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A first iteration of an eco-efficiency assessment of Sofia's urban water system

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Abstract

The recent publication of ISO standard 14045 for eco-efficiency assessment requires a focus on its implementation in a variety of contexts. The ISO standard gives only a general framework; its practical implementation requires a scientific approach. This paper demonstrates how the requirements of the standard were taken into account in an eco-efficiency assessment of technological improvements to Sofia's urban water system. The definition of critical elements - product system, system boundary, system value and environmental performance is discussed. Methods for quantification of the system value and environmental assessment are proposed. Two types of indicators, based on life cycle inventory and life cycle impact assessment, are suggested.

Keywords: Eco-effficiency; ISO 14045; indicators; life cycle assessment; urban water systems

1. Introduction

An oft-repeated mantra from the business world says that "what gets measured gets managed" (Kuosmanen, 2005). Eco-efficiency assessment is a modern quantitative management tool which enables stakeholders to select the most environmentally friendly and the least costly from the range of available alternatives. In 1969 Ford and

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Warford initiated research work on the efficiency of urban water management (Ford and Warford, 1969), and this has been followed by many eco-efficiency related studies. In 2005 Huppes and Ishikawa made an attempt to rationalise eco-efficiency terminology, concluding that “consensus on terminology requires a broader social endeavor, involving the many fora involved” (Huppes and Ishikawa, 2005). In view of the importance of eco-efficiency and the need for a common approach, an ISO standard on eco-efficiency assessment was developed and issued in May 2012 (ISO14045, 2012). The standard describes the overall principles and requirements for eco-efficiency assessment, thus finally providing a sound basis for common interpretation of eco-efficiency and its quantification.

This paper discusses the application of the ISO14045 standard for assessment of the eco-efficiency of Sofia’s urban water system. In compliance with the principles of the standard, a scientific approach is applied in order to adapt the general standard framework to the specific case of an example urban water system (ISO14045, 2012). Eco-efficiency is a relative tool for comparison of different systems or alternatives (ISO14045, 2012). In this study it has been used to compare the current system, called the “baseline scenario” with other scenarios in which different innovative technologies and practices replace some of the existing ones. According to the standard, the eco-efficiency assessment comprises five phases, whose execution requires an iterative approach (ISO14045, 2012).This paper presents the first iteration, which is the development of the methodological framework. The discussions are focused on the most critical elements.

Since publication of this standard less than a year ago, no other research papers addressing the subject have been found, although there are number of past studies of the eco-efficiency of the urban systems (Flower et al., 2007; Lane et al., 2011; Venkatesh et al., 2011, etc.).

Nomenclature

CSOs	combined sewer overflows
GHG	green house gases
LCA	life cycle analysis
LCI	life cycle inventory
LCIA	life cycle impact assessment
PAHs	polyaromatic hydrocarbons
WPP	water purification plant
WSI	water stress index
WWTP	wastewater treatment plant

2. Quantification of the eco-efficiency

Eco-efficiency quantification requires environmental performance to be related to the product value, according to the goal and scope definition (ISO14045, 2012). The most commonly used mathematical expression is:

$$Eco\text{-}efficiency = \frac{Product\ value}{Environmental\ performance} \tag{1}$$

Determination of these categories – goal, scope, product value and environmental performance for the case study at Sofia are discussed below.

3. Sofia case study

3.1. Sofia urban water system - baseline scenario

Sofia's urban water system serves a population of about two million, of whom some 1.3 million are permanent residents. There are also non-domestic users (industries and public facilities). The percentage utilized water in 2011 was approximately 60% for domestic and 40% for non-domestic users. The water supply system consists of 2 main water sources, 3 water treatment plants, 23 pumping stations, 112 water tanks and around 4000 km distribution network. The sewerage system, serving around 98% of users, is combined and gravity-driven with total length of around 1500 km, with 169 CSOs. Before being discharged into the Iskar River, the wastewater is treated at the Sofia WWTP. The plant has suspended activated biomass for removal of organic compounds, phosphorus and nitrogen and the sludge is treated using mesophyll digestion in methane tanks.

3.2. Justification of selected innovative technologies for the comparative scenarios

There are two major operational problems in Sofia's urban system: first high leakage in the water supply distribution networks, due to old pipes and high pressure; and secondly incidental river pollution from overflow of the CSOs. Possible innovative technologies to improve urban water systems are shown in Table 1. Two innovative technologies appropriate for mitigating Sofia's major operational problems are T1 and T5 in Table 1, and these are selected for further consideration.

