Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2017.0523

63 (2017) 343–350
February

Systemic eco-efficiency assessment of industrial water use systems

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Received 10 May 2016; Accepted 26 October 2016

ABSTRACT

Eco-efficiency can become the basis of an environmental decision making framework, towards a greener economy, by combining the economic welfare with the ecological impact of products. It has been already highlighted that a potential enhancement to the eco-efficiency of a given system may also lead to the improvement of its sustainability, if it is successfully linked with resource efficiency and eco-innovation. Thus, there is the need to develop a set of eco-efficiency indicators, for measuring the environmental and economic performance of a given system, and, more importantly, to define a range for each one of them in order to allow better interpretation of the calculated numerical values. The current paper briefly presents a systemic eco-efficiency assessment methodological framework, which is then applied to three industrial water use systems, a bottling plant, a textile dyeing industry and a dairy industrial unit, in an attempt to frame and compare the selected eco-efficiency indicators. The proposed approach captures the complexity of all interrelated aspects and each 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 does not attempt to identify the industry with the best eco-efficiency performance but to reveal the most important environmental impacts of each system through a relative comparison on eco-efficiency basis is conducted. It also provides useful insight about the weaknesses of the methodology and suggests ways to overcome them.

Keywords: Eco-efficiency indicators; Industrial sector; Water use systems

1. Introduction

During the 1990s, when the industrial development was followed by global environmental degradation and increasing pressures, it was critical to simultaneously assess the economic and environmental performance of industrial systems. Thus, the concept of eco-efficiency was introduced as a common basis among the industrial world in order to describe the efficiency with which ecological resources are used to meet human needs [1]. 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].

Moving further from the initial approach, several studies attempting to measure eco-efficiency have been conducted on different scales, national [3,4], regional [5,6] or even for a specific sector/industrial plant [7,8] by applying various alternative methodologies [9,10]. As a result, in 2012, a standardized process for the eco-efficiency assessment of a product system has been introduced, using an LCA-oriented approach [11].

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Presented at the 5th International Conference on Environmental Management, Engineering, Planning and Economics (CEMEPE), 14–18 June 2015, Mykonos, Greece.

However, the proposed framework does not define a clear and homogeneous way of estimating the economic performance of the system. Moreover, there is a lack of benchmarking values for the most widely used eco-efficiency indicators which would facilitate the comparison between different systems or alternative configurations of the same system.

Towards that end, a systemic methodological framework has been developed during the "EcoWater - Meso-level eco-efficiency indicators to assess technologies and their uptake in water use sectors" Project [12], a research project supported through the 7th Framework Programme of the European Commission. The methodological framework has been already presented by the authors in detail [12,13] but in this paper, it has been updated in order to include the impacts from the background systems. The main objective of the paper is to apply the methodology to an industrial meso-level water use system, a soft drink bottling plant, and compare the results with two other industrial case studies. Such comparison will not lead to a ranking of the industries based on their eco-efficiency but will reveal the environmental or economic weaknesses of the systems and thus identify potential actions to improve their eco-efficiency. Moreover, the application of the methodology in several water use systems will eventually lead to the definition of a range of values for the selected eco-efficiency indicators.

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 systems, as the basis for the analysis, arises from the fact that water is a critical resource for all activities in a human society while it can be confirmed that the 3-fold increase of the global population in the last century was followed by a 6-fold increase in the global water consumption [14].

2. Methodology

The proposed methodological framework consists of four main steps [12,13]: (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. For the purposes of the current paper only the first two steps will be applied in the selected systems but for coherency reasons, the entire approach is briefly summarized below.

2.1. System framing

The initial step towards eco-efficiency assessment is the definition of the system's boundaries, the identification of all involved activities, where materials are processed and converted into other materials, and the selection of a functional unit. A key characteristic element in a typical life-cycle approach is the distinction between "foreground" and "background" systems. The distinction is based on the direct or indirect linkage to the examined system. The foreground system includes all processes, whose operation is affected directly by decisions based on the study, and which can be described based on case-specific primary data. The background system comprises of all the processes which produce and deliver energy and all the supplementary resources required for 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 [15]. The first step of the analysis is completed with the definition of the functional unit. The functional unit is the foundation of a Life Cycle Assessment (LCA) [16], because it sets the scale for comparison of two or more products or services delivered to the consumers and provides a reference to which results are normalized and compared [17]. 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

An eco-efficiency indicator can be expressed quantitatively as the ratio of an economic output (benefit) provided by the system to the environmental impacts (costs) associated with that. Thus, the eco-efficiency assessment of a system includes the environmental and economic assessment. According to the ISO for the eco-efficiency assessment of product systems [11], the environmental impacts should be assessed using a LCA approach while the value of the product or service system may be chosen to reflect its resource, production, delivery or use efficiency, or a combination of these. Consequently, an eco-efficiency assessment shares with LCA many important principles and approaches such as life cycle perspective, life-cycle inventory and Life Cycle Impact Assessment (LCIA).

2.2.1. Environmental assessment

The evaluation of the environmental impacts follows the main stages of the typical LCA (Life Cycle Inventory Analysis and LCIA) [17]. Life Cycle Inventory Analysis involves creating an inventory of flows entering and leaving every process in the foreground system, while the LCIA aims at evaluating the significance of potential environmental impacts based on the inventory of flows.

The assessment of the environmental performance of the water-use system is implemented by using of standardized midpoint impact categories [17]. 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 comparison. The overall contribution for each impact category c is expressed as a score (ES_c):

$$ES_c = \sum_r cf_{r,c} \times f_r + \sum_e cf_{e,c} \times f_e + \sum_r ef_{r,c} \times f_r \quad (1)$$

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 ($cf_{r,c}$ and $cf_{e,c}$), 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*. These are calculated based on background or secondary data retrieved from LCA databases.

Impacts from the use of freshwater are far from being standardized in current LCIA practice. Most studies have neglected this issue or treated it as a simple indicator, expressing the volume of abstracted water by the product system. However, in the case of water use systems, freshwater resource depletion cannot be neglected. In the proposed approach, the methodology presented by Mila I Canals et al. [18] is used. It is based on the Freshwater Ecosystem Impact (*FEI*) indicator, which addresses the potential effects on aquatic ecosystems caused by changes in freshwater availability due to abstraction, and is defined as:

$$FEI = f_w \times WTA \tag{2}$$

where f_w is the freshwater abstracted and *WTA* is the water withdrawal to availability ratio. The latter can be defined as:

$$WTA = WU / WR \tag{3}$$

where *WU* is the total annual freshwater withdrawal in a river basin and *WR* represents the annual freshwater availability in the same basin.

2.2.2. Economic assessment

The economic performance of a value chain is assessed using the total value added (*TVA*) to the product due to water use, expressed in monetary units per period (i.e., €/year) and estimated as follows:

$$TVA = TVP + VP_{BP} - TFC_{WS} - TFC_{WW} - EXP_{NW} - FC \tag{4}$$

where all system related expenses are subtracted from the income generated from the products (*TVP*) and by-products (VP_{BP}) of the system. TFC_{WS} represents 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, EXP_{NW} the expenses for all the non-water inputs as well as the costs related to emissions in the water use stage and *FC* the annual equivalent future cash flow generated by the introduction of new technologies in the system.

2.2.3. Eco-efficiency quantification

The eco-efficiency indicator (EEI_c) for each impact category *c* is defined as the ratio of the *TVA* to the corresponding ES_c:

$$EEI_c = TVA / ES_c \tag{5}$$

Thus, an increase in the value of the indicator reflects an improvement of the overall system's eco-efficiency performance, which may be the result of an increase of the *TVA*, a decrease of the environmental impact or even both. It should also be noted that the value of eco-efficiency indicators does not depend on the functional unit considered.

2.3. Selection of innovative technologies

The upgrading of a water use system can be achieved through one or more alternative ways [19]. 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. 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. Industrial water use systems

The proposed approach has been applied to three industrial meso-level water use systems, a soft drink bottling company and a dairy industry located in Greece and a textile dyeing industry in Italy. In all three cases, water is one of the most essential raw materials required for the respective production chain. More specifically, for the beverage production unit, water is mostly used as a component of the final product whereas for the dairy and textile industry, water is an important supplementary resource used for steam production and cleaning purposes. Seven relevant eco-efficiency indicators are estimated and compared, with a twofold objective; (a) to identify the weaknesses of each system and (b) to attempt defining a set of reference values for the eco-efficiency indicators in the industrial sector.

The following sections present the system framing and the eco-efficiency assessment of the three selected industrial case studies. Emphasis is given on the bottling company, which has not been presented again extensively, whereas the other two are briefly outlined and are mainly used for comparison and benchmarking purposes. More details can be found in the corresponding papers, presenting them in detail [20,21].

3.1. System framing

3.1.1. The case of the bottling plant

The studied beverage bottling company is located at the administrative area of Peloponnese. The unit operates approximately 240 days per year and the maximum daily capacity reaches 177,600 polyethylene terephthalate (PET) bottles or equivalently 266,400 L 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 1.5 L PET bottles. The schematic representation of the examined system is presented in Fig. 1, 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 the plant while the data for the background activities were retrieved from 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.

The main raw materials required for the production of soft drinks are juice concentrates, sugar, carbon dioxide and water, with daily required amounts 805, 18,315, 1,831, and 266 m^3, respectively. Hot water, used for cleaning and sterilizing the bottles (both empty and full) and for machinery cleaning, 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 1.58, 3.96 and 55.4 kWh per m^3 of soft drink, respectively, while the plant cleaning machinery consumes 0.12 kWh m^{-3}.

Water is abstracted from two private owned drilling installations located in the premises, using diesel pumps with a specific consumption of 0.035 L per m^3 of water. In the studied system, 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 background processes that are taken into consideration for the calculation of the indicators are energy production and supply (crude oil, diesel, and electricity) and chemicals production.

The unit costs of the raw and supplementary resources were provided by local suppliers, for the year 2013 (sugar 0.63 € kg^{-1}, sodium hydroxide 1.6 € L^{-1}). Concerning the energy sources, the average price of electricity is assumed to be 0.03 € kWh^{-1}, diesel price is approximately 1 € kg^{-1} while the price of heavy fuel oil is 0.6 € kg^{-1}. Furthermore, it is also assumed that the concentrates are not bought but provided

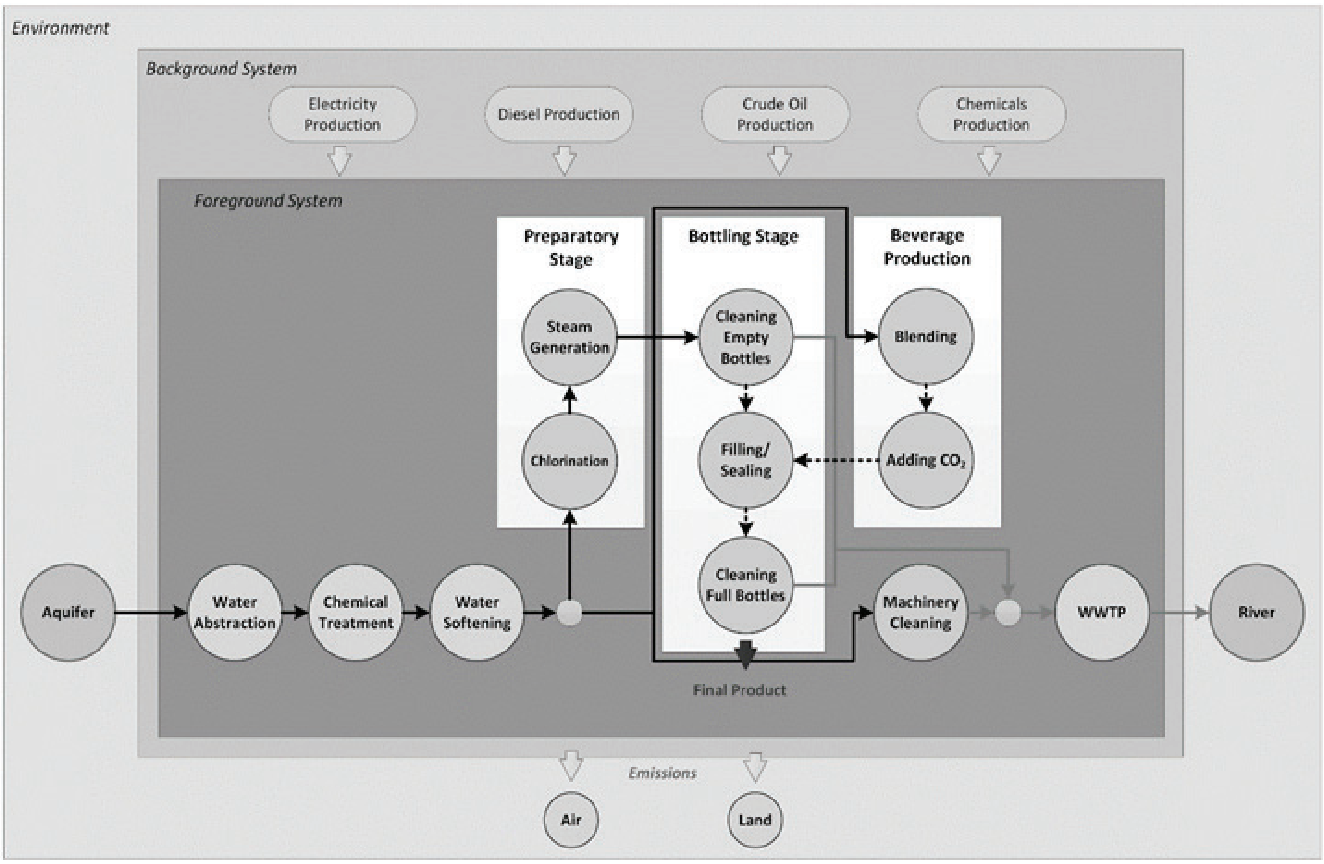

Fig. 1. Schematic representation of the bottling plant.

by another industrial unit of the same company, so there are no expenses related to these. 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 1.5 L was 1.8 € in 2013 [11].

3.1.2. The case of the textile industry

The selected system comprises of two textile industries located in Biella, a province of northern Italy in the Piedmont Region. They produce 990 tonnes of dyed product, of which 892 tonnes using conventional chemical dyeing techniques and 98 tonnes of naturally dyed product, on an annual basis. The foreground system consists of four stages, namely water abstraction, distribution, use (focusing on dyeing) and wastewater treatment. The background system consists of the production processes of the supplementary resources (electricity and natural gas) and raw materials (dyes, additives, wool). However, only the electricity and natural gas production processes are taken into consideration for the eco-efficiency assessment, due to lack of data for the other processes. The functional unit is 1 m^3 of water used in the dyeing process.

It is estimated that 1 kg of dyes and additives, 0.15 m^3 of water, 1.2 kWh of electricity and 0.6 m^3 of natural gas are consumed per kg of chemically dyed wool. The natural dyeing process requires less electricity (1.27 kWh per kg of wool) but higher quantities of dyes and water (0.5 kg of dyes and 0.2 m^3 of water per kg of wool), while the required amount of natural gas remains the same. Water is abstracted from private wells and from the local river using electric pumps, with average specific consumption of 0.12 kWh per m^3 of water abstracted. Finally, there is an in-house WWTP that consumes 0.7 kWh of electricity per m^3 of wastewater treated [20]. All financial details required for the calculation of the TVA have been collected through the local stakeholders. The price of electricity is 0.18 € kWh^{-1} and of natural gas is 0.45 € m^{-3}. Chemical dyes and additives can be bought for 5.2 € kg^{-1} but the price may reach 10–11 € kg^{-1} for a natural dye. However, the difference in the price of the final product is inversely proportional, and ranges from 7 to 8 € kg^{-1} for a high quality chemically dyed product up to 15–20 € kg^{-1} for a naturally dyed one. The unit pays a fixed annual fee to the municipality for water abstraction rights (2,200 €) and the O&M cost for the operation of in-house WWTP are assumed to be 0.35 € m^{-3} of treated wastewater. Finally, the variable annual O&M costs of the plant are estimated, approximately, 0.16 € kg^{-1} product.

3.1.3. The case of the dairy industry

The selected dairy industry produces and delivers of a variety of dairy products, such as milk, cheese, yogurt etc. In the current paper only the bottled milk production chain is examined. Thus, the foreground system consists of the main industrial processes involved (filtering, mixing, pasteurization, standardization, bottling and storage), as well as all stages required for water supply and wastewater treatment. Two interrelated actors are mainly involved; the industrial unit and the national water and sewerage company, as the operator of water supply network processes and wastewater treatment facilities. The background system includes the supplementary resources (electricity and natural gas) production and distribution network.

The annual average milk production of the unit is estimated to be 190,000 m^3 of milk and the average water requirements are 4.75 m^3 of water per m^3 of milk (67% for cleaning purposes, 26% for steam production and 7% for cooling). Moreover, 6 kg of sugar are consumed per m^3 of milk during the standardization process. Steam is produced using a natural gas fed boiler with average efficiency of 60%. All other energy requirements of the industrial unit are satisfied using electricity, bought from the grid. The total electricity requirement for water abstraction, treatment and distribution is 0.29 kWh m^{-3} of water abstracted whereas 3.5 g of chemicals are used for treating 1 m^3 of water. Before being discharged to the water stream, wastewater is being treated in a WWTP with COD removal efficiency 97% and average electricity consumption of 0.25 kWh m^{-3} of wastewater treated. The unit costs of the raw and supplementary resources were provided by local suppliers, for the year 2013 (sugar 0.4 € kg^{-1}, cleaning chemicals 0.32 €/kg electricity 0.09 € kWh^{-1} and natural gas 0.5 € m^{-3}). The dairy industry buys water from the water utility operator for 1.5 € m^{-3}, pays as a fee 1 € m^{-3} for wastewater collection and treatment and sells the bottled milk for 0.4 € L^{-1}. Finally, the O&M costs (including salaries, taxes, other expenses) of the plant are estimated, approximately, 1 M€ [21].

3.2. Environmental and eco-efficiency assessment

The environmental performance of each studied system is assessed through seven common environmental impact categories. The environmental score for each impact category is estimated using the characterization factors retrieved from the CML-IA database [15]. Moreover, based on the unit costs of the raw and supplementary resources, the TVA to each final product from water use is calculated. Both the environmental scores and the TVA for all three cases are exhibited in Table 1, whereas Table 2 presents the absolute values for the seven eco-efficiency indicators in each case.

A direct cross comparison between the case studies does not directly offer a meaningful insight. The examined production lines differ a lot concerning both the resources used (energy, raw materials) and the value of the final product. Thus the industry with the better eco-efficiency performance cannot be easily determined and, moreover, that is not the objective of the proposed methodology. However, the cross comparison can highlight the environmental strengths and weaknesses of each system. The comparison reveals that the majority of the environmental problems can be identified as common environmental pressures among the industries. Fig. 2 also presents the relative environmental score for the three case studies and it can easily reveal the environmental weaknesses for each one of the industrial plants.

More specifically, the bottling company is the most energy intensive among the three of them, due to both electricity consumption and in-house steam generation (with a low efficiency boiler), resulting to the worst performance in four of the categories (especially climate change and acidification, which are closely related to energy consumption). On the

Table 1
Environmental and economic performance assessment of the three water use systems

Midpoint impact category	Environmental Scores and TVA (in Unit m^{-3} water used)		
	Bottling industry	Textile industry	Dairy industry
Climate change, kg CO_2 eq	83.7	13.6	30.4
Photochemical oxidation, kg C_2H_4 eq	0.03	<0.01	0.01
Eutrophication, kg PO_4^{-3} eq	0.03	0.02	0.01
Acidification, kg SO_2^- eq	0.56	0.05	0.28
Human toxicity, kg 1,4-DB eq	1.52	2.68	1.9
Freshwater ecotoxicity, kg 1,4-DB eq	13.3	22.5	1.36
Freshwater depletion, m^3	0.15	0.15	0.17
TVA, €	46.2	18.3	45.5

