Assessing and improving the eco-efficiency of a bottling plant using a systemic approach

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Abstract
Eco-efficiency has recently become an important concept of environmental decision making, and, if linked with resource efficiency, can enhance sustainability. Based on the recognition of eco-efficiency as a suitable measure of progress towards a greener industrial sector, the current paper presents a systemic approach for the eco-efficiency assessment of a meso-level water use system and its application in a soft drink bottling industry in Greece. The proposed approach captures the complexity of all interrelated aspects and the studied system includes the corresponding production chain, the water supply chain and the background system (energy, raw materials and supplementary resources production processes). The analysis reveals the most important environmental impacts of the system and leads to the identification and assessment of indicative alternative solutions which could potentially improve both the economic and the environmental performance of the system.
Key words: eco-efficiency, water use system, industrial sector

1. INTRODUCTION

The concept of eco-efficiency was originally defined during the 1990s when it became evident that the economic spur and industrial development were the main causes for the global environmental deterioration. Initially, eco-efficiency was described as the ability of a business to deliver competitively priced goods/services while reducing ecological impacts and resource use throughout their lifecycle [1]. Since then many definitions have been formulated and among them the more generic one states that eco-efficiency is the efficiency with which ecological resources are used to meet human needs. It can be expressed as the ratio of an output (the value of products and services produced by a firm, sector or economy as a whole) divided by the input required (the sum of environmental pressures generated by the firm, the sector or the economy) [2]. Therefore, eco-efficiency appears to be a relative term that can be increased with an improvement in the economic performance, a decrease in the environmental impact or both. Thus, it needs to be linked with resource efficiency to enhance sustainability by aiming to minimize the use of the required resources while reducing the impacts on the environment. The assessment of the eco-efficiency enables studying the environmental impacts of a product or service system along with its added value.

The objective of this paper is to briefly present a methodology for the systemic eco-efficiency assessment of a meso-level water use system, developed during the EcoWater Project [3], a Research Project supported through the 7th Framework Programme of the European Commission. In general, a meso level water use system combines the typical water supply chain, including all the processes needed to render the water suitable (both qualitatively and quantitatively) for use, with the treatment and discharge of the generated effluents to the environment and with the corresponding production chain. The motivation for choosing water use system arises from the fact that water is a critical resource for all activities in a human society, confirmed by the fact that the three-fold increase of the global population in the last century was followed by a six-fold increase in the global water consumption [4].

The proposed approach has been applied to an industrial meso-level water use system, built around on a soft drink bottling company in Greece. Eight relevant eco-efficiency indicators are estimated, both for the current situation and after upgrading the system, and are compared in order to identify potential improvements or deteriorations to the eco-efficiency of the system.

2. METHODOLOGY

The methodology has been already presented by the authors in detail [5] but for the purposes of the current paper has been expanded in order to include in the analysis the background processes, i.e. the processes that supply all the necessary resources to the studied system. For coherency reasons the entire approach is summarized in the following sections.

Four main steps can be identified: (a) the framing of the system, (b) the baseline eco-efficiency assessment, (c) the identification of innovative technologies/practices towards improving both environmental and economic performance of the system and (d) the eco-efficiency re-assessment of the system.

2.1 System framing

The mapping of the system includes the definition of its boundaries, its special characteristics and the functional unit. A generic meso-level water use system is represented as a network of unit processes (Figure 1) and incorporates both the physical structure of the system and the rules governing the operation, performance and interactions of the system components. Each process corresponds to an activity where materials are processed and converted into other materials, while emissions are released to the environment (air, land, water) or into the system water flow.

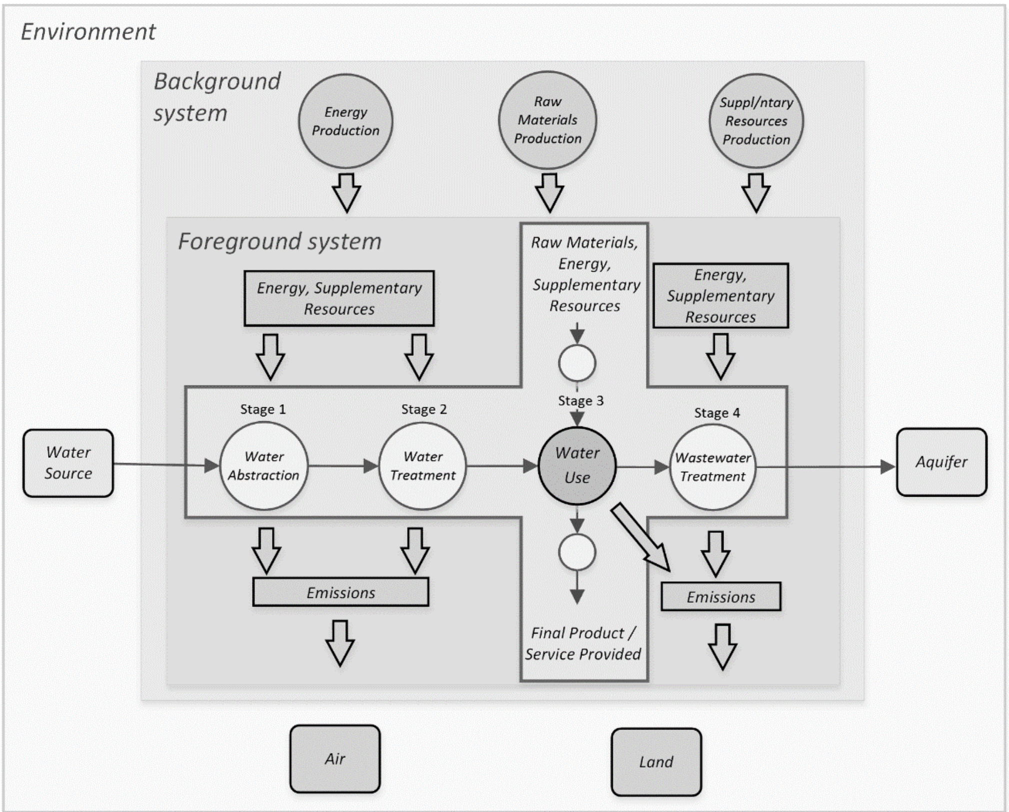

Figure 1. The generic meso-level water use system

An important element of the approach is the distinction between "foreground" and "background" system. The foreground system consists of the set of processes, whose selection or mode of operation is affected directly by decisions based on the study, and which can be described based on case-specific primary data. The background system includes all other activities which produce and deliver energy, raw materials and other supplementary resources materials to the foreground system. It is assumed this is achieved via a homogeneous market so that individual plants and operations normally cannot be identified. Thus, data for the background system is considered to be generic, normally representing a mix or a set of mixes of different processes [6]. The first step of the analysis is completed with the definition of the functional unit that provides a reference to which results are normalized and compared [7]. Possible functional units for a meso-level water use system are: (a) one unit of product/service delivered or (b) one unit (e.g. m^3) of water used.

2.2 Baseline eco-efficiency assessment

A typical eco-efficiency assessment consists of three phases [8]:

- Environmental performance assessment;
- Value assessment; and
- Quantification of the eco-efficiency.

The environmental performance of the water-use system is assessed following a life-cycle oriented approach and entails the use of standardized midpoint impact categories [9]. Representative categories of different impacts on human health, natural environment and availability of resources, are selected and provide a common basis for consistent and robust environmental performance analysis. The overall contribution for each impact category c is expressed as a score *(ES_c):*

$$ES_{c,fore} = \sum_r cf_{r,c} \times f_r + \sum_e cf_{e,c} \times f_e + \sum_r ef_{r,c} \times f_r \tag{1}$$

The first two terms express the contribution of the foreground system, which is calculated by multiplying the actual resource and emission flows (f_r and f_e, respectively) with the corresponding characterization factors (cf_r and cf_c), available in LCA databases. The final term expresses the contribution of the background system. It is estimated by using environmental impact factors ($ef_{r,c}$), representing the environmental impacts from the production and/or transportation of one unit of a resource r to each impact category c. They are calculated based on background or secondary data taken from LCA databases, either open-source (such as the ELCD database) or included in commercial LCA software.

However, since a standardized environmental midpoint indicator for the freshwater resource depletion has not been yet unanimously defined, the Freshwater Ecosystem Impact (*FEI*) indicator is used and estimated as follows:

$$FEI = f_{w,abs} \times WTA \tag{2}$$

where $f_{w,abs}$ is the freshwater abstracted and *WTA* is the water withdrawal to availability ratio for the examined basin. Due to lack of standardization, there is no available data for the background processes.

The economic performance of a value chain can be assessed by using either a physical quantity or a financial term. In the case of a water use system, which combines a water supply chain and a production chain, the selected indicator to express its economic performance, is the Total Value Added (*TVA*) to the product due to water use, expressed in monetary units per period, in general per year (€/year). It is estimated as:

$$TVA = EVU + VP_{BP} - TFC_{WS} - TFC_{WW} - FC \quad (3)$$

where *EVU* is the total economic value from water use, VP_{BP} the income generated from any by-products of the system, TFC_{WS} the total financial cost related to water supply provision for rendering the water suitable for the specific use, TFC_{WW} the total financial cost related to wastewater treatment and *FC* the annual equivalent future cash flow generated by the introduction of new technologies in the system. The *EVU* is calculated using the residual value approach by subtracting the expenses for all the non-water inputs as well as the costs related to emissions in the water use stage (EXP_{NW}) from the total value of the products *(TVP)*.

$$EVU = TVP - EXP_{NW} \quad (4)$$

The Eco-Efficiency Indicator (EEI_c) for each impact category *c* is defined as the ratio of the *TVA* to ES_c.

$$EEI_c = TVA/ES_c \quad (5)$$

Thus, an increase in the value of the indicator reflects an improvement of the overall system's eco-efficiency performance. Eco-efficiency indicators do not depend on the functional unit considered.

2.3 Selection of innovative technologies

A preliminary selection of innovative technologies can be made based on existing lists of Best Available Techniques and the relevant literature for the corresponding industrial sector. The upgrading of a water use system can be achieved through one or more of the following alternative ways [10]:

- Process upgrading aiming to a more efficient transformation of the inputs into outputs, by introducing new technologies or by recycling/reusing the generated wastewater/effluents;
- Product upgrading, by changing to a more profitable product line (i.e. a product with higher economic value); and
- Functional upgrading, by acquiring new functions in the value chain (i.e. marketing).

In accordance to the European policy framework, resource efficient technologies, pollution preventing technologies and technologies enhancing circular economy can be case applicable. The final selection is guided by the baseline eco-efficiency assessment of the system that reveals its vulnerabilities and its environmentally weak stages.

2.4 Eco-efficiency re-assessment of the system

The selection of technologies is followed by the development of alternative technology scenarios. A technology scenario can be defined as "the implementation of (at least) one innovative technology in the system under study, assuming that all other parameters remain the same". For each technology scenario an individual eco-efficiency assessment is conducted in order to be compared to the baseline scenario and to reveal potential improvement to the eco-efficiency performance.

3. THE CASE OF A BOTTLING PLANT

The industrial sector is one of the main water consumers both on European and national level, by consuming more than 15% of the total freshwater abstracted in the EU, while at the same it aggravates the environmental pressures, through the disposal of contaminated effluents into receiving water bodies. More specifically, for the beverage production industry, water is the one of the most essential raw materials required for the production of soft drinks, as well as a necessary supplementary resource, used for steam production and cleaning purposes.

3.1 System framing

The selected beverage bottling company is located at the administrative region of Peloponnese. The unit operates approximately 240 days per year and the maximum daily capacity reaches 177600 polyethylene terephthalate (PET) bottles or equivalently 266400L of soft drinks. More specifically, the plant produces soft drinks by mixing juice condensates with sugar and essence. The mixture is stirred until it becomes homogeneous, and then fed to the bottling lines with the simultaneous addition of carbon dioxide (if necessary depending on the product). The bottles are capped, washed, labeled and packaged in 1.5L PET bottles. The schematic representation of the examined system is presented in Figure 2, where black arrows represent the water flows, gray arrows represent the wastewater flows and dotted arrows the production line.

The foreground system includes three stages related to the production chain (preparatory and cleaning processes, beverage production and bottling) and two stages related to water supply and wastewater treatment. The background system consists of the activities that produce and deliver energy (heavy fuel oil, diesel, electricity) and chemicals (e.g. sodium chloride, sodium hydroxide, chlorine) to the system. The detailed flowchart and preliminary data were acquired from an Environmental Impact Assessment study of an existing bottling plant in Greece while the data for the background activities is obtained by LCA databases. The selected functional unit is the 1 m^3 of water used in the production of the soft drink as the flow of interest is the water used for the production.

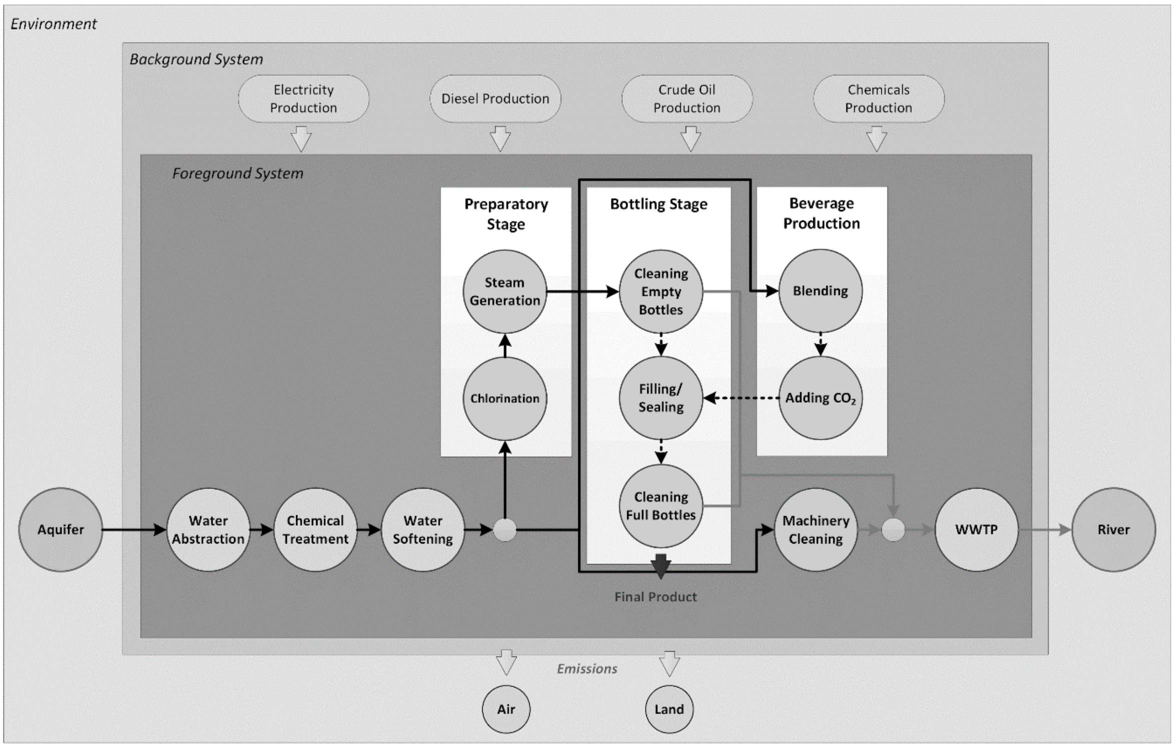

Figure 2: Schematic representation of the studied system

3.2 Baseline eco-efficiency assessment

The main raw materials required for the production of soft drinks are juice concentrates, sugar, carbon dioxide and water, with daily required amounts 805 kg, 18315 kg, 1831.5 kg and 266.4 m^3 respectively. Water can be also considered a supplementary resource, as hot water is used for cleaning and sterilizing the bottles (both empty and full) and for machinery cleaning. Hot water is produced in three heavy fuel oil fired steam boilers, with an average oil consumption of 4.6 kg/m^3

of soft drink. All the other machinery of the unit consume electricity. More specifically, the processes of blending, filling and cleaning of full bottles require 1.58kWh, 3.96kWh and 55.4kWh per m^3 of soft drink, respectively, while the general machinery cleaning consumes 0.12kWh/m^3.

Concerning water supply, water is abstracted from two private owned drilling installations located nearby, using diesel pumps with a specific consumption of 0.035 L per m^3 of water. In the studied system, the wastewater, from the production chain, is considered to be the main source of pollution and thus, a Wastewater Treatment Plant (WWTP) operates to ensure that the concentrations of the released effluents comply with the environmental regulations. The environmental performance of the system is assessed through eight environmental impact categories. The characterization factors included in the CML-IA database [11] are used for the calculation of the corresponding indicators and the results are presented in Table 1.

The TVA to the final product from the water use is calculated based on the unit costs of the raw and supplementary resources for the year 2013, which were provided by the local suppliers. Concerning energy sources, the average price of electricity is assumed to be 0.01 €/kWh, diesel price is approximately 1 €/kg while the price of heavy fuel oil is 0.6 €/kg. Furthermore, it is also assumed that the concentrates are not bought but provided by another industrial unit of the same company. The O&M costs (including salaries, taxes, other expenses) of the plant are estimated, approximately, 5000€ while the O&M cost for the operation of WTP is assumed to be 2000€, both on monthly basis. Finally, the average unit price of a soft drink bottle of 1.5lt was 1.8 € in 2013 [12]. Based on this data, the *TVA* is estimated to be 65.3 €/m^3 of soft drink produced or 46.2 €/m^3 of water used.

The eight relevant eco-efficiency indicators are calculated and presented in Table 1. However, the absolute values do not directly indicate the weaknesses of the system. By comparing them to the values of two other water use systems, a dairy industrial unit producing milk powder and a typical Mediterranean farm [3], it can be pointed out that the main environmental pressures are freshwater ecotoxicity, terrestrial ecotoxicity and climate change, with values lower than at least one of the two other systems.

Table 1. Environmental and eco-efficiency indicators for the examined bottling industry compared with eco-efficiency indicators for a dairy industry and a typical farm

Midpoint Impact Category	Unit	ES_C	EEI_C (in €/Unit)	Dairy Industry	Typical Farm
Climate Change	kg CO_2eq	83.7	0.55	0.03	1.08
Photochemical Oxidation	kg C_2H_4 eq	0.03	1397	3271	8417
Eutrophication	kg PO_4^{-3}eq	0.03	1668	0.99	109
Acidification	kg SO_2^- eq	0.56	82.5	3.1	82.6
Human Toxicity	kg 1,4-DB eq	1.52	30.4	28.5	19.9
Freshwater Ecotoxicity	kg 1,4-DB eq	13.3	3.47	737	74.5
Terrestrial Ecotoxicity	kg 1,4-DB eq	0.13	369	630	3886
Freshwater Depletion	m^3	0.15	308	203	7.0

A breakdown analysis of the environmental impacts (Figure 3) is also necessary in order to reveal whether the foreground or the background system has the greater contribution to the overall environmental impacts. It is obvious that the background system, and more specifically electricity and heavy fuel oil production, are responsible for the majority of the environmental impacts. The foreground system mainly contributes to (a) freshwater depletion, due to increased water consumption and high losses among the stages of the production process, (b) acidification and climate change due to the emissions from diesel and heavy oil consumption and (c) eutrophication due to the presence of P and N in the water effluents.

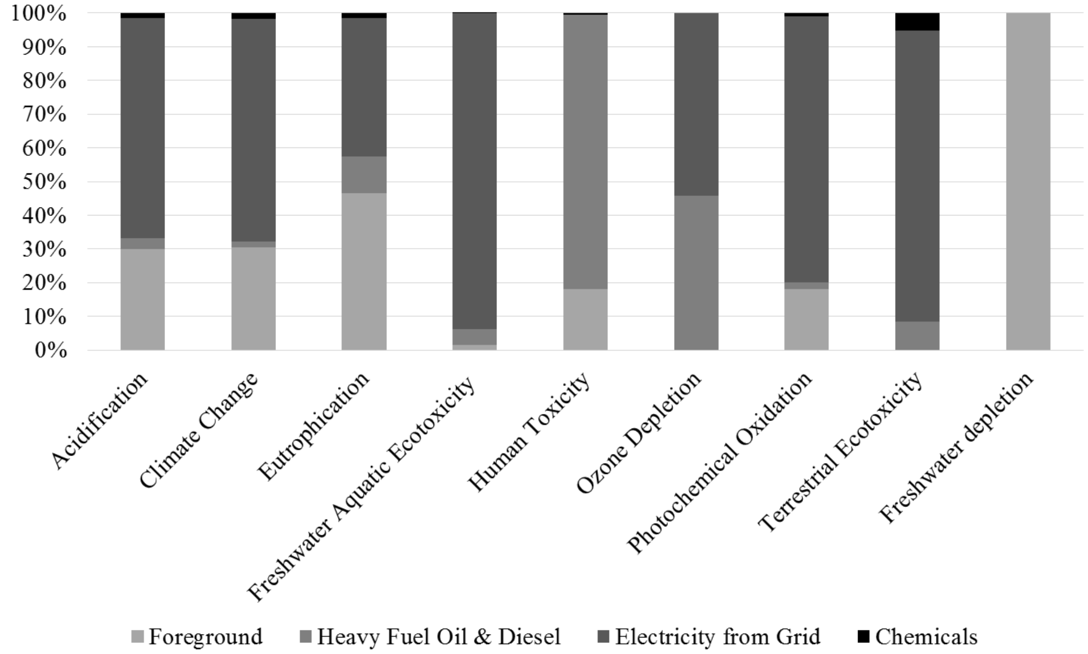

Figure 3. Breakdown analysis of the environmental impacts

3.3 Selection of innovative technologies

The upgrading of the value chain is mainly driven by the weaknesses of the foreground system. However, according to the breakdown analysis, such interventions may not entail significant improvement on all eco-efficiency indicators but only on the ones affected by the foreground. Having said that, two alternative solutions were proposed in order to improve the eco-efficiency of the system: (a) recycle and reuse of water for cleaning purposes, which will mainly affect the impact of the foreground system and (b) installation of a natural gas fired CHP system which will have a positive impact both on the foreground (by reducing direct emissions) and the background system (by reducing the resources used and eliminating the use of heavy fuel oil). However, only the first solution was examined since the second one was judged to be not economically viable, due to the high investment cost and the prevailing economic conditions in Greece.

Table 2. Eco-efficiency indicators of baseline and water reuse scenario

Midpoint Impact Category	Unit	Total		Foreground	
		Baseline	Water Reuse	Baseline	Water Reuse
Climate Change	€/kg CO_2eq	0.55	0.55	1.82	1.81
Photochemical Oxidation	€/kg C_2H_4eq	1397	1394	7699	7683
Eutrophication	€/kg PO_4eq	1668	1768	3590	4093
Acidification	€/kg SO_2 eq	82.5	82.4	276	275
Human Toxicity	€/kg 1,4-DBeq	30.4	30.5	168	174
Freshwater Ecotoxicity	€/kg 1,4-DBeq	3.47	3.48	237	306
Terrestrial Ecotoxicity	€/kg 1,4-DB eq	369	368	292	312
Freshwater Depletion	€/m^3	308	312	1.82	1.81

3.4 Eco-efficiency re-assessment of the system

The water recycle and reuse scenario includes the installation of a stainless water recovery tank with capacity of 250L. The water tank collects and stores the run-off water from the cleaning of empty bottles in order to reuse it within the industry for externally cleaning filled bottles and for other general cleaning purposes. It is assumed that the total installation cost is 500€ and its lifetime 5 years. The TVA from water use in that case is 65.3 €/m^3 of soft drink produced or 49.4 €/m^3 of water used. Table 2 presents the eco-efficiency indicators for the two scenarios. It is obvious that the water reuse scenario slightly improves the majority of the indicators; however, the impact is more obvious when comparing only the contribution from the foreground systems. Nevertheless, the improvement is very low and alternative more radical solutions should be sought, which may require higher investment costs.

4. CONCLUSIONS

The concept of eco-efficiency has proven to be a suitable measure of progress towards a greener and more sustainable economy. This paper presented a methodological framework that uses eco-efficiency indicators in meso-level water use systems. This approach was applied successfully to the water use system of bottling plant. Apart from the case specific solutions that were examined, the application has also revealed one main weakness of the approach; the lack of reference values for eco-efficiency indicators which will allow a better interpretation of the calculated numerical values. The application of the methodology to other water use systems is thus suggested as an area of further research in order to outline a range for each indicator and define reference values for normalizing them.

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