Sofia is situated in the Upper Iskar basin, which is under water stress, as indicated by the WSI varying around 0.4 (Ribarova, 2009). The available natural water is not sufficient to supply all needs – human, agricultural and industrial consumption. This provides the stimulus for more efficient water use and justifies the adoption of technology T2 of Table 1.

Flower et al. (2007) revealed that residential water use appliances are responsible for significantly more GHG emissions than all upstream and downstream operations. They conclude that urban water systems should focus on reducing the energy and water consumption associated with household water use. Because of these findings and since global warming is one of the biggest environmental problems, two technologies for reducing the energy demand in households were included for study, T3 and T4 of Table 1.

Table 1. Technologies, which will be used in the comparative scenarios

N	Technology name	Unit of implementation	Description
T1.	Hydropower generator which functions as a pressure reduction valve	Distribution network	Reduce pressure and flow while generating electricity which can be used on site or exported to the grid.
T2	Water saving appliances (low flushing toilets, shower heads, dishwashers)	Households	Appliances which reduce the consumption of water in households
T3	Solar water heating	Households	Use of solar energy for heating the water in the households
T4	Heat recovering from waste water	Households	Use of the heat of the wastewater for heating the water in the household
T5	CSOs	Sewerage system	CSOs which retain more of the pollutants discharged to the environment with the overflow

There are ways to solve the identified problems of Sofia's urban water system in addition to those presented in Table 1. The selection of the technologies to be included in this study was based on the following criteria: 1) the impossibility of assessing the eco-efficiency trend before and after technology uptake when the entire chain (water supply and sewerage systems) is considered; 2) the interests of the stakeholders.

4. Defining the goal of the Sofia case study

The definition of goal and scope is the first phase in eco-efficiency assessment (ISO14045, 2012). The goal for our case study, as required by the standard, is shown in Table 2. Goal determination is a relatively simple and well-recognised task, but is included here because of its influence on later phases.

Table 2. Defining the goal of the study

Item	Content
Purpose of the eco-efficiency assessment	To promote innovative technology uptake in urban water systems by presenting the difference in eco-efficiencies between a baseline scenario and scenarios with new technology implemented
The intended audience	Research community, water operators
The intended use of the results	Provides indicators to decision makers when new technology is recommended to be implemented

5. Defining the scope of the Sofia case study

There are several issues which should be clarified in defining the overall scope of the assessment (ISO14045, 2012).Those which need more attention and are not easily determined, are discussed below.

5.1. Defining of the product system to be assessed

According to the standard, the product system should be defined on the basis of: 1) The nature of the product (as goods or services); 2) the life cycle of the product - “from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end-of-life treatment and final disposal”; 3) The unit processes with elementary and product flows, performing one or more defined functions (ISO14045, 2012); and 4) the main stakeholders. The product system for Sofia urban water system is presented in Fig. 1.

With respect to urban water systems, there is debate in the literature as to what the “product” is, i.e. whether water should be treated as a good or a service. Some authors state that the water in the urban water system is a good, because of its economic value (Rogers et al., 2002). An alternative interpretation is that the product in the urban water system is not the water itself, but the satisfied human water needs through the water services - “delivering water to the consumers with the required quality and quantity” and “transporting away the generated wastewaters”. This understanding is in line with the core concept of the Water Framework Directive, namely “water is not a commercial product like any other but, rather, a heritage which must be protected, defended and treated as such” (EU - Water Framework Directive). Here it was accepted that the product is the water service.

To consider the life cycle from the perspective the standard requires, the product system should include the entire water chain – from water abstraction to its return to the natural environment (Fig. 1). In the case of Sofia’s urban system, 100% of the users are connected to a centralized water supply system and around 98% of the users are connected to a centralized wastewater collection system. The users without centralized wastewater system are negligible 2%, so they will be excluded from the further analysis. The product system then includes the two engineering systems – the water supply system and the sewerage system. All variables (quantity of abstracted water, energy used, reagents, etc.) of the water supply system, which refer to 100% served users, are proportionally reduced to correspond to 98% connected to centralized collection system. It is clear that this is a rough estimation, but since the percentage of users connected to the sewerage system is close to 100%, it is not expected this approximation will result in significant deviations from reality.

