analysis

One can observe that fossil fuels dominate the assessment in CML2001 and EDIP2003, in terms of contribution to the total impact. In the latter method, only iron consumed during the operation of the plant shows a significant contribution.

In the comparison between infrastructure and operation, individual metals makes the impact of infrastructure significant as compared to operation, despite their total contribution is negligible. As a result, the ratio R is driven by fossil fuels, mainly crude oil, in both methods but results are quite distant (9% according to CML2001 and 26% for EDIP2003). ReCiPe and Stepwise show the same trend for minerals (same resources, same R) but lead to completely different results concerning fossil fuels at endpoint level. The single score at endpoint (fossil fuels+minerals) is led by fossil fuels for ReCiPe and by minerals for Stepwise, which does not regard fossil fuels to be significant. These evaluations do not include water resources. Their evaluation has been tackled using the endpoint approach of [3], CExD and the SED method. [3] led to the conclusion that contribution of water resource use is negligible, since the proposed characterization factor for the AoP Resource is null for the region (Brittany) where the resource is withdrawn.

The results for CExD are illustrated in Fig. 4.

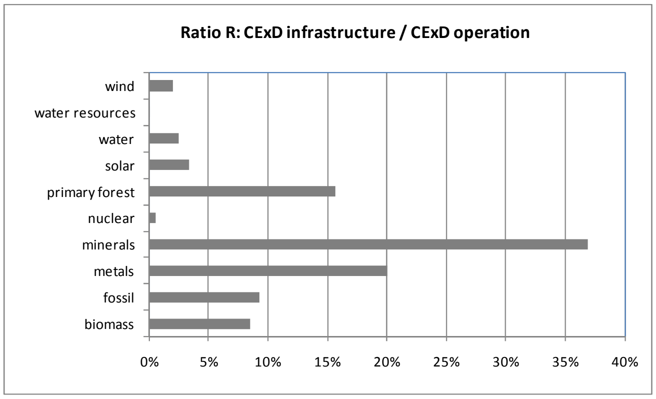

Fig.4: CExD: ratio R

The CExD results for the different categories, especially non renewable and renewable, cannot be aggregated because of the information loss and non substitutability. CExDs measure the utility supplied by natural resources and consumed in the system, on a common basis (exergy). When comparing the R ratio for the different categories, one can observe that mineral and fossil fuels are mainly supporting the significance of infrastructures as compared to operation, in line with some for the previous results. However, the contribution of renewable resources is not negligible.

SED method considers the quality of resources and their relative contribution to the total SED is shown in Tab. 3. Interestingly, the contribution of water resources (including the whole functional flow which enters into drinking water) is still rather negligible as compared to sodium chlorite and calcite, in the operational phase. Similarly, renewable resources are not in the top list of contributors. For the infrastructure, gravel and calcite dominates. The R ratio is surprisingly low, i.e. the significance of infrastructure is definitively negligible.

Tab.3: SED: gravity analysis and ratio R

Gravity analysis [%]	**Operation**	**Infrastructure**
Sodium chlorite	86	7
Calcite	5	25
Water, river (including functional flow)	3	-
Gravel	-	36
Clay	-	6
Iron	-	10
Oil, crude	-	3
Nickel,	-	3
Magnesite,	-	2
Coal, brown and hard unspecified	-	3
Total	94%	95%
Ratio SED infrastructure / SED operation	**3.3**	

5 Discussion and conclusions

The assessment results are quite heterogeneous and do not provide a clear evaluation of natural resource use. Some methods (CML2001, ReCiPe, EDIP2003) are clearly driven by fossil fuels. For the midpoint approach, these resources are implicitly considered very scarce and associated to high rates of consumptions. At endpoint level, the assumptions behind ReCiPe calculations (e.g. the ignorance of technology shifts) led to very high (and unrealistic) costs. The evaluation of Stepwise is quite at the opposite, i.e. fossil fuels are not considered as a real problem. The R ratio is around 9 to 17%, which means that contribution of infrastructure is not negligible.

Water resources use is however completely ignored by all these approaches. At the endpoint level, following [3] there is no contribution of water to the damage to AoP Resources since the average water withdrawal is lower than the average hydrological availability, i.e. the water resource is considered as abundant. CExD does not provide any additional information since the results cannot be added up over the categories. The R ratio is up to 40% but the relative contribution of the highest categories as compared to the lowest is unknown due to the impossibility of aggregation. What can be said is that the use of renewable resources is consistently considered, independently from the notion of scarcity, but it is refrained to aggregate renewable and non renewable CExDs into a single score because of the loss of information and non substitutability. The SED method overcomes this limitation by implicitly considering the quality of energy sources behind the generation of natural resources. However, the significance of renewable resources, and especially water resources, is still much lower than expected. This result is the combined effect of two reasons. First, solar energy characterization factors (SEFs) of minerals are generally two or three orders of magnitude higher than SEFs assigned to renewable resources. The calculation of SEFs is based on sheer allocation of baseline emergy to all the minerals considered as co-products of earth process, i.e. does not consider intrinsic properties (i.e. composition) neither the actual transformation processes of past geological ages from which minerals originated. This leads to possible overestimation of the SED of minerals like "sodium chloride", which dominates the SED for operation. The same does apply to metal resources, where SEFs are based on ore grade cut-off (OGC) values and enrichment ratios [11] which are quite uncertain and depend again on economic demand and extraction technology. As a result, the SED fails in providing a more accurate picture of the use of (renewable) natural resource mainly because of the lack of accuracy and transparency of the calculation of SEFs, which are largely based on old literature values.

To conclude, this study has shown that a consistent framework for natural resource use evaluation is far from being settled at the moment. First current LCIA methods centred on the notion of scarcity (AoP Resources) essentially focus on fossil fuels (and partly mineral and metals) and provide heterogeneous results with no clear guidance. Renewable resources, and especially water resources, are not evaluated at all or at best not properly considered. An emergy-based method like SED could provide a suitable scheme for a proper consideration of renewable and non renewable sources (through the consideration of the effort spent by nature to make the resources available) and for their further aggregation into a single score accounting for their different quality. However, this approach is still at its infancy and needs important research efforts to develop more consistent calculation of SEFs. A paradigm shift, from human-oriented to nature-oriented perspective, is needed. The authors are currently actively involved in these scientific challenges and will disseminate further results in the near future.

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