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Holistic Wastewater Reuse Solutions – Evaluation of Treatment Efficiency, Environmental Impacts and Costs

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Abstract

The reuse of municipal wastewater is becoming a well-accepted solution for the management of water resources affecting various water-using sectors. Configuring the most sustainable and effective treatment system for the reuse of municipal wastewater, however, is still challenging. The present study offers an approach favoring the use of various sustainability metrics such as targeted or delivered treatment efficiency, environmental and economic impacts, area footprint and energy consumption for the configuration and selection of treatment systems for specific non-potable reuse applications and site characteristics. The results show that the presented approach can clearly provide information about trade-offs between performance, environmental impact and economic cost for different plant sizes and potential reuse demands. The provided real-case example, based on an extensive international study of various treatment systems, further illustrates that focusing on only one of the sustainability metrics may not provide the most sustainable solution. For some reuse applications, higher effluent quality than targeted will be provided at lower overall environmental impact and lower energy consumption but at higher costs. The study also demonstrates that the same treatment system may not be the most sustainable option for all plant sizes. The approach presented here provides a way to identify the most sustainable solution for each individual case, based on local requirements and plant size, through the holistic evaluation of treatment system sustainability.

Keywords: Non-potable water reuse; Sustainable evaluation; Life-cycle assessment (LCA); Life-cycle cost (LCC); Energy consumption

Introduction

Population growth, increasing living standards, and environmental pollution are all factors contributing to an increasing water stress in many parts of the world. While access to drinking water is becoming more costly due to environmental pollution and increased water demands, human consumption of potable water conflicts with other major water consumers, such as agricultural and industrial uses. The competition of these various water-using sectors can however be avoided as the use of water for non-potable purposes can be based on reclaimed wastewater. The reuse of treated municipal wastewater has been identified as the most responsible solution to manage water scarcity issues while building a sustainable society [1-3]. Wastewater reuse for non-potable applications is already applied in some regions but a wider implementation is mainly driven by acute needs and not by a common understanding of this approach as an overall sustainable solution meeting society's demands. This includes misconceptions regarding treatment cost and efficiency of wastewater reuse systems. In European countries that face water scarcity, the reuse of wastewater as a resource is hindered by a lack of wider knowledge and visibility of the environmental and economic impacts of advanced treatment solutions [4].

In order to reuse water safely, usually stringent effluent quality requirements are set which are not typically met using conventional wastewater treatment limited to primary and secondary treatment steps. To accomplish this, various tertiary filtration and disinfection technologies are combined to create a reuse solution that meets the removal targets for organics, solids, pathogens and emerging chemical contaminants without the need for highly cost and energy demanding processes such as reverse osmosis (RO).The evaluation of reuse treatment systems in terms of sustainability can be based on three main aspects in sustainability: efficiency, environmental and economic impact. These aspects of sustainability can then further be expanded to include technical and functional aspects such as robustness of different technologies and their performances as proposed by the Swedish Urban Water Programme [5,6]. The task of conducting sustainability assessment by integrating these different sustainability aspects becomes difficult given the multiple dimensions and complexity of such evaluations. Process efficiencies such as the removal of specific pollutants from wastewater by various techniques are best evaluated using actual tests rather than modeling. Further, there are a number of different decision supporting tools available and used for different evaluation needs. Using Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) evaluation are some of the most commonly used tools when mapping environmental and economic performance of technologies [7,8].

Various studies have used Life Cycle Assessment (LCA) to compare the environmental impacts of different wastewater treatment technologies to supply water for reuse applications such as agricultural irrigation, urban or industrial use [9-14]. Some studies focused only on specific environmental key performance indicators (KPIs) such as global warming potential [15], while others considered several KPIs (16-19). Common for all these studies is that results are not prepared to allow comparisons of various treatment systems or studies. The studies are further limited as they evaluate the environmental impacts of single factors on a case-by-case approach and not complete treatment systems and various aspects simultaneously, which would be required for a holistic evaluation.

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Baresel et al. [20] studied the influence of water quality (or intended water use), treatment technology selected, and the plant size,on environmental impacts of water treatment systems under well-specified conditions. Baresel et al. [21] and Lazic et al. [22] enhanced the evaluation by discussing the importance of factors commonly treated as externalities and not usually included in optimization strategies, but that are necessary for environmental assessment of wastewater reclamation systems. Even so, electricity demand is one of the most common parameter used in environmental assessments [23,24,13] the actual impact of the energy mix used and impacts on the overall environmental performance of systems by altering this energy mix has often been overlooked.