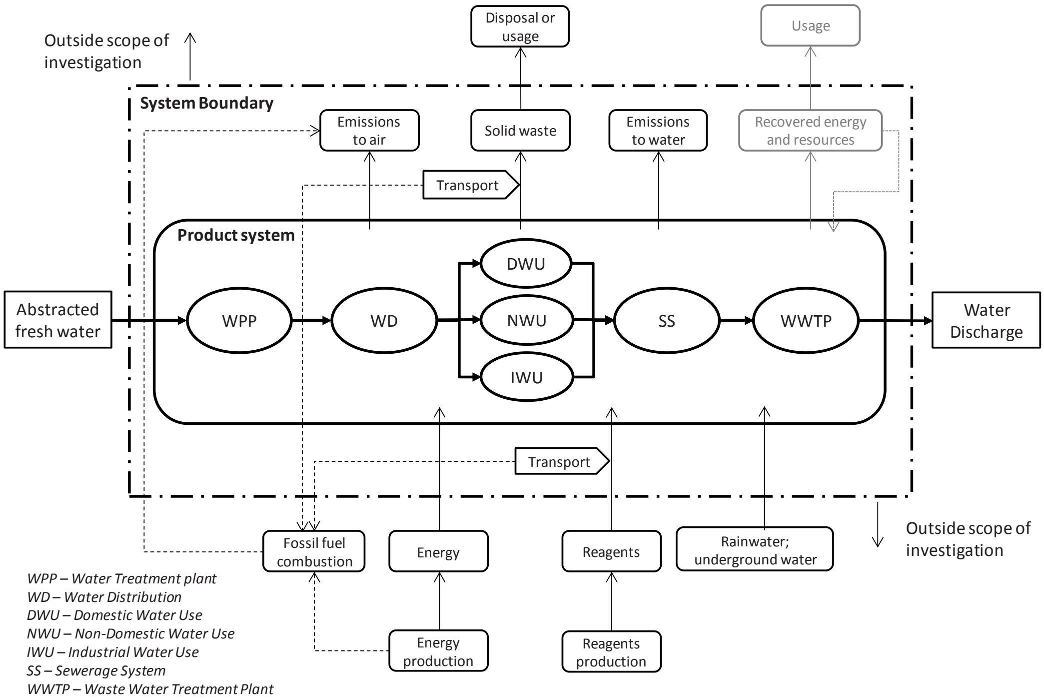

Fig. 1. Product system and system boundary for Sofia urban water system

The unit processes defined in this study follow the engineering infrastructures along the water and wastewater pathways – water purification, water distribution, water use, wastewater collection and wastewater treatment (Fig.1). In the sense of the terminology of EU Directive 91/271 "industrial wastewater" is any wastewater which is discharged from premises used for carrying on any trade or industry, other than domestic wastewater and/or run-off rain water. To be consistent with this definition, the water users in Sofia were divided into three groups – domestic water use (households), non-domestic water use, generating however domestic type of wastewater (administrative buildings, schools, Universities, offices, etc.) and industrial water use - all other users, for which wastewater differs from domestic wastewater (Fig.1). Each of these three groups has a characteristic flow regime and water/wastewater quality, so should be considered separately. There are data on water consumption for each of these groups. All other variables common to the entire system, including the quantity of the abstracted water, used energy, reagents, costs, etc. are distributed to these three groups proportionally to the quantity of the water used by each of them for the water supply part of the system and to pollution load for the sewerage part of the system. To calculate the pollution load from domestic users, widely accepted values for the load per person are used. For industrial users, data from the chemical analyses of their final effluent is used.

The main stakeholders for the urban water system are the water operator and the users. Other important stakeholders are the energy providers, the reagent providers and the state institutions, which determine quotas for water abstraction and the requirements for the quality of the discharged water. This study considers eco-efficiency with an emphasis on the two main stakeholders.

5.2. System boundary

Figure 1 presents the system boundaries selected in this study. This appeared to be one of the most difficult and critical elements in eco-efficiency assessment. Two important aspects needed to be clarified: 1) whether the users will be inside or outside system boundary and 2) the length of the accessory chains.

Many assessments of the eco-efficiency of urban water systems exclude the users (Lane et al., 2011; Venkatesh et al., 2011). However in studies where they are included, the common conclusion is that the users are the most significant system component in terms of energy and water savings (Flower et al., 2007). In this study the users are included, not only because of the previous finding of their significant contribution towards energy consumption in the product system. They are within the system boundaries, on the current understanding that urban water systems are not engineering systems alone, but include a functionality defined by actors who decide on its infrastructural and technological changes (Ferguson et al., 2013).

Urban water systems have two major external material inflows – energy and reagents. The determination of the system boundary requires clarification of the length of these chains, e.g. should the assessment include the production of these two groups of consumables (with their respective values and environmental impact). There are “pros” and “cons” for the two possible solutions – inclusion or exclusion. In this study we have decided to exclude them because of the complicated and uncertain interactions between their inputs and outputs. We choose to study only the direct interactions of the product system with the environment. All other interactions are excluded from the scope (Fig.1).

6. Assessment of product system value

The ISO 14045 standard provides only general requirements for assessment of the product system value. The difficulty with its determination is that different stakeholders may attach different values to the same product system (ISO14045, 2012). Economics often determines the value of the product to the supplier (the water operator in our case) as a difference between income and cost, equal to the profit (ISO14045, 2012). For customers the value is called “surplus value” and is most often equivalent to willingness to pay (ISO14045, 2012). When comparable products are considered Monczka et al. (2005) suggest a value can be calculated as a ratio between function and costs:

$$Product\ system\ value = \frac{function}{costs} \tag{2}$$

In the case of urban water systems, the product is unity - the water service to the customers, as indicated above. As in other studies using equation (2) the function may therefore be accepted as equal to 1, where “1” means that the product system fulfills its functions (Michelsen , 2006; Monczka et al., 2005). So, the product system value is:

$$Product\ system\ value = \frac{1}{costs} \tag{3}$$

This approach sidesteps the difficulty with the different valuations of the stakeholders, because it considers only the associated costs of operation of the system and is not interested in the pricing policy, profits for the company or the benefits of the users. This makes its determination relatively easy, because it does not require confidential data such as profits and non-quantifiable data such as benefits to the users.

7. Environmental Assessment

For the environmental assessment, ISO 14045 refers to ISO 14040 and ISO 14044. An obligatory step is generating a life cycle inventory (LCI). The results of this exercise may be used directly as input to the eco-efficiency assessment or alternatively a life cycle impact assessment (LCIA) could be carried out and its impact category indicator results used as input for the eco-efficiency assessment (ISO14045, 2012).These possibilities are shown in Figure 2. Both approaches were applied in this study.

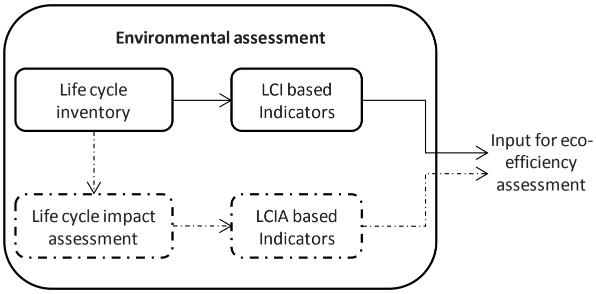

Fig.2. Environmental assessment approaches according ISO14045

7.1. Life cycle inventory

According to ISO 14044 (2006) the inventory analysis is “characterized by the compilation and quantification of inputs and outputs for a given product system through its life cycle”. The inventory analysis done for Sofia’s urban water system is given in Table 3. Further analysis assesses whether the technologies which will be applied would significantly change one or more material flows (columns 2 and 5 in Table 3).

Table 3. Life cycle inventory – material flows (inputs and outputs) of the product system and their change after technology uptake

System unit	Input to the system unit	Expected change after technology uptake*	Output from the system unit	Expected change after technology uptake*
1	2	3	4	5
Water purification plant	Quantity of fresh abstracted water	Yes, T1 and T2	Quantity of wastes (sludge and sand)	Yes, T1 and T2
	Quantity of reagents used in WPP	Yes, T1 and T2	Quantity of emissions to the air due to transport for delivery of reagents	Yes, T1 and T2
	Quantity of energy used in WPP	Yes, T1 and T2	Quantity of emissions to the air due to transport of the wastes	Yes, T1 and T2
Water distribution network	Quantity of energy used for water transportation	Yes, T2	Quantity of recovered energy	Yes, T1
Households – plumbing systems and appliances	Quantity of energy for heating the water	Yes, T2, T3 and T4	Quantity of fugitive emissions to the air	No
	Quantity of energy for operation of appliances (dishwasher/ cloth washers)	Yes, T2		
Sewerage system	Quantity of rainwater	No	Quantity of exfiltrated water	No
	Quantity of infiltrated water	No	Quantity of water overflowed through CSOs	No

	Quantity of PAHs	No	Quantity of pollutants washed through CSOs	Yes, T5
	Quantity of solid particles (sand)	No	Quantity of fugitive emissions to the air	No
Waste water treatment plant	Quantity of energy used in WWTP	Yes, T5	Quantity of emissions to the air	Yes, T5
	Quantity of reagents used in WWTP	Yes, T5	Quantity of emissions to the water	No
			Quantity of sludge	Yes, T5
			Quantity of removed sand	No
			Quantity of the energy produced	Yes, T5
			Quantity emissions to the air due to transport for delivery of reagents	Yes, T5
			Quantity emissions to the air due to transport of the wastes	Yes, T5

**For the number of the technology see Table 1*

Given that eco-efficiency assessment is a relative tool and the goal is to compare a baseline scenario with scenarios after the introduction of new technology, the unaffected material flows from Table 3 could be excluded from further analysis. In view of this, the relative eco-efficiency assessment is done taking account only of flows which are expected to change after introducing new technology.

7.2. Life cycle impact assessment and determination of indicators

The two mandatory steps of the LCIA will be done, namely: 1) Selection of impact categories and classification; 2) Characterization (ISO 14044, 2006). For this purpose, the material flows have been disaggregated to components, which were further identified with corresponding impact categories (Table 4, columns 3 and 4).

Table 4. From material flows to indicators

LCI based indicators 1	Material flow 2	Substance 3	LCA mid point impact category 4	LCIA based indicator 5
Quantity of fresh abstracted water	Quantity of fresh abstracted water	Fresh water	Freshwater ecosystem impact	Water use per resource
Energy balance (provides information for non-recoverable energy sources and is equal to total energy used minus recovered and green energy)	Quantity of energy used: - energy used in WPP - energy used for water transportation - energy for heating the water - energy for operation of appliances (dishwasher/ cloth washers) - energy used inWWTP Recovered and green energy: - recovered energy in distribution network - recovered energy from biogas combustion in co-generators in WWTP	coal, crude oil (51% of the produced electricity) combustion byproducts NOx, SOx, CO	Climate change Resource depletion of fossil sources	Global warming potential Resource depletion potential

	- recovered heat energy from waste water - solar energy for water heating			
Distance per year for transportation of reagents and wastes	Quantity emissions to the air due to transport - for delivery of reagents in WPP - for delivery of reagents in WWTP -of the wastes out of WPP - of the wastes out of WWTP	CO_2, VOCs, NOx, CO, SOx	Resource depletion of fossil sources Climate change Ozone depletion Human eco toxicity	Resource depletion potential Global warming potential Ozone depletion potential Human eco toxicity potential
Removed N Produced biogas	Quantity of emissions from WWTP to the air -N_20 from denitrification; -biogas from digester; - combustion byproducts NOx, SOx, CO	N_2O, CH_4, CO_2 NOx, SOx, CO	Climate change Ozone depletion	Global warming potential Ozone depletion potential
Aquatic pollution – PAHs load	Quantity of pollutants washed through CSOs	PAHs	Aquatic eco toxicity	Fresh water eco toxicity potential
Aquatic pollution – nutrients (PO_4 and NH_4 load)		PO_4	Aquatic nutrient enrichment	Fresh water eutrophication potential
Aquatic organic pollution (COD load)		COD NH_4	Aquatic oxygen depletion	Fresh water oxygen depletion potential
Reagents	Quantity of reagents: - reagents used in WPP; - reagents used in WWTP	NA	Impact outside scope of the investigation	NA
Wastes	Quantity of wastes -sludge in WPP -sludge in WWTP -sand in WPP	NA	Impact outside scope of the investigation	NA

The last step in the environmental assessment is the selection of indicators. Two types of indicators were determined in compliance with Fig. 2. The first type is based on the results of the LCI and corresponds directly to the material flows (column 1 in Table 4). It is based on direct calculations using direct measurements. These indicators are easily understandable and meaningful for the stakeholders. However, they do not provide information on the scale of the environmental impact. For this purpose, the second type of indicator is used, corresponding to the LCIA categories (column 5 in Table 4). The two types of indicators have been kept to be studied in parallel in the first iteration, because they provide different information.

8. Conclusion

Many studies dealing with different aspects of the eco-efficiency of urban water systems have been reported, but this one is among the pioneering works following the publication of ISO 14045 in 2012. The general framework of the standard has been adapted for the purpose of an eco-efficiency assessment of Sofia's urban water system. In particular, the procedures for definition of the critical elements - product system, system boundary, product system value and environmental performance have been elaborated. The study shows that these elements are logically interlinked and the best approach is to follow this logic.

The selected method for determination of the product system value takes into account that the functionality of the system is defined by two directly involved actors – the water operator and water users. With respect to environmental performance it is demonstrated that by considering the goal of the study, the analysis can be simplified by including only the respective flows. Two types of indicators are suggested, those based on LCI and those based on LCIA, so as to provide simple feedback to the stakeholders.

The methodology developed in this study will be applied to quantify the eco-efficiency of five scenarios for technological improvement of Sofia's urban water system. This will be followed by any necessary further iterations in the eco-efficiency assessment based on a quantitative analysis of the results of the first iteration.

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