Table 2
Eco-efficiency indicators for the examined systems

Midpoint impact category	EEI_C (in €/Unit)		
	Bottling industry	Textile industry	Dairy industry
Climate change, kg CO_2 eq	0.55	1.35	1.50
Photochemical oxidation, kg C_2H_4 eq	1490	1830	4550
Eutrophication, kg PO_4^{-3} eq	1540	915	4780
Acidification, kg SO_2^- eq	82.5	366	162.5
Human toxicity, kg 1,4-DB eq	30.4	6.83	23.9
Freshwater ecotoxicity, kg 1,4-DB eq	3.47	0.81	33.5
Freshwater depletion, m^3	308	122	267.6

contrary, the textile industry, while exhibits a better performance in these indicators, has the worst scores in the indicators related to toxicity (eco-toxicity, human toxicity), due to the disposal of treated wastewater which contain residues of toxic chemical dyes. Finally, all three industries are characterized by a similar score for freshwater resource depletion.

The application of the methodology in various systems could also lead in defining a range for each indicator and possibly estimate reference values for normalizing them. Such an analysis would help towards technology benchmarking for a specific sector by providing a reference value for eco-efficiency improvements. When having a sufficient number of case studies, an initial approximation of this range of values could be achieved through the calculation of the average eco-efficiency indicator values together with the minimum and maximum values. However, this is in our case meaningless and can even be misleading when the sample is too small.

Complementary to that, Fig. 3 illustrates the eco-efficiency assessment results for the three industries. The dairy industry demonstrates the best performance, with above average indicators in six out of seven categories. Moreover, the weak points of the other industries are further highlighted, since the economic performance of all of them is of the same order of magnitude.

Concerning the definition of a range of values for each eco-efficiency indicator, it can be easily pointed out that all three values for each impact category are in the same order of magnitude. This was not the case when comparing water use systems from entirely different sectors (e.g., automotive industry vs. greenhouse) [12], where an eco-efficiency indicator could range from a few decades to a couple of thousands.

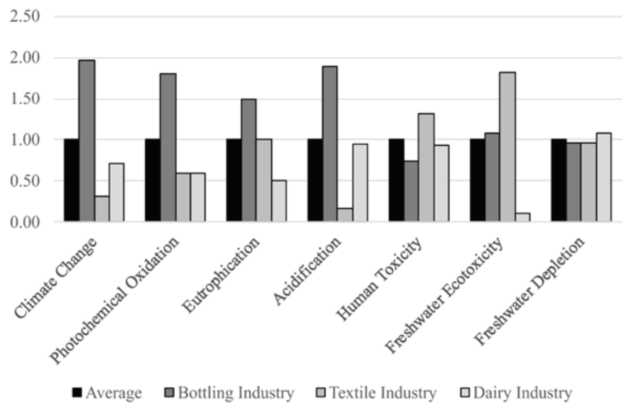

Fig. 2. Relative environmental performance assessment for the three industrial plants.

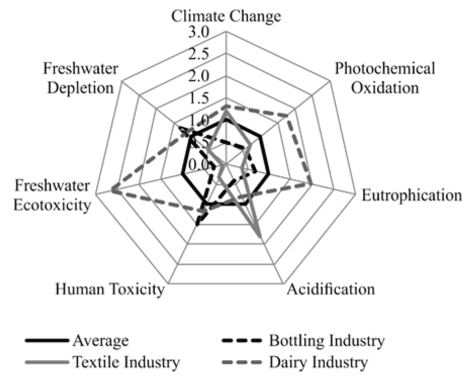

Fig. 3. Relative eco-efficiency assessment for the three industrial plants.

Thus, in order to be able to benchmark and interpret the results of an eco-efficiency assessment, it might be wiser to create range of values for each sector of economic development (e.g., agricultural, services, light industry, heavy industry). Of course, three case studies are not a complete sample but give an overall indication about each one of the indicators.

4. Discussion and suggestions for further research

The concept of eco-efficiency has proven to be a suitable measure of progress towards a greener and more sustainable development. The proposed methodological framework for the systemic eco-efficiency assessment of water use systems can easily highlight the environmental hotspots of a given system and at the same time assess alternative solutions which could lead to better informed decision making towards the improvement of the system's performance.

Moreover, by linking the stages to the corresponding actors, who are responsible for their operation and management, the economically weak actors as well as those who will be negatively affected by the implementation of an alternative solution, could be identified. This could be valuable in order to prioritize specific policy actions, to target the losing actors (e.g., economic incentives such as subsidies or tax exemptions), or to even provide insight when reviewing the legal framework for promoting industrial cooperation or public private partnerships.

However, as it has been previously outlined, the lack of reference values and of a range for each eco-efficiency indicator, which would allow a better interpretation of the calculated numerical values, is a prohibiting factor towards the wide application of the framework. As a starting point to resolve this issue, the proposed methodological framework has been successfully applied to more than fifteen case studies [12,13,20,23]. Yet, the main identified problem has always been the homogeneity in its application among various examined systems. The results are more accurate in the comparison of two different systems with a similar product or two (or more) alternative configurations of the same system [12]. The homogeneity issue is even more pronounced in the case of industrial systems, where the analyzed processes differ significantly in each system, especially if compared to an agricultural or urban water use systems, where a set of common processes and technologies is identified. Moreover, while only specific supplementary resources are consumed in an agricultural water use system (energy, fertilizers, pesticides and seeds) or an urban water supply system (energy and cleaning chemicals), the industrial systems use a variety of chemical substances and supplementary materials. Due to that, a direct impact to the accuracy of the calculation of the environmental scores is noticed as the boundaries of the background system may be over-expanded if it is not defined whether or not the production and distribution processes for all the supplementary resources will be included in the analysis. Thus, a set of cut-off criteria should be applied, which will relate the background processes with the percentage of their contribution to the environmental impacts, in order to define which processes will be excluded.

An environmental breakdown analysis can contribute in setting such criteria, by revealing whether the foreground or the background system has the greater contribution to the overall environmental impacts. In order to create a common basis for comparison and avoid any underestimation, the breakdown analysis should be conducted for all examined systems. However, in the current paper only the bottling industrial plant is examined in such a detail, where six different background systems have been taken into account (Fig. 4), whereas the environmental performance of the textile and dairy industry include only two processes in the background system (electricity and natural gas production and distribution).

From the breakdown analysis of the environmental impacts for the bottling company, it is obvious that 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. Among the background processes, only electricity and heavy fuel oil production are responsible for the majority of the environmental impacts, while the chemicals have a very limited impact to the performance of the system and could have been easily excluded. This also indicates that the comparison among the three case studies is valid since, in reality, the results are affected by the foreground system and the same two background processes.

The last critical issue is to formulate a common approach for the calculation of the TVA to the product due to water use. Originally, the methodology was developed for comparing different configurations of the same system [19,22,23]. In these cases, there was no need for a detailed estimation of the net economic output of each actors, provided that the omitted values (e.g., personnel cost) remained the same under the different configurations. However, when attempting to compare entirely different systems, a more strict definition of the TVA is necessary. This has been the case in the current paper were a common approach has been adopted and all the major components of the industrial plant's economic performance have been taken into account. All these observations may lead us to the conclusion, that it might not be necessary to develop overall generic reference values for the eco-efficiency indicators. Instead, it might be more useful to define a range of values for each sector of economic development (e.g., agricultural, services, light industry, heavy industry).

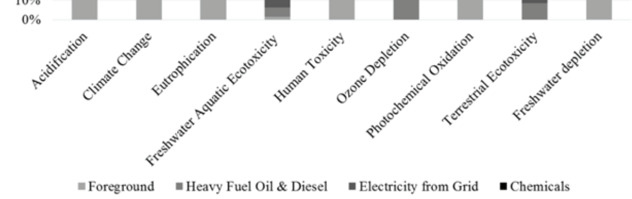

Fig. 4. Breakdown analysis of the environmental impacts of the bottling company.

Acknowledgements

The methodology presented in the paper arises from 'EcoWater: Meso-level eco-efficiency indicators to assess technologies & their uptake in water use sectors', a collaborative research project of the 7th Framework Programme, Grant Agreement No. 282882, coordinated by the National Technical University of Athens (NTUA).

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