When evaluating economic sustainability, usually the LCC cost comparison between different treatment systems is done based on assumptions of different fractions in investment and operating costs, and not based on real cost data; or it is based on comparing one system and one full-scale size at a time [25]. An incomplete LCC analysis can lead to major misjudgment of the actual total cost of the plant in a net present value format.

Generally, when evaluating sustainable water treatment without integrated sustainability assessment, there is a tendency to focus on either environmental impact evaluation or economic evaluation of wastewater systems (with or without reuse). There are only a few studies taking into account both environmental impact and economic impact analysis of a wastewater system [23, 26-28]. These studies are mostly based on monetarization of LCA data [29], or on real Life Cycle Cost (LCC) and LCA analysis of evaluated systems for one selected plant size [30-32]. To the best of the authors' knowledge, there is no study investigating the combination of treatment efficiency, environmental and economic impacts, with technical and functional aspects of sustainability for different plant sizes.

The objective of this paper is to present a practical approach for identification and evaluation of the most sustainable wastewater treatment solution for different reuse applications based on common and well-understood tools. This is done by using the described sustainability aspects and a descriptive example based on the evaluation of eight wastewater reuse treatment systems for various plant sizes: 20,000 personal equivalents (pe), 100,000 pe and 500,000 pe.

Material and methods

For each studied treatment system and each plant size, the following sustainability metrics were evaluated:

- Treatment efficiency in terms of reached effluent quality based on regional targets plus additional evaluation of emerging contaminants
- Life Cycle Assessment (LCA) [33] considering the 10 most common and for water treatment system relevant environmental impact indicators (KPIs, see methods)
- Life Cycle Cost (LCC) evaluation based on the net present value, capital investment and operating expenditures.
- Energy consumption of treatment systems (in kWh/m^3 of treated water)
- Water recovery, which is defined as the percentage of treated water flow rate compared with influent raw wastewater flow rate)

Area footprint (area occupied by a treatment unit in m2)

Studied treatment systems

Eight (8) advanced treatment systems were setup and tested at the research facility Hammar by Sjöstadsverk, Sweden, for a period of over two years. The eight systems were targeting effluent qualities for three reuse application fields: agriculture use (AG), groundwater recharge (GW) and industrial use (I) (Table 1)

For maximum significance and realistic data use, only existing and available technologies were used, including:

- SBR - Secondary biological treatment: an advanced sequential batch reactor with continuous inflow (ICEASTM, Sanitaire, Xylem). The system was operated in partial/incomplete nitrification mode (P-NIT) for nutrient recovery or in full nitrification/denitrification mode (NDN) for nutrient removal.
- Tertiary filtration treatment – conventional technologies such as rapid gravity dual media filtration (RGSF; Leopold, Xylem) and disk filtration (DF; Nordic Water) were used for solids removal, including phosphorous removal when needed. For higher additional particulate removal at certain effluent quality requirements, two different ultrafiltration (UF) membrane technologies were tested i.e. submerged UF (sUF; ZW1000 from GE) and pressurized UF (pUF; Xiga 55 from X-flow).
- Disinfection was implemented using UV treatment (Wedeco, Xylem) at varying intensity based on microbial content and transmittance of the feed water, in order to reduce total coliform concentrations to less than 2.2/100 ml. Chlorine was not considered as a primary disinfectant. Residual chlorine of 1 ppm was included for distribution.
- For the removal of emerging contaminants (micro pollutants), ozone (system I2) and ozone-enhanced biologically active filtration (Oxelia^{TM}, Xylem) were evaluated (systems GW2 and GW3).

Each treatment system was thoroughly tested and optimized to meet the target effluent quality requirements (see Table 2 and Baresel et al. [30] for more technical and operational information). The required effluent qualities were selected, as monthly averages, according to the regional targets from selected regions: India, Middle East, Australia and Latin America [20]. Target effluent quality varies depending on the application (for example food crops vs. non-food crops for agriculture reuse, infiltration basins vs. injection wells for groundwater reuse) and local regulation. For example, Australia has one of the most stringent effluent quality requirements for GW reuse applications, while India has notably stringent requirements for industrial reuse applications. Micro pollutants (MP) removal, for example, might be necessary for groundwater [34] and industrial applications depending on the regions of implementation. Targeted effluent concentrations of MP were defined in accordance with Swiss guidelines [35-37]. Performance data from the pilot treatment systems and operational data from several full-scale plants around the world were used to develop a full sustainability reuse evaluation.

Sustainable Reuse Evaluation

An ideal sustainable wastewater reuse solution would be the solution that meets effluent quality targets at minimum total environmental impact and minimum life cycle cost. This optimum solution may be different depending on various impacting factors such also cation, flow to be treated, application-specific requirements and conditions, i.e. functional and technical aspects, and dominating environmental challenges in the region of system implementation. This also includes the water quality required when reusing the water for agriculture, industrial or groundwater recharge purposes, and the protection of environment and human health. The eight different treatment systems were investigated as they provide different level of removal for solids, turbidity, organics (COD), nutrients (nitrogen N and phosphorous P), pathogens such as total and feacal coliforms and different micro pollutants (as shown in Table 2), which would meet the different reuse category requirements for the selected regions.

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Reuse application	Treatment system	Process description
Agriculture		
AG1	SBR (P-NIT) + RGSF + UV	SBR-Sequential Batch Reactor (P-NIT=partial nitrification; NDN=nitrification/denitrification)
AG2	SBR (P-NIT) + DF + UV	RGSF-Rapid gravity dual media filter
Groundwater recharge		DF-Disk Filter
GW1	SBR (NDN) + RGSF + UV + Cl	UV-Ultraviolet irradiation
GW2	SBR (NDN) + DF + Ozone + BAF + UV + Cl	BAF-Biologically Active Filter
GW3	SBR (NDN) + Ozone + BAF + UV + Cl	Cl-Sodium hypochlorite treatment
Industry		Ozone-Ozone treatment
I1	SBR (NDN) + pUF + UV + Cl	pUF-pressurized ultrafiltration
I2	SBR (NDN) + sUF + Ozone + Cl	sUF-submerged ultrafiltration
I3	SBR (NDN) + sUF + UV + Cl	

Table 1: Studied treatment systems

	AG1	AG2	*Target AG*	GW1	GW2	GW3	*Target GW*	I1	I2	I3	*Target I*
Total Nitrogen (mg/L)	15	15	*20*	5	5	5	*10*	5	5	5	*<10*
NH_4-N (mg/L)	4.5	4.5	*5*	0.7	0.2	0.2	*1*	0.7	0.7	0.7	*1*
Total Phosphorus (mg/L)	2.0	2.0	*2*	0.2	1.0	1.0	*1*	0.2	0.2	0.2	*1*
COD (/10) (mg/L)	3.5	3.5	*<4*	3.5	2.3	2.8	<3	3.0	2.5	3.0	*<3*
BOD_5 (mg/L)	5.0	5.0	*<8*	3.6	2.0	3.0	<5	2.0	3.0	3.0	*<5*
Turbidity (NTU)	0.5	2.0	*<2*	0.4	0.5	0.5	<2	0.14	0.15	0.27	*<1*
Total Suspended Solids (mg/L)	1.0	2.0	*5*	1.0	1.0	1.0	<5	1.0	1.0	1.0	*<2*
Total Coliforms (cfu/100 mL)*	<2.2	<2.2	*<2.2*	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2	<2.2	*<2.2*
*Micropollutants (examples)**:*											
Carbamazepine (µg/L)			-		0.05	0.04	*0.5*		0.014		*0.5*
Diclofenac (µg/L)			-		0.06	0.04	*0.05*		0.05		*0.05*
Ibuprofen (µg/L)			-		0.043	0.04	***0.3***		0.173		***0.3***

Table 2: Targeted and reached effluent quality for eight investigated treatment systems
Where: AG- Agriculture (irrigation of food and non-food crops), GW- Groundwater recharge (Infiltration basins, injection wells for aquifer recharge), I-Industry (Cooling water, industrial process water)
*California Title 22 Standard (1); reached values below target
** Swiss guideline (29-31)

Environmental impacts are evaluated by a Life Cycle Assessment (LCA) according to the ISO standard (ISO, 2006), which comprised the treatment from the influent water to the reclaimed water. This approach takes into account all resources needed to construct, operate and decommission a plant including materials, energy and chemicals used throughout the plants life cycle. For the LCA modeling, scale-up effects were considered by performing all analyses on three typical plant sizes: 20,000, 100,000 and 500,000 pe over 20 years of assumed plant life. The system boundaries included onsite sludge treatment, but excluded the cost/revenue and environmental impacts/benefits of the reclaimed water use. The environmental analysis considered both upstream and downstream impacts of the treatment itself, e.g. production of chemicals, energy use. The performed LCA evaluated ten selected environmental KPIs:

- global warming potential (GWP)[kg CO_2-Eq./m^3],
- acidification potential (AP)[kg SO_2-Eq./m^3],
- eutrophication potential (EP)[kg Phosphate-Eq./m^3],
- photochemical ozone creation potential (POCP)[kg Ethene-Eq./m^3],
- Human toxicity potential (HTP)[kg DCB-Eq./m^3],
- Freshwater ecotoxicity potential (FAETP)[kg DCB-Eq./m^3],
- Marine ecotoxicity (MAETP)[kg DCB-Eq./m^3],
- Terrestric ecotoxicity (TETP)[kg DCB-Eq./m3], and
- Depletion of abiotic resources (AD) due to consumption of elements [kg Sb-Eq./m^3]and fossil fuels[MJ/m^3].

Spain was chosen as a model country and all results are therefore based on the Spanish electricity grid. Main regions of focus for water reclamation projects are e.g. the Middle East, India, Latin America, and Australia. However, even in the European country Spain, water reclamation is considered due to water shortage and in addition, Spain is a good proxy for the other regions. Further, region-specific inventory data necessary is more easily available for Spain than for the above-mentioned regions.

The economic evaluation of the eight investigated treatment systems for wastewater reuse was performed over their 20 years of lifetime and was based on Spanish prices. Each of the treatment systems was designed for the three selected full-scale sizes and actual construction projects were used as a database. The applied Life Cycle Cost (LCC) analysis comprised the calculation of the total annual treatment costs, including both capital expenses (CAPEX) and operating expenses (OPEX).CAPEX consists of civil, mechanical and electrical costs, including the cost of installation. It further accounts for replacing consumables as for example, the change of diffusers or UV lamp sat regular intervals. OPEX includes energy and chemical costs for operation, manpower and maintenance costs. The LCC model was constructed in accordance with DWA guidelines [38]. LCC was expressed as a net present value (NPV) and is calculated for 20 year life of the plant assuming an interest rate of 5.5%. The economic KPI's service life, CAPEX, and OPEX were calculated for a given functional unit as $/m3 of treated water/year. More details on methods can be found in Baresel et al. [20], and Baresel et al. [30].

Results and Discussion

Treatment system efficiency

Treatment performances of the eight treatment systems were evaluated against the targets for AG, GW and I applications for non-potable reuse. Influent water quality is given in supplemental information in Table S1. Operation and evaluation data for the eight treatment systems show that all systems comply with respective targets for non-potable reuse (Table 2). Systems AG1 and AG2 preserve nutrients (N and P) in the effluent for their reuse as fertilizers during irrigation. This treatment is achieved with incomplete nitrification and no targeted phosphorous removal. However, for AG1, the media filtration demonstrated a higher solids removal (both TSS and turbidity) than the disk filter in AG2, which results in a higher effluent quality achieved. For all GW and I systems, nutrients and additional solids removal were targeted. This was achieved using media filtration or biological active filters (BAF) for GW and ultrafiltration for I systems, respectively. Among industrial systems, I2, including membrane ultrafiltration and ozone oxidation, improved the effluent quality in comparison to systems I1 and I3 by additional reduction of turbidity, residual COD and elimination of all targeted MPs. For GW systems, MP removal and additional removal of organic carbon (i.e., COD and BOD) were achieved by ozone oxidation and BAF. These systems provide the best overall effluent quality because of their additional reduction of ammonium (NH_4-N), residual COD, and the elimination of all targeted MPs.

Life Cycle Assessment

Results of the environmental assessment are shown in Table 3.Details on inventory data is provided by Baresel et al. [30]. For plant size of 100,000 pe, ten evaluated KPIs and three additional indicators (energy consumption, water recovery and area footprint) are compared against the simplest treatment system AG1including media filtration. The results indicate that the treatment systems with the least stringent effluent quality (without nitrogen removal and with less stringent solids and organics levels), i.e. the AG systems for irrigation, have the lowest environmental impact for all indicators except for GWP and water recovery. As the effluent quality increases (AG1→GW1→I3→GW3), the calculated environmental impact increases as well for all KPIs except for GWP. The different behavior of GWP is due to targeted incomplete nitrification of AG systems that requires less operational energy and provides nitrogen in the treatment effluent available for irrigation purposes. However, this targeted and common approach in water reuse for irrigation causes compared to complete nitrification-denitrification processes of GW and I systems, increased emissions of the significant greenhouse gas nitrous oxide (N_2O; see Baresel et al. [20] for a detailed discussion). In addition, increasing water quality by targeting enhanced nutrient and solids removal (GW1 and I1, I3) implies a change in technology (e.g. from media filtration to ultrafiltration), which increases especially energy demands. This required technology change further causes an increase in HTP, ecotoxicity potentials and AD due to elements by more than 50% compared to systems with less nutrient and solid removal. MP elimination and additional COD removal achieved with ozone and BAF (GW2, GW3) or ultrafiltration and ozone (I2) increases all KPIs by an additional 20% compared to GW1 and I3systems. GW3 has lower POCP and AD due to elements comparing to GW2. This is due to the impact the chemicals used for the operation of the plant (polymer for POCP), and materials used to construct the additional disk filter used in GW2, have on these two KPIs. In addition, GW3 has the highest water recovery of the three systems capable of MP removal.

Table 3 shows that treatment systems having the same effluent quality target can have very different environmental impact for all evaluated KPIs. For example, sUF (system I3) has between 5 and 17% lower KPIs compared with pUF (system I1),as the technologies consume energy and use materials in different ways. With increasing plant size, the difference between the two systems increases for all KPIs implying that I3 becomes a more environmentally friendly option with increasing plant size (see supplemental information Figure S1).

Energy consumption used to operate the treatment systems has a dominating effect on almost all (seven out of ten) investigated environmental KPIs: GWP, AP, EP, HTP, FAETP, MAETP and AD due to elements. Further information is available in Baresel et al. [20]. One example where AP was correlated with the energy consumption of all eight treatment systems and plant sizes (see supplemental information Figure S2) showed that as the size of the plant increases from 20,000 pe to 500,000 pe, the impact of energy consumption on AP decreases, R2 ranging from 0.96 to 0.84. This is because the decrease of energy consumption per m3 of treated water occurs due to the increasing process/equipment efficiency with increasing size of treatment systems. Thus, increasing plant size generally reduces the environmental impact of all KPIs per m3 of treated water for the same treatment system.

KPI	AG1	AG2	GW1	GW2	GW3	I1	I2	I3
Global Warming Potential (%)	100	100	59	70	71	64	64	59
Acidification Potential (%)	100	99	121	146	148	132	133	121
Eutrophication Potential (%)	100	100	123	150	151	134	135	123
Photochemical Ozone Creation Pot. (%)	100	117	106	130	113	110	109	107
Human Toxicity Potential (%)	100	102	142	178	176	157	165	149
Freshwater Aquatic Ecotoxicity Pot. (%)	100	102	127	162	161	139	156	140
Marine Aquatic Ecotoxicity Pot. (%)	100	99	124	154	155	137	140	126
Terrestrial Ecotoxicity Potential (%)	100	99	186	219	217	213	205	189
Abiotic Depletion, elements (%)	100	103	227	287	272	271	261	232
Abiotic Depletion, fossil (%)	100	99	120	146	147	131	131	120
Additional Indicators/resources								
Energy consumption (%)	100	98	103	122	125	121	111	103
Water recovery (%)	100	101	100	99	100	91	93	93
Area Footprint (%)	100	95	118	143	141	123	120	120

Table 3: Environmental KPIs and resources used given as a comparison against AG1, for 100,000 pe size
Where: AG- Agriculture, GW- Groundwater recharge, I- Industry

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The type of electricity grid used for energy supply has significant impact on environmental KPIs. When LCA results using the U.S., Swedish and Australian electricity grids were compared with the base case that uses the Spanish electricity grid, it was found that exchanging 45% of the fossil fuels with green energy decreases GWP by 60% for the same treatment system and for the same energy consumption [21, 22].

Life Cycle Costs

Economic assessments of the eight treatment systems for the plant size of 100,000 are presented in Table 4. It can be seen that investment costs (CAPEX) are not directly related to effluent quality. For example, MP elimination with system GW3 with ozone enhanced BAF can be obtained at a lower CAPEX than that of the Industrial reuse systems involving membranes. This is due to different impacts civil and mechanical costs have on the CAPEX. The largest fraction of CAPEX, more than 50%, is due to the civil cost that is closely related to the area/volume footprint [30]. Since the secondary treatment step has the largest footprint in the treatment system, the significance of civil cost of tertiary treatment is comparatively low. The second largest fraction of CAPEX is mechanical cost, at approximately 30%. In this example, mechanical cost of ultrafiltration membranes (UF) is much higher than the cost of BAF, even though BAF uses larger footprint and therefore has higher civil cost than UF.

Operating costs (OPEX) on the other hand are related to the effluent quality, demonstrating that the energy needed to remove additional contaminants increases as effluent quality demands increase. This is because energy consumption accounts for more than 50% of OPEX. It is shown (see supplemental information Figure S3) that the correlation between OPEX and energy consumption is similar for all three plant sizes and the investigated eight treatment systems, and R2 ranges between 0.85 and 0.89.Upon evaluating the overall LCC, calculated here as NPV, it was found that for 100,000 pe plant size, OPEX is the dominating cost over the whole 20 years of the plant's lifetime and therefore determines the overall LCC, as shown in Table 4. This finding questions the common practice of focusing on CAPEX when evaluating economic impacts, and strengthens the need for LCC evaluation. Here it is shown that high initial investments do not imply high LCC for 20 yrs. In addition, LCC increases with increasing effluent quality (AG2 ⟶ GW1 ⟶ I3 ⟶ GW3) as more costly equipment is used with higher energy consumption.

In a similar manner as for the environmental impacts, the size of the plant also has an impact on the cost. Increasing the plant size decreases the cost difference in \$/m^3 treated water between certain treatment systems. One example is the cost difference between the two AG systems (given in supplemental g information as Figure S4) where AG1 with media filter becomes the more cost-effective solution than AG2 with disk filter for largest plants as the difference in NPV cost between systems decreases from 8% for the smallest size to being equal for the largest plant size. This is due to the CAPEX difference between two systems, which decreases from 13% to 1% as the size of the plant increases, and due to the increased impact of OPEX on the total NPV cost, to 60% for both systems.

It becomes clear from the economic analysis is that the selection of the process equipment and configuration of the unit processes within the treatment systems can have a significant impact on the LCC. It was also shown that initial capital investment cost (CAPEX) is not an adequate indicator of the sustainable economic solution. In addition, operating cost (OPEX) often governs the overall LCC, as it is the larger fraction of LCC. Therefore, when seeking an economic solution over the full lifetime of a plant, the overall evaluation of the full LCC should be done, rather than focusing on CAPEX. In order to optimize performance of the treatment system and decrease the overall LCC cost, two focus areas will have the largest impact: decreasing OPEX by decreasing energy consumption through energy-efficient designs, and decreasing CAPEX by decreasing the civil cost (focus on the secondary treatment step) and mechanical cost.

	AG1	AG2	GW1	GW2	GW3	I1	I2	I3
NPV (%)	100	96	101	117	115	112	115	110
CAPEX (%)	100	92	105	118	114	118	123	123
OPEX (%)	100	99	98	116	117	108	108	100
OPEX/NPV (%)	56	58	54	55	57	54	53	51

Table 4: NPV, OPEX and CAPEX given as a comparison against AG1, for 100,000 pe size

Overall sustainable evaluation of Reuse treatment system

To illustrate the use of various sustainability aspects, energy consumption (indirectly representing even energy-related environmental KPIs), POCP (an environmental KPI not dominated by energy consumption), LCC (expressed as NPV and CAPEX) and area footprint, have been selected for this example as they dominate the various sustainability indicators. Any of the investigated sustainability aspects may however be chosen depending on regional or other importance or preferences. The selected indicators have been normalized against treatment system AG1 and are plotted against each other as shown in Figure 1 for the three full-scale plant sizes evaluated. The increase of effluent quality from AG1 to GW1, I3 and GW3 was considered but it was not plotted in the Figure 1.

LCA, LCC and effluent quality performance analyzes indicate that there is not one single optimal solution for a targeted plant size and effluent quality. It is neither always the same system that has both the lowest environmental and economic impact and at the same time the best effluent quality. Thus, the definition of an optimal solution requires a prioritization of all evaluated sustainability indicators based on local requirement and specifications: environmental impact (with 10 evaluated KPIs), effluent quality, area footprint, energy consumption, water recovery, and economic evaluation through the net present value (LCC), CAPEX and OPEX.

Comparing for instance industrial systems, it can be seen that I1 with pUF achieves better effluent quality (lower turbidity concentration) at lower investment cost, which varies from 5 to 14% depending on the plant size, when compared to I3 including sUF. In addition, I1 has similar total cost (NPV) as I3 (varies from 3 to -2%) but it consumes 9 to 18% more energy than I3 and has higher POCP by 3-6% for 20,000 pe -500,000 pe plant sizes, respectively. Thus, the design of a system with sUF, such as I3, appears to be a more suitable option especially for larger plant sizes if environmental impact with energy consumption and total LCC are the highest priorities in the project specifications. On the other hand, a system with pUF, such as I1, appears as a more suitable option for projects that require higher effluent quality at low investment cost.

The comparison of the systems I1 including pUF and UV and system I2 including sUF and ozone demonstrate that an important increase of effluent quality, such as the full elimination of micro pollutants, can be reached with a minimal increase in LCC. The LCC for these two lines indicates that despite the increase in cost from the ozone investment, the low energy consumption of the sUF (when compared to the pUF) allows reducing the full LCC of the line to a cost close to parity with that of the pUF and UV line.

The impact the plant size has on sustainable metrics can be seen in the example with agriculture reuse systems. Agriculture effluent quality targets can be reached by both systems investigated but, for the 20,000 pe and 100,000 pe, the system including the DF (AG2) is the most capital efficient solution. However, this cost effective system is less environmentally friendly due to the use of a polymer during operation of the DF affecting the POCP KPI. As the plant size increases to 500,000 pe,

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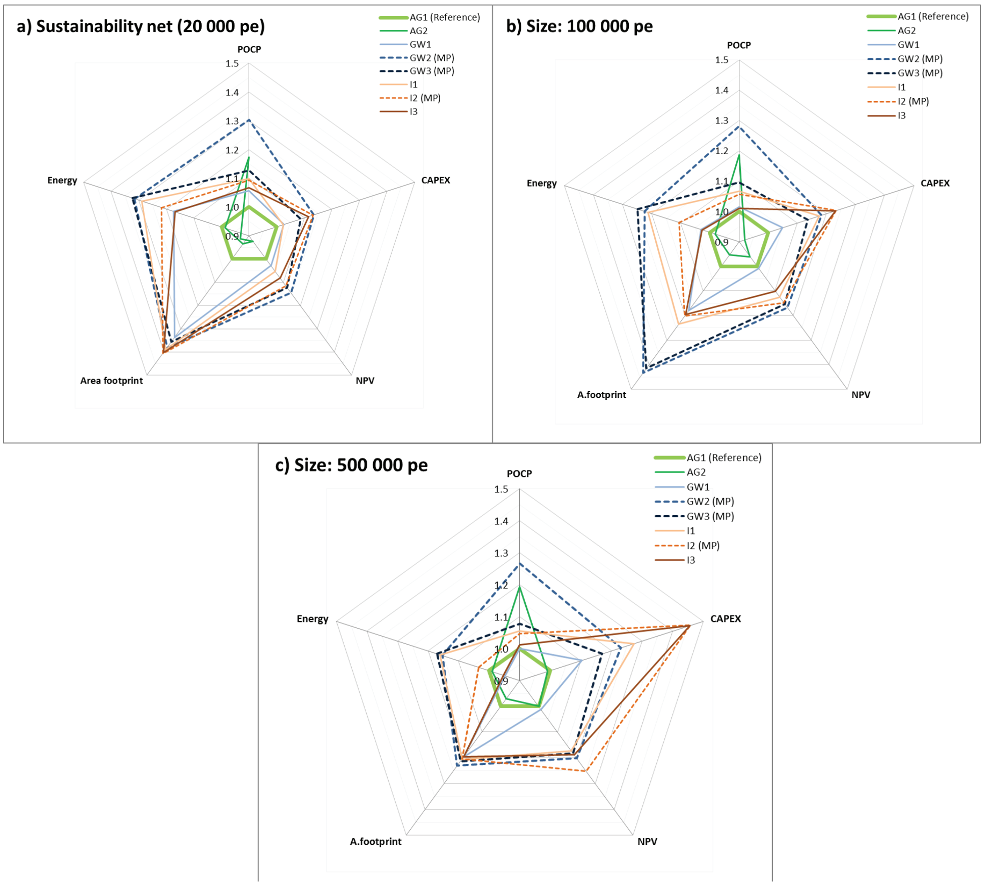

Figure 1: Sustainability evaluation of the eight investigated treatment systems given as a comparison against AG1, for a) 20,000 pe size; b) 100,000 pe size; and c) 500,000 pe size

the cost variance between the two AG lines reduces resulting in parity in their LCC. In this example, the analysis demonstrates that the plant size can have a drastic impact on one or several of the sustainability aspects and strongly influence the definition of the most sustainable solution for this application.

As shown in these examples, the best solution is a tradeoff between environmental impacts (KPIs and impact categories), economic cost, effluent quality and the size of the plant, which has to be determined for each specific case.

Generally, improving water quality significantly with removal of micro pollutants implies higher LCC, more area footprint, higher energy consumption but in some cases lower GWP. The difference in sustainability indicators will be much smaller if the treatment systems for industrial reuse in this study are upgraded to groundwater recharge quality, by selecting appropriate technologies, but this will also vary depending on the plant size. For example, the increase of the GWP from the optimized treatment system for industrial application with ultrafiltration and UV (system I3) to the ground water recharge application with ozone and BAF (system GW3), was 16% for the smallest plant size. This difference will increase to 23% as the size of the plant increases to 500,000 pe. It should be noted that the benefit of reusing the water has not been within the system boundaries, as this study focuses only on technology evaluation. Therefore, possible beneficial impacts of replacing fresh water with reclaimed wastewater on certain KPIs were not considered. Upgrading the effluent quality from I3 to GW3, LCC difference decreases from 5% for the smallest plant size to 0% for the largest size. This indicates that it is more beneficial to upgrade large plants to the highest effluent quality. This means that reuse solutions for ground water application with MP removal have similar LCC as solution for industrial applications without MP removal. Looking only on the capital side, CAPEX decreases from 3% to 25% for the largest plant size showing that GW3 is the most capital efficient solution for all three sizes.

Conclusions

The study shows an approach to how environmental, economic and efficiency dimensions can be used to define the most sustainable and optimal solution for a certain application. The results indicate that there can be more than one preferred reuse solution when all of the different aspects presented above are introduced. Various wastewater treatment systems can reach the same effluent quality target for reuse purposes while having different environmental and economic impacts. Further, higher effluent quality does not necessarily mean higher environmental and economic cost. Therefore, variable sustainable metrics as suggested here (effluent quality, environmental KPIs, LCC, energy consumption, area footprint, and water recovery) should be used to provide a more complete understanding of the environmental, economic and treatment efficiencies when selecting the most sustainable reuse treatment train for a particular reuse application and of a certain size. This becomes even more important when considering local needs and regulations including individual conditions of each wastewater reuse implementation.

The study illustrates that increasing the water quality does not always mean higher LCA and LCC cost. Both the plant size (as shown in the example of two industrial systems), electricity grid used [21,22], regional

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costs, etc., need to be assessed using sustainability metrics for each specific project. As process efficiency increases with increasing plant size, the overall environmental impact (per m3 of treated water) of various direct and indirect emissions from the treatment decreases.

In addition, it was shown that the preliminary assessment of the sustainability of a specific treatment solution can be facilitated by using energy as a reliable surrogate to complex modeling, when the focus is on OPEX and on certain KPIs such as GWP, AP, that are mostly governed by energy consumption. This conclusive statement is however highly dependent on local energy sources and costs [21] and emissions of N_2O from the biological step [20], but demonstrates the applicability of the findings for specific targeted regions. Thus, all the efforts in decreasing of the energy consumption of the treatment plant, and specifically of the secondary treatment step that is the largest consumer, will lead to more sustainable solution. This could be done by implementing high-efficient technologies and advance process control systems. Additional research confirming this statement, performed using the data from this study to investigate regional greenhouse gas abatement opportunities from energy efficiency in the wastewater sector, showed that the global wastewater industry could cut electricity-related greenhouse gas emissions by 50 percent using high-efficient technologies that are available today. 95 percent of these reductions either will have no cost or will actually save money, as savings from energy efficiency would exceed spending on the abatement measure [39].

The tradeoffs between performance, economics, and environmental impacts can be quantified and evaluated using sustainability metrics. This study, being one of the first to develop such comprehensive sustainability metrics, provides a general approach for the assessment not only of reuse treatment systems but also in a wider context of regional (or even larger) sustainable water management and strategic planning.

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