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Life cycle assessment as a decision support tool in wastewater treatment plant design with renewable energy utilization

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ABSTRACT

This study presents how the life cycle assessment (LCA) approach was used as an analysis and decision support tool to formulate and finalize the design of a biological wastewater treatment plant (BioWWTP) for Bartın Province, Black Sea Region, Turkey. The system was designed to serve not only for its primary goal of treating wastewater, but also for providing an integrated engineering solution to today's multi-dimensional environmental problems and offering an installation serving for the well-being of the society and the environment. The design was improved by using photovoltaic panels for energy generation and rainwater harvesting, constructing a natural conveyance channel and a recreational pond to collect and retain water prior to discharge. The sequential phases of LCA were implemented, various cases were structured, multiple scenarios were tested, scenario analyses were conducted and results were comparatively evaluated. In one of the cases tested (Case-1), results implied that placing photovoltaic panels over the biological treatment units to meet 60% of the electricity demand of the system helped, i.e., reduce the global warming potential, hence the carbon footprint of the system by 50%, while mediating the use of a renewable energy source and enabling rainwater harvesting for possible water recycling-reuse; thus contributing to the sustainability of the entire installation.

Keywords: CO_2 emissions; Environmental impacts; Life cycle assessment; Photovoltaic panels; Scenario analysis; Sustainability; Wastewater treatment

1. Introduction

Sustainable economic development necessitates incorporating the concept of sustainable development, defined as "*meeting today's demands without compromising the ability of next generations to meet their needs*" [1], into today's economic strategies and activities. Accordingly, communities are required to develop and/or adapt strategies for protecting existing resources and controlling wastes while seeking for economic advancement with the focus of providing answers to physical (ecology), biological (health) and sociological (community) concerns of sustainable development. With regard to the water sector, sustainable water management has become a necessity since global climate change and increase in human population have been threatening water resources and freshwater ecosystems throughout the world. In this context and due to increasing scarcity of water resources, attaining efficient wastewater treatment and water reuse have become crucial for sustainable water management.

Wastewater treatment plants (WWTP) are among the main components of the water sector and are primarily designed and operated for pollution prevention in water resources. However, energy sufficiency of those public service installations is becoming a critical issue since maintaining sustainable water and energy supplies and reducing carbon footprints are crucial for sustainable urban development [2]. One of the major problems in WWTPs is excessive energy consumption, mainly originating from the use

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of blowers providing air to the biological treatment. Therefore, design and operation of WWTPs need to be optimized by incorporating energy conservation practices as much as possible and also water recycle/reuse practices when applicable.

Relating to the biological concerns of sustainable development, WWTPs are facilities having the potential of posing risks on human health. Odor generation might frequently be encountered during wastewater collection and treatment, regardless of how well the facilities are designed [3]. Accordingly, odor problems, especially when including CH_4 and H_2S emissions, might entail human-health risks at different severity levels ranging from public nuisance to life-threating cases. Those risks should be addressed by implementing appropriate design solutions. Another dimension of sustainable development includes sociological concerns which are related with human relations, public opinion and perception, sociological ecosystem, and organization of the society [4], and should be addressed as well when designing and operating WWTPs.

With those perspectives, a sustainable WWTP is then expected to provide engineering solutions not only for pollution prevention but also meeting the needs of sustainable economic development including but not limited to economic feasibility, technological applicability, energy conservation and/or production, waste minimization, source reduction, resource recovery, as well as taking into account the social and political dimensions [5,6]. Life cycle assessment (LCA) could be a powerful decision support and analysis tool in the design and operation of such facilities [5]. LCA is defined as *"the process of compiling and evaluating the inputs, outputs and the potential environmental impacts of a product (any good or service) system throughout its life cycle"* [7–9]. With the increasing concerns about water scarcity all around the world and the negative environmental impacts of energy consumption; recycling-reusing the resources and exploring the possibilities of decreasing energy demand and/or shifting to energy generation from renewable resources, have become other focal points of LCA, i.e., in the water sector. In this context, LCA has been implemented to WWT practices since the '90s to link the treatment processes – of wastewater and sludge – to environmental impacts, to determine risks, and to use the estimated results in selecting the best-case scenarios in terms of feasibility and environmental impacts [10]. Research on analyzing WWTPs by LCA as a decision tool has been increasing in recent years [11]. While early LCA studies were used to assess WWTP processes, the system boundaries were enlarged in many recent studies to include other complex issues that should be carefully considered in investment and operational decisions such as sludge treatment alternatives [12]. LCA has also been used to evaluate the control strategies in WWTPs [13] and was useful to assess resource recovery alternatives for nutrients and water reuse [14].

Corominas et al. [11] have pointed out that LCA studies are challenged by the regional differences in the sense of considering local environmental uniqueness and stated that location-specific factors are critical to understand the impact of WWTP effluents on the receiving bodies. Therefore, it is essential to include local environmental status in LCA studies in a set of "accepted"characterization factors. Such detailed LCAs in the water sector are rare in Turkey, where "water stress" is experienced with a technical and economical available renewable water quantity of 1,500–1,700 m^3/person per year [15]. Thus this study presents a pioneering research since it not only provides an example of LCA for a WWTP system with nutrient removal in Turkey in spite of data inadequacies, but also incorporates the evaluation of an innovative-locally unique WWTP design. Sample scenarios were selected in accordance with the design parameters and country effluent standards for the presented LCA study. *SimaPro®* software was used to conduct the scenario analysis based on regional conditions taking into account the parameters available in the software database. In this context, this study summarizes how the LCA approach was implemented and used as an analysis and decision support tool to formulate and finalize the design of a full-scale biological wastewater treatment plant (BioWWTP) meant to serve for Bartın Province, Black Sea Region, Turkey. Main design targets were to eliminate high risks of eutrophication in the Black Sea and to overcome the difficulties in sustainable nutrient removal due to severe weather conditions, marked by heavy rainy seasons and unexpected extreme storms and floods in the region. The concepts of generating energy from solar power, harvesting rainwater, and retaining the treated wastewater and the harvested rainwater in a recreational pond prior to discharge or for possible recycle-reuse were also implemented, providing innovative integrated engineering solutions and contributing to sustainable development.

2. Background

2.1. System description – Conventional design

Currently, the wastewater generated at the central district of Bartın Province is collected by the sewer system and discharged to the nearby Bartın River without any treatment. That, together with the direct discharges from individual households, has been threatening the water quality and aquatic life in the river which is flowing into the Black Sea. Collecting and appropriately treating the wastewater prior to discharge into the receiving water body becomes an indispensable necessity to address those problems and is expected to serve for preservation, protection, and remediation of the environment while providing public services to the community in the region.

Consequently, a BioWWTP was designed for the Bartın Province within the framework of this study for an 86,389 population equivalence and a design wastewater overflow rate of 15,160 m^3/day. Nutrient removal was required and the wastewater had a medium strength in terms of organic matter content (500 mg COD/L; 310 mg BOD_5/L). Therefore, the plant was designed as a BNR system with Johannesburg configuration. The system comprises of primary and secondary wastewater treatment units, and also sludge treatment facilities. An anoxic tank added to the sludge recycling line provides denitrification through endogenous decay and protects the anaerobic zone from nitrate leakage deteriorating the phosphorus removal due to competitive organic carbon utilization for denitrification and anaerobic P-release. Effluent from the secondary clarifiers is directed to the UV-disinfection units prior to discharge. Waste activated sludge (WAS) from the secondary clarifiers enters a dissolved air flotation unit for sludge thickening and further dewatered in decanters with addition of cationic polyelectrolyte. Dewatered sludge is directed to the solar sludge drying basin to obtain a solids content of 90%. Finally, treated sludge is transported to a cement factory (6 km away) to be used there as fuel additive.

2.2. Sustainability and energy management concerns – Innovative integrated design solutions

Primary design of the treatment system had two major drawbacks; namely (i) high energy costs and (ii) risk of decrease in treatment performance due to possible dilution of wastewater caused by rainwater entering the biological treatment units [16]. An innovative and integrated engineering solution was formulated to mitigate both problems concomitantly; placing photovoltaic panels over the activated sludge units and secondary clarifiers of the WWTP and using those both for harvesting the rainwater falling on the biological treatment units and for generating electricity from solar power (Fig. 1a). This integrated design offers the possibility of decreasing the energy demand/cost, CO_2 emissions, carbon footprint, and related adverse environmental impacts of the plant (i.e., global warming potential), while mitigating the risk of not meeting the discharge standards due to decreased discharge quality.

The rainwater harvested from the photovoltaic panels located on the biological treatment units is directed to a natural conveyance channel (Fig. 1b), which collects the rainwater from the catchment area, pavements, roads, and buildings, and conveys the flow to an artificial recreational pond [17,18] located between the WWTP and Bartın River. Treated wastewater from the UV-disinfection units is also discharged to the recreational pond which is designed primarily for recreational purposes and also as a reservoir to facilitate; retention of harvested rainwater, retention and slow release of rainwater, flood control, and storage of treated wastewater for reuse in dry periods [19] and/or for other future reuses; hence providing a capacity for water recycling-reuse. Moreover, the pond has the potential of providing additional removal of pollutants by the help of aquatic plants [20] and thus contributing to amendment of dissolved oxygen level in the final receiving water body; the Black Sea.

Another engineering solution incorporated into the design of the treatment plant was about mitigating odor problems and related human-health risks, which are among the biological concerns of sustainable economic development applicable to WWTPs. The design solution structured to address those problems includes placing the primary treatment units in a building, collecting the indoor air – containing odor from the treatment units, and treating the indoor air using a bio-scrubber. The system enables removing aerosols and pathogens (e.g., viruses) present in or released to ambient air, hence contributes to protection of the health of employees.

3. Materials and methods

The general framework of the step-wise LCA methodology as outlined in the ISO 14040 [7,8] was adapted when conducting the LCA for the Bartin BioWWTP, and the frameworks and standards set in the ISO 14040 and ISO 14044 guidelines were followed [7,21]. Four main steps of the LCA were "goal and scope definition", "inventory analysis", "impact assessment", and "interpretation".

3.1. Goal and scope definition

The objective of the work was to design a BioWWTP including sludge treatment and disposal for the Bartın Province. In addition to the conventional design, innovative integrated design solutions were also considered within the framework of goal and scope definition. Main goal of implementing the LCA for the BioWWTP was to reveal the potential environmental risks of the system and determine the best-case scenarios in terms of environmental sustainability, while meeting the treatment needs and feasibility targets; thus use LCA as an analysis and decision support tool to formulate and finalize the design of the system. Construction and decommissioning phases of the facility (mainly the concrete structures and the machinery) were left out of the scope [5] and overall frame was defined as the operational phase lasting 30-years. One exception was that, production and construction of the photovoltaic panels were taken into account, so to provide a more realistic estimation of the impact of that innovative-integrated solution. Main features related with the intended audience (target groups), system boundaries, and impact categories were also briefly outlined in this phase and then refined in the following steps of LCA.

3.2. Inventory analysis

This step included identification and quantification of all inputs and outputs in and out of each unit process present

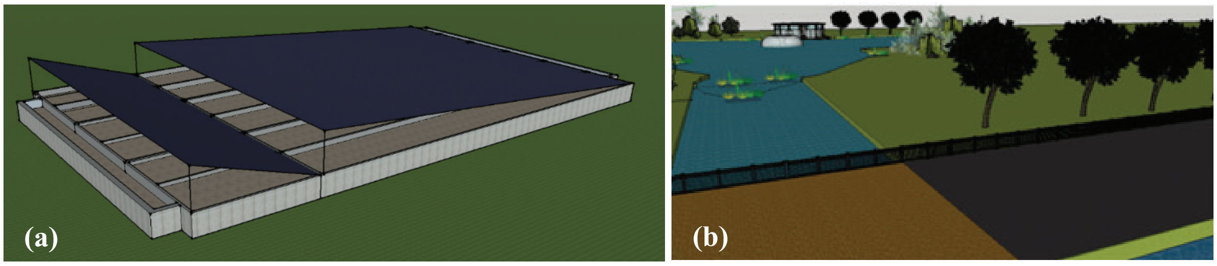

Fig. 1. Photovoltaic panels on activated sludge units of the BioWWTP for renewable energy generation and rainwater harvesting (a); natural conveyance channel for collecting and conveying rainwater to the artificial recreational pond (b).

in the designed treatment train. Inputs were material and/or energy flows entering the units and outputs were those leaving the units. Wastes and emissions out of the units were other important flows included in the inventory analysis. Information and data collection was carried out where applicable. However, since the system was not an operating one but in the design stage, real operational data was not available. Therefore, inputs, outputs, and wastes were quantified by calculating their amounts using the data from process calculations, system design, and equipment selection. Emissions were also calculated mainly as CO_2 equivalence.

3.3. Impact assessment

Impact assessment is defined as the "*phase of LCA aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product*" [7] and the critical element in that is referred as the impact category [8].There is a long list of various impact categories to choose from, especially when using an LCA software [8,22,23] whereas it is critical to determine the relevant impact categories matching the studied system to obtain a meaningful impact assessment. In this context, the impact categories evaluated in this study were identified by considering the nature and main function of the system (BioWWTP), re-visiting the goal and scope of the LCA, and taking into account the major elements in the inventory analysis. Accordingly, the following impact categories, of which some have been listed as being widely-used in life cycle impact assessments [8], were selected: abiotic depletion, global warming potential, ozone layer depletion, toxicity, freshwater and marine aquatic eco-toxicity, terrestrial eco-toxicity, photochemical oxidation, acidification, and eutrophication. Impact assessment was carried out by using a commercially available software -*SimaPro® LCA Package* [22].

3.4. Interpretation

In the final step, results from the previous steps are evaluated for deriving conclusions, recommendations, and for decision-making in relation to the goal and scope definition [7,8]. The following analyses of the final step of LCA were executed in this study by running numerical analyses: consistency- and completeness- checks and contribution-, comparison-, sensitivity-, and uncertainty-analyses. Total of five cases with multiple scenarios, seen in Table 1, were structured and impact assessment in selected impact categories were conducted for all options by running scenario analyses. Since the aim of the study was to implement and use LCA as an analysis and decision support tool for the design of the BioWWTP for the Bartın Province, the cases and the scenarios included the innovative-integrated design solutions proposed in this study, namely use of photovoltaic panels, rainwater harvesting and recreational pond.

For the first three cases, that is for meeting energy demand (case-1), disposal of treated sludge (case-2), and use of chemicals for sludge dewatering (case-3), scenario testing and simulations were conducted by using the *SimaPro® LCA Package* and the life cycle inventory (LCI) database integrated in the software [22,23] and the simulation results were comparatively evaluated for each case. For the last two cases, namely increase in dissolved oxygen level in the receiving water body (case-4) and improvement in effluent quality (case-5), scenarios with and without the recreational pond were generated by running the necessary calculations.

4. Results and discussion

4.1. System boundaries and identified flows

System boundaries determined for the LCA of the Bartın BioWWTP are schematically presented in Fig. 2

Table 1
Cases and scenarios tested

Case-1	Alternatives for meeting the energy demand of the BioWWTP
	Scenario-1: dual source for electricity: 60% from the photovoltaic panels + 40% from the main grid
	Scenario-2: mono source for electricity: 100% from the main grid
Case-2	Alternatives for disposal of the treated sludge
	Scenario-1: transportation to a cement factory 6 km away from the WWTP
	Scenario-2: transportation to a cement factory 100 km away from the WWTP
	Scenario-3: transportation to a cement factory 500 km away from the WWTP
	Scenario-4: transportation to a cement factory 1000 km away from the WWTP
Case-3	Alternatives for chemicals used as aid for sludge dewatering
	Scenario-1: use of polyelectrolytes as sludge dewatering aid
	Scenario-2: use of ferric chloride as sludge dewatering aid
Case-4	Alternatives for increase in dissolved oxygen (DO) in the receiving water
	Scenario-1: increase in DO level in Bartın River; without the recreational pond
	Scenario-2: increase in DO level in Bartın River; with the recreational pond
Case-5	Alternatives for effluent quality
	Scenario-1: effluent concentrations after biological treatment
	Scenario-2: effluent concentrations after biological treatment and recreational pond

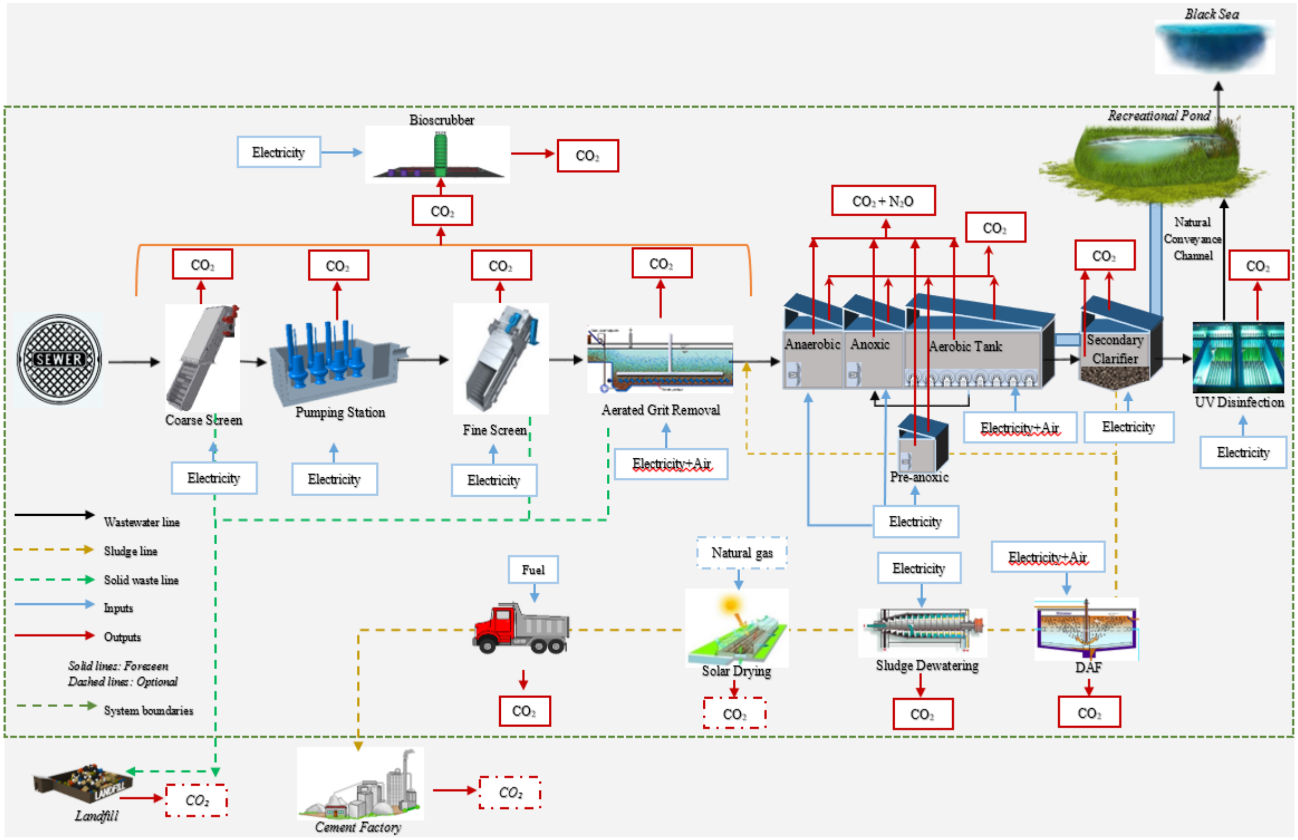

Fig. 2. Identified flows and system boundaries of LCA for the BioWWTP designed for the Bartın Province, Black Sea Region, Turkey. Main biological treatment units designed in Johannesburg configuration.

together with the plant layout. Material-, energy-, waste-, and emission flows identified in the inventory analysis as entering and leaving the main treatment units -the BioWWTP and the sludge management parts-, as well as the innovative engineering solutions comprised of photovoltaic panels designed for the dual purpose of electricity generation from solar power and rainwater harvesting, are also marked on the plant layout. Two interconnected sub-systems, namely the natural conveyance system and the recreational pond designed for collection and retention of the treated wastewater and the harvested rainwater for possible recycling-reuse, were also included in the LCA.

4.2. Inventory analysis results and GHG emissions

Results of the inventory analysis including quantification of the relevant flows in and out of each unit of the designed BioWWTP are given in Table 2. Quantified values were required to be normalized to enable comparative evaluation. Accordingly, a volumetric functional unit (FU) was preferred; thus 1 m^3 of treated wastewater was defined as the functional unit and used for normalizing the inventory analysis data given in Table 2.

Greenhouse gases (GHG) emission from the designed BioWWTP, as well as those from each unit present within the system boundaries, were estimated by using the quantified flows compiled and calculated in the inventory analysis phase of LCA given in Table 2. Indirect GHG emissions arising from electricity consumption throughout the plant are estimated as 8.4×10^{-2} kg eCO_2/m^3 treated wastewater, accounting for 71% of the total. Direct emissions originating from biological treatment are estimated as 3.4×10^{-2} kg eCO_2/m^3 ww, comprising 29% of the total emissions.

Contribution of each unit to the indirect GHG emissions (71% of the total) were also calculated. Partitioning of the indirect emissions from each unit is plotted in Fig. 3. As seen from the figure, almost half of the total indirect emissions are originating from the biological treatment units; mainly from the aerobic modules which have a significant energy demand to operate the blowers supplying oxygen to the system. Total GHG emission of the Bartın BioWWTP was calculated as 0.12 eCO_2/m^3 ww; a value lower than 0.2–0.4 eCO_2/m^3 ww reported as the range of GHG emissions from operating WWTPs [24].

4.3. Impact assessment and interpretation results

This section focuses on presentation and discussion of the results from the scenario analyses of the interpretation step since comparative evaluation of the outputs from those tests were eventually used as decision support inputs for fine tuning the design of the Bartın BioWWTP.

Table 2
Life cycle inventory (LCI) analysis of the Bartın BioWWTP

Unit processes and flows	Amount per 1 m^3 of treated wastewater
Pretreatment	
Energy	
Electricity (kWh)	3.67×10^{-2}
Waste generation	
Grit (m^3/day)	4.93×10^{-5}
Screen wastes (m^3/day)	2.53×10^{-4}
Transport	
Lorry 7.5–16 t (grit) (kg·km)	*n.a.*
Lorry 7.5–16 t (MSW) (kg·km)	*n.a.*
Indirect GHG emissions	
CO_2 (kg)	1.43×10^{-2}
Biological reactors	
Energy	
Electricity (kWh)	1.04×10^{-1}
Direct GHG emissions	
CO_2 (kg)	3.40×10^{-2}
Indirect GHG emissions	
CO_2 (kg)	4.08×10^{-2}
Secondary clarifiers	
Energy	
Electricity (kWh)	2.40×10^{-3}
Indirect GHG emissions	
CO_2 (kg)	0.93×10^{-3}
Sludge treatment	
Energy and chemicals	
Electricity (kWh)	4.52×10^{-2}
Polyelectrolyte (kg/day)	6.59×10^{-4}
Indirect GHG emissions	
CO_2 (kg)	2.35×10^{-2}
Transport	
Lorry 16–32 t (kg·km)	1.58×10^{-2}
Indirect GHG emissions	
CO_2 (kg)	3.0×10^{-5}

n.a.: not available

4.3.1. Comparative evaluation of scenario outputs for case-1

The first case tested with scenario analysis was of particular importance in relation to the overall aim and scope of the study, since it enabled comparative evaluation of the impact assessment of the designed BioWWTP with and without the innovative integrated design solution of placing photovoltaic panels over the biological treatment units and using those primarily to generate electricity from solar power. The tested scenarios included meeting 60% of the electricity demand of the system from the photovoltaic panels and 40% from the main grid (scenario-1) versus feeding the system only from the main grid (scenario-2). Simulation results obtained from the *SimaPro*® and showing the environmental impacts of the two tested scenarios of case-1 are presented in Fig. 4.

As seen from Fig.4; (i) the two scenarios are no different from each other in terms of their contribution to "*eutrophication*", (ii) use of electricity partly from the photovoltaic panels (scenario-1) has a slightly higher contribution to "*ozone layer depletion*", mainly due to the impact of production and construction processes of the photovoltaics, and (iii) scenario-1 has considerably lower negative impacts in all other impact categories. As apparent from the results of those scenario tests, scenario-1 was determined to have a marked advantage over scenario-2 in terms of decreasing the probable adverse environmental impacts of the designed public installation. Accordingly, the overall final interpretation of the detailed LCA was adopted as a decision support input to finalize the design and feasibility study of the BioWWTP to incorporate the innovative integrated design solution of placing photovoltaic panels over the main biological treatment units and generating electricity for on-site use. As stated previously in section 2.2, the other prominent advantage of the photovoltaic panels was to use those to collect rainwater for possible recycling/reuse and to prevent interference of the rain-water with the biological processes; altogether contributing to the overall sustainability of the system.

4.3.2. Comparative evaluation of scenario outputs for case-2

The second case was also particularly selected to troubleshoot the backup plan for final disposal of the on-site treated waste activated sludge by transport to a cement factory to be used there as fuel additive. Primarily a cement factory which is currently operating in the area and located 6 km away from the BioWWTP was identified, contacted, and made deal with for accepting the treated sludge from the treatment site. However, as seen in Fig. 2, that cement factory is located out of system boundaries, and more importantly is an external commercial enterprise. Therefore, it was required to consider the probable risks that might arise from involvement of such an externality. Accordingly, environmental risks/impacts of transporting the treated sludge to different cement factories at different distances (6, 100, 500, 1000 km in scenario-1, 2, 3, 4, respectively) from the treatment site (Table 1) were analyzed. Results of the scenario tests are given in Fig. 5. As seen from the figure, comparative evaluation of scenario analysis indicates that there is no apparent difference -in terms of contribution to *Global Warming Potential*; CO_2 eq.- between transporting the treated sludge to cement factories located 6 km or 100 km away from the plant, and both options are significantly advantages in terms of decreasing the negative impacts in "*ozone layer depletion*" and "*terrestrial eco-toxicity*" categories compared to the other scenarios. Hence, the second cement factory is proved to be a sound backup alternative for final sludge disposal with no additional burden put on the environment.

4.3.3. Comparative evaluation of scenario outputs for case-3

The two scenarios structured for case-3 were using polyelectrolytes (scenario-1) versus ferric chloride (scenario-2) as chemical aids for sludge dewatering in sludge management. This case was selected to test the use of different chemicals to provide flexibility in term of replacing one chemical

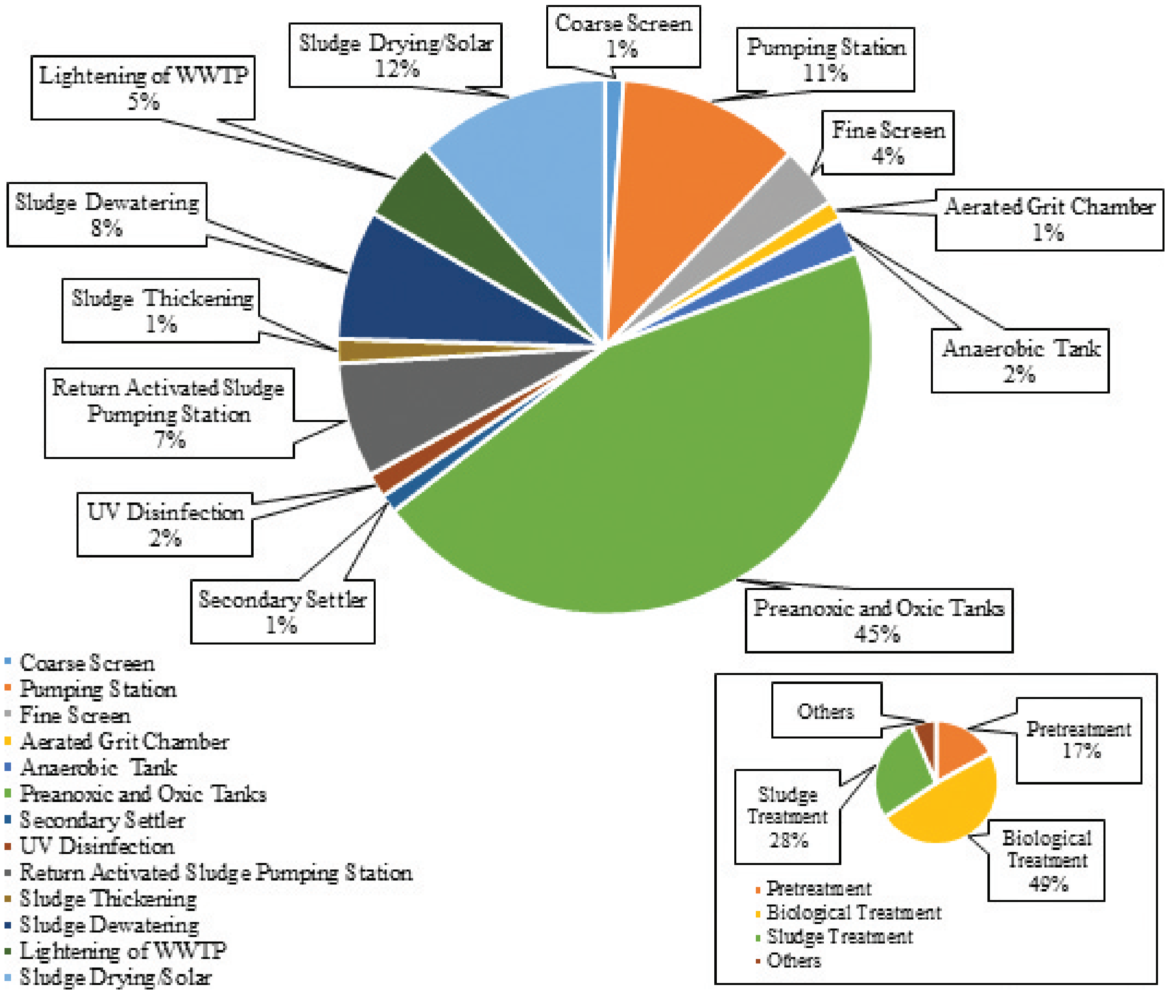

Fig. 3. Percent distribution of indirect GHG emissions arising from using electricity in the treatment units of Bartın BioWWTP (calculated based on kg eCO_2/m^3 wastewater treated).

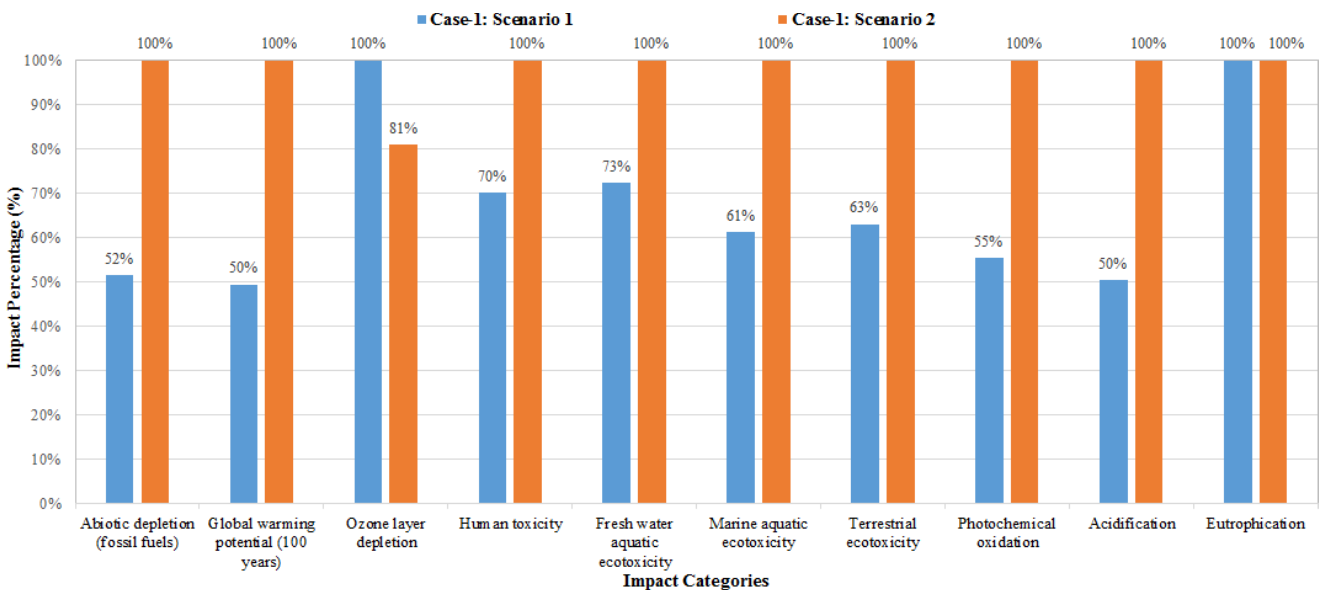

Fig. 4. Impact assessment results for case-1 with two scenario alternatives for meeting the energy demand of the BioWWTP.

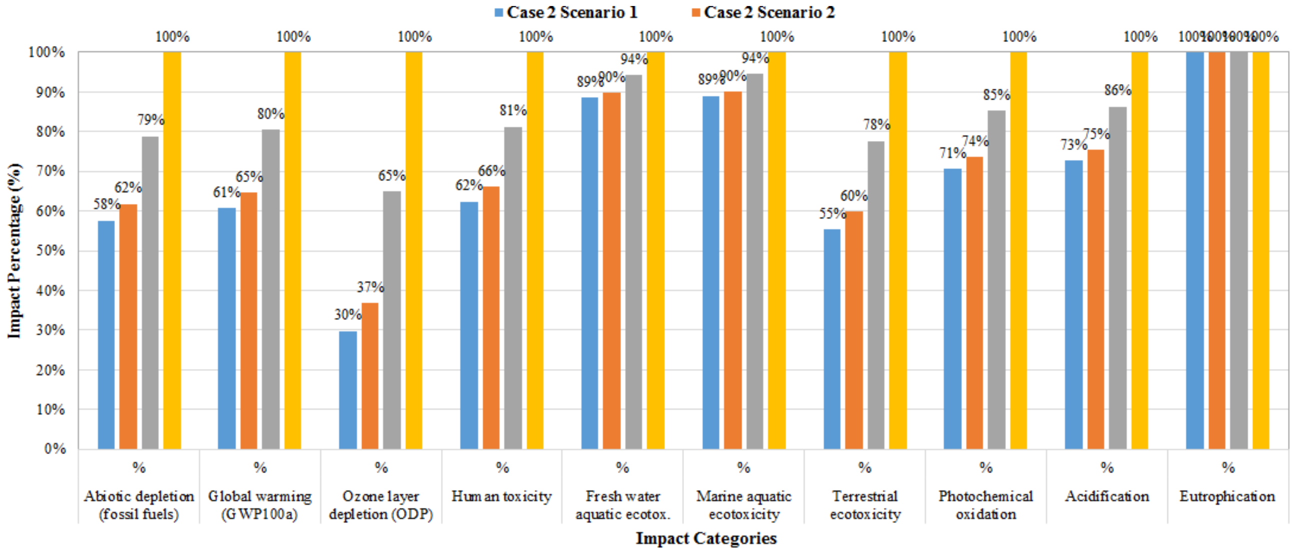

Fig. 5. Impact assessment results for case-2 with four scenario alternatives for transportation and final disposal of the on-site treated waste activated sludge.

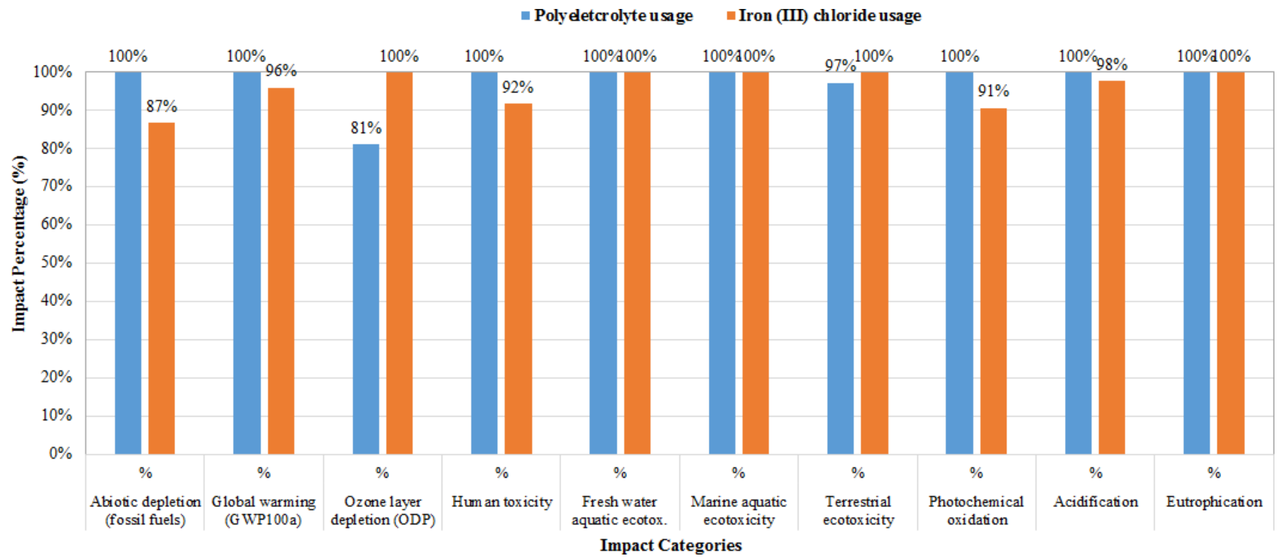

Fig. 6. Impact assessment results for case-3 with two scenario alternatives for chemicals used as sludge dewatering aid.

experiencing market price and supply disadvantages with another offering advantages. As seen from the results of the scenario testes given in Fig. 6, there is no obvious difference between those two options in terms of their contribution to any of the considered impact categories. Consequently, those chemicals are determined as appropriate alternatives of each other, thus might be used interchangeably, if needed, without compromising on sustainability.

4.3.4. Comparative evaluation of scenario outputs for case-4

The natural conveyance system and the recreational pond were the two interconnected systems designed to collect and retain the treated wastewater and the harvested rainwater (from photovoltaic panels located on the biological treatment units, from roads, pavements, etc.), before discharge to the receiving water body. Accordingly, the fourth case was selected to estimate the impact of the recreational pond on the quality of the receiving water (Bartın River) in terms of increase in dissolved oxygen (DO; mg/L), and two scenarios -with and without the recreational pond- were structured. As seen from the scenario analysis given in Fig. 7, compared to discharging the treatment effluent directly to the receiving water (scenario-1), retaining the treated wastewater and the harvested rainwater in the recreational pond prior to discharge (scenario-2) results in a higher increase in the DO level of the Bartın River (0.01 vs 0.23 mg/L increase in DO, respectively).

4.3.5. Comparative evaluation of scenario outputs for case-5

To determine the impact of retaining the treated wastewater and the harvested rainwater on the effluent quality

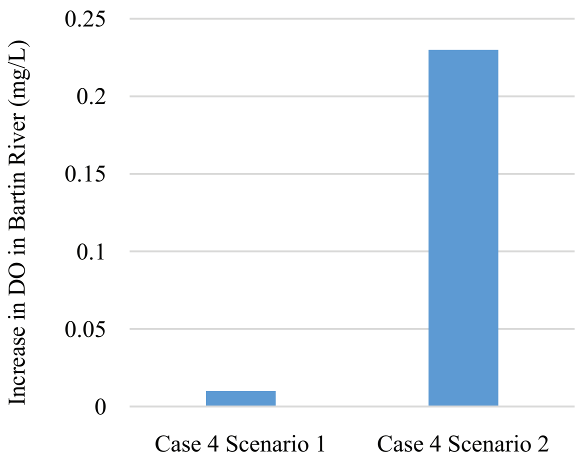

Fig. 7. Impact assessment results for case-4 with two scenario alternatives for increase in dissolved oxygen (DO) in the receiving water.

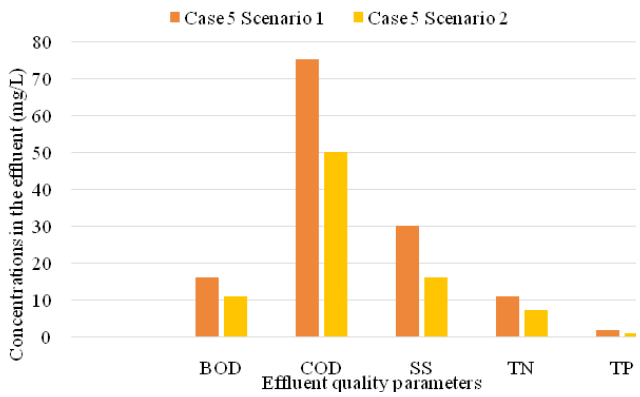

Fig. 8. Impact assessment results for case-5 with two scenario alternatives for effluent quality.

and the potential of further treatment, two scenarios in the absence and presence of the recreational pond were structured in case-5 (scenario-1 and scenario-2, respectively). As seen from the results presented in Fig. 8, retaining the treated wastewater and the harvested rainwater in the recreational pond prior to discharge to the receiving water provides more than 30% improvement in effluent quality: presence of the recreational pond facilitates 5–25 mg/L further removal in organic species, 0.6–4 mg/L in nutrients, and 14 mg/L in suspended solids.

In the current study, different cases including main environmental sensitive scenarios were evaluated for the BioWWTP designed for the Bartın Province: in case-1 where the electricity needs of the treatment plant were supplied from dual source, namely 60% from the photovoltaic panels and 40% from the main grid, scenario outputs showed that it was possible to reduce human toxicity by 30%, fresh water eco-toxicity by 27%, marine aquatic eco-toxicity by 37%, acidification by 50%, and global warming potential by 50%. In the study by Li et al. [26] it was estimated that direct electrical consumption by the WWTP had the highest impact on abiotic resource depletion (91%), global warming (94.9%), photochemical oxidation (88.8%) and acidification (78.9%). The study revealed that the environmental impacts such as acidification, global warming and abiotic resource depletion caused by direct electricity consumption would be decreased by using wind power. These findings are in agreement with those presented in the current study. Corominas et al. [11] also pointed out that conventional WWTP technologies were energy demanding and Emmerson et al. [27] emphasized that CO_2 emissions associated with energy production was extremely important in the evaluation of environmental performance, therefore electricity use contributed at the highest level to greenhouse gas emissions. In this context the use of renewable energy sources which have lower environmental impacts should be preferred to cope with the high energy requirements of WWTPs.

In case-2 where alternatives for final disposal of the treated sludge by transport to a cement factory to be used there as fuel additive were compared, scenario results indicated that the longer the distance, the worse the effects such as increase in global warming potential up to 39%. Although Garrido-Baserba et al. [12] have concluded that thermal technologies such as incineration and gasification have higher costs and global warming potential when compared to other alternatives like digestion, composting and super critical water oxidation since thermal technologies are not self-sufficient from the energetic point of view, the external thermal process preferred in the current study has been found to be a suitable alternative for sludge disposal due to low amount of sludge produced and having a nearby facility already running which could use excess sludge as fuel additive in their process.

Renewable energy utilization instead of high carbon foot-print electricity consumption have also proven to be extremely cost effective. A striking example is provided by The Sonoma County Water Agency which had a goal to produce carbon-free water by the year 2015. In order to achieve this goal, the Agency has integrated three photovoltaic systems in three existing WWTPs with a total capacity nearly 2,000 kW. It is estimated that the Agency would be able to save an estimated amount of 2.3M USD off the operational costs over the lifetime of the systems [28]. The current study has also shown that implementation of the innovative-integrated solutions, namely using photovoltaic panels for energy generation from renewable energy source and for rainwater harvesting, use of natural conveyance system and retaining the treated effluent and the harvested rainwater in recreational pond, in the design of the Bartın BioWWTP has contributed to the sustainability of the system and helped significantly reduce the GWP impacts.

5. Conclusion

Overall final interpretation of the detailed LCA was adopted as a decision support input to finalize and improve the design and feasibility study of Bartin's BioWWTP by incorporating the innovative integrated design solution of placing photovoltaic panels over the main biological treatment units. Pronounced advantages of the improved design are:

- generating electricity from renewable resources for on-site use,

- collecting rainwater for possible recycling-reuse,
- preventing interference of rainwater with biological processes;
- altogether contributing to the overall sustainability of the system.

Implementation of LCA, enriched by numerical analyses and/or software simulations, is considered as a powerful and reliable analysis and decision support tool for refinement of WWTP design and feasibility studies, especially when to offer innovative integrated engineering solutions, such as those presented in this study; using photovoltaic panels for energy generation from the renewable resource-the sun, and for collecting rainwater to be recycled/reused.

The improved design alternative presented and evaluated in this study is considered to have the potential of setting a sustainable and innovative example in the field of WWTP design [25].

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