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The environmental footprint of a membrane bioreactor treatment process through Life Cycle Analysis

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Abstract

This study includes an environmental analysis of a membrane bioreactor (MBR), the objective being to quantitatively define the inventory of the resources consumed and estimate the emissions produced during its construction and operation. The environmental analysis was done by the life cycle assessment (LCA) methodology, in order to establish with a broad perspective and in a rigorous and objective way, the environmental footprint and the main environmental hotspots of the examined technology. Raw materials, equipment, transportation, energy use, as well as air- and waterborne emissions were quantified using as a functional unit, 1 m^3 of urban wastewater. SimaPro 8.0.3.14 has been used as the LCA analysis tool, and two impact assessment methods, i.e. IPCC 2013 version 1.00 and ReCiPe version 1.10, have been employed. The main environmental hotspots of the MBR pilot unit were identified to be the following: (i) the energy demand, which is by far the most crucial parameter that affects the sustainability of the whole process, and (ii) the material of the membrane units. Overall, the MBR technology was found to be a sustainable solution for urban wastewater treatment, with the construction phase having a minimal environmental impact, compared to the operational phase. Moreover, several alternative scenarios and areas of potential improvement, such as the diversification of the electricity mix and the material of the membrane units, were examined, in order to minimize as much as possible the overall environmental footprint of this MBR system. It was shown that the energy mix can significantly affect the overall sustainability of the MBR pilot unit (i.e. up to 95% reduction of the total greenhouse gas emissions was achieved with the use of an environmentally friendly energy mix), and the contribution of the construction and operational phase to the overall environmental footprint of the system.

Keywords: impact assessment; inventory analysis; life cycle assessment; membrane bioreactor; sensitivity analysis; urban wastewater

1. Introduction

In the last decade, MBRs have attracted a great deal of attention for the treatment of both municipal and industrial wastewater (Trouve et al., 2014), with more than 2500 MBR plants operating worldwide (Meng et al., 2012). The MBR technology features various distinct advantages over the conventional activated sludge (CAS) process. Advantages include the excellent effluent (i.e. permeate) quality, good disinfection capability (membranes with small pore size), higher volumetric loading, reduced footprint and sludge production, process flexibility towards influent changes and improved nitrification (Hospido et al., 2012; Lin et al., 2014).

In addition, the occurrence of contaminants of emerging concern, including pharmaceuticals (i.e. licit and illicit drugs) and personal care products in treated wastewater and receiving waters is an issue which concerns conventional wastewater treatment. Drugs' removal during CAS treatment occurs through various mechanisms, including biodegradation (biotic process, mainly by bacteria and fungi), and abiotic transformations (e.g. hydrolysis and sorption to biomass or suspended solids) (Cirja et al., 2008). Biodegradation of drugs in CAS systems ranges from almost no biodegradation to high biodegradation, depending on the type of microcontaminant and its biodegradability, but it is far from complete biodegradation (Ternes et al., 2004). On the other hand, MBRs hold a promise for more efficient or even complete degradation of some microcontaminants from different water matrices, compared to the conventional biological systems; mainly due to the high sludge concentration and relative high sludge age, at which they operate (Sipma et al., 2010). More specifically, according to the scientific literature, MBR has been proved to be a sufficient treatment technology for the removal of various licit and illicit drugs (i.e. antibiotics, such as sulfamethoxazole, trimethoprim and clarithromycin, non-steroid anti-inflammatory drugs, such as diclofenac, acetaminophen, ketoprofen and ibuprofen, psychiatric drugs, such as carbamazepine and illicit drugs, such as cocaine and its corresponding metabolites, such as benzoylecgonine) (Kimura et al., 2005; Bernhard et al., 2006; Radjenovic et al., 2007; Reif et al., 2008; Shariati et al., 2010; Postigo et al., 2011; Sahar et al., 2011).

Nevertheless, membrane fouling is still the main obstacle in the industrial application and commercialization of MBR systems. Fouling reduces filtration performance and membranes operational life, leading as a consequence to higher operating costs (Rodriquez-Hernández et al., 2014) and energy demands. Elevated energy demands also negatively affect the environmental sustainability of MBR systems

It is well known that MBR technology is an efficient wastewater treatment option that produces an effluent with high quality. Among others, MBR-treated effluent can be safely used for irrigation purposes. Nevertheless, MBRs' overall environmental sustainability remains largely unknown and thus this study will try to shed light and give a better insight on this, applying the LCA methodology.

Since the mid-1990s, the LCA method has proven its worth in the evaluation of the environmental sustainability of water systems by using a whole system approach over their entire life cycle, and by addressing all relevant types of environmental impacts from global to local (Risch et al., 2014). Wastewater treatment has been studied using LCA analysis, with various studies mainly focusing on: (i) comparisons and assessment of new treatment technologies, in order to identify the most environmentally friendly ones (Vidal et al., 2002; Foley et al., 2010), (ii) the identification of wastewater treatment plants' (WWTPs) optimal operating conditions, pointing out their major environmental hotspots as well(Clauson-Kaas et al., 2001, Hospido et al., 2004), and (iii) the integration of the environmental vector at the design/construction phase of a WWTP, in order to optimize the whole system from an environmental point of view (Page et al., 2011).

To the best of our knowledge, LCA has been applied to MBR systems only in a few cases for treating urban wastewater (Tangsubkul et al. 2005; Ortiz et al. 2007; Pasqualino et al., 2009; Hospido et al. 2012) and greywater (Memon et al. 2007). It should be highlighted that the comparison of the results of different LCA studies, cannot be direct, since each study has a different goal and scope definition, different impact assessment methods are used, the assumptions made are not totally equivalent, while also the energy mix and the geographical location of each study are different. Tangsubkul et al. (2005), compared conventional wastewater treatment with additional microfiltration (CMF), MBR system followed by reverse osmosis, and wastewater stabilization ponds (WSP)) in terms of their environmental performance. The estimated scores, ordered from the highest to lowest were WSP better than MBR better than CMF, for all impact categories, while the treatment efficiency of MBR was significantly higher than WSP and CMF. In addition, in the study of Memon et al. (2007), the environmental impacts of an MBR used for the treatment of household greywater were compared with those of three other treatment technologies (i.e. reed beds, membrane chemical reactor (MCR) and green roof recycling system (GROW)), pointing out that the technologies based on natural treatment processes (i.e. GROW and reed beds) have lower environmental impacts. Moreover, according to Ortiz et al. (2007), both external and immersed MBR systems have shown lower environmental loads than a CAS system followed by tertiary treatment, for the treatment of urban wastewater. In this study electricity use, emissions of nutrients to the water, and application of sludge for agricultural purposes were identified as the main impact contributors. A comparison of four different MBR configurations was performed in the study of Hospido et al. (2012), indicating that the main contributors to the environmental impacts were identical for all four MBR configurations, with electricity consumption and agricultural application of sewage sludge playing the most important role. Also, the environmental impacts of a submerged anaerobic MBR (SAnMBR) system for the treatment of urban wastewater at different temperatures (i.e. 20 and 33 ^{o}C), was assessed in a study by Pretel et al. (2013). The LCA results revealed the importance of maximizing the recovery of nutrients, and thus reducing the 'eutrophication' impact category by up to 50%, as well as the recovery of dissolved methane, in order to obtain positive environmental impacts on 'toxicity' and 'freshwater aquatic ecotoxicity' impact categories.

From all the above, it can be concluded that existing literature is mainly focused on environmental assessment and comparative analyses of new treatment technologies, including MBR systems. The general conclusion is summarized to the fact that most of the environmental impacts are traced back to the energy use. As a consequence, significant environmental improvements are possible. However no measures for improving MBRs' overall environmental sustainability have been systematically investigated. Moreover, the environmental footprint of an MBR pilot unit treating urban wastewater containing targeted antibiotic compounds is largely unknown. Thus, a comprehensive LCA study of the MBR technology focusing on the identification of the majoring environmental hotspots, including also sensitivity/improvement analyses in order to optimize the whole system from an environmental point of view, is still missing.

This study uses the standardized LCA framework, as set in the International Organization for Standardization (ISO) 14040:2006 and 14044:2006 (ISO, 2006 a,b), to quantitatively define the inventory of resources consumed and estimate the emissions produced in an MBR system used for the biological treatment of urban wastewater. According to the authors' opinion, this is a first attempt to comprehensively assess the environmental footprint and the main environmental hotspots of an MBR unit used for the treatment of urban wastewater containing targeted antibiotic compounds. Also, this work includes a sensitivity analysis and a life cycle improvement analysis of this treatment technologywhich is a key element but still missing from the existing scientific literature.

2. Methodology

2.1 Goal and scope definition

The main objective of this work was to examine and assess the environmental sustainability of an MBR pilot unit, used for the treatment of urban wastewater. A single- and a multi-issue environmental impact assessment methods, namely IPCC 2013 and ReCiPe, were employed. The former was used in order to better communicate results to non-academic audiences and the latter to identify the impact categories (midpoint) and the areas of protection (endpoint) that are affected by the MBR pilot unit.

2.2 Functional unit

The functional unit of this study is directly linked to the effective treatment of urban wastewater and the removal of a specific antibiotic compound (i.e. sulfamethoxazole (SMX)). Therefore, the functional unit that was chosen is the "effective treatment of 1 m^3 of urban wastewater". It has to be noted that the effluent quality parameters that were achieved at the optimum operational conditions were the removal of at least 67% of effluents' COD (residual COD equal to 40 mg/L) and 82% of SMX (Table 1). It is important to mention that the quality of the treated wastewater fulfills the quality criteria of the Cypriot legislation (Regulation 772/2003) (i.e. COD: 125 mg/L and TSS: 35 mg/L), in order to be safely reused for irrigation or to be disposed of in surface waters.

2.3 System boundaries

In Figure 1, the system boundaries of the MBR pilot unit are presented. These include the construction materials, the MBR equipment, the treated effluent, as to its qualitative and quantitative chemical characteristics, land use, other system outputs to the environment, such as airborne emissions (i.e. from acidification and greenhouse gases (GHG)), the transportation for construction and operation of the unit within the country, where it is installed, and the effluent storage tank. The influent primary treatment (i.e. screening) and the solid sludge waste (i.e. screened grit, removed solids) were not considered within the scope of this LCA study and hence are not included in the system boundaries. This is because a cradle-to-gate approach was used, i.e. the final disposal/reuse of the treated effluent is outside of the system boundaries. The reason is that the route of the effluents' disposal/reuse can affect the overall sustainability of the MBR system and therefore its inclusion would make results valid for the specific route. For example, conventionally-treated urban effluents are enriched with organic load, and therefore their reuse for field irrigation can provide nutrient content (Bengtsson et al., 1997), lowering thus fertilizing needs and in theory reducing the total environmental footprint. On the other hand, if these effluents are directly released into a freshwater ecosystem they may impose stresses on the 'eutrophication' impact category, increasing thus the total environmental footprint, while marine ecosystems are less sensitive to the eutrophication potential than the freshwater ecosystems (e.g. rivers, lakes, etc.). Therefore, the route of disposal, as well as the local conditions and technology used (e.g. piping, pumps, electricity mix, etc.) can have an effect on the total environmental footprint, but this depends on too many local and specific assumptions, which can limit the overall applicability of the results. Similarly, sludge treatment and disposal were not considered within the system boundaries. Solid sludge waste is the main by-product of the MBR pilot unit and as such it could be examined by a separate LCA study. Moreover, different methods to manage the sludge exist, each one with its own limitations, considerations and specific assumptions, and therefore each method is expected to have its own environmental footprint. As a result, including a sludge management scheme in this case study would limit the general relevance of the results obtained by the present study.

Finally, a useful lifetime of 20 years for the MBR pilot unit was taken into account. This is in line with relevant information in the literature (Emmerson et al., 1995; Vlasopoulos et al., 2006) and also with the advice obtained by the manufacturer.

2.4 Description of the MBR pilot unit

The submerged membrane bioreactor considered in this study, consists of two compartments: (i) the pre-aeration tank (mentioned as pre-aeration stage), where ammonia nitrogen is converted to nitrates biologically through nitrification, and (ii) the membrane bioreactor (mentioned as MBR stage), where the treated effluent permeates through flat-sheet microfiltration (MF) membranes immersed in the bioreactor to a common manifold, and then is stored in a final effluent tank (Schematic 1). The unit has a rectangular shape (2.3 m x 1.4 m x 2.5 m), is made by stainless steel (SS304) and it is designed to treat 10 m^3 day^{-1} of primary-treated wastewater.

The screened wastewater flows through a pumping station, inside the MBR reactor, by a self-priming feed pump of a capacity between 0.25 - 0.85 m^3 h^{-1}, at 2 bar. A constant supply of air provides content mixing and enhanced oxidation of organic carbon substances with the use of two blowers (33 m^3 h^{-1}) in pre-aeration tank and the MBR stage. The air blowers are connected with four fine bubble diffusers in order to provide the surge of air inside the MBR unit. The MBR consists of 25 flat-sheet cartridges (type FF25, Kubota) with a total effective membrane surface area of 100 m^2. The nominal pore diameter of the membranes is 0.4 μm, while the designed flux is 0.5 m^3 m^{-2} day^{-1}. The polymeric material of the membrane structure is chlorinated polyethylene. The cleaning of the membranes is conducted with sodium hypochlorite (NaClO) (0.5%), whilst for the treatment of 1 m^3 of wastewater 37.5 mg of NaClO is needed. The final effluent (permeate) passes to an irrigation tank through a permeate pump controlled by a frequency converter. Finally, a control panel completes the installation.

2.5 Assumptions/Hypotheses

The main hypotheses made for the MBR pilot unit operation are:

- According to standard practice, the MBR pilot unit works at full capacity (10 m^3) all year round.
- A useful life of 20 years is considered, as advised by the manufacturer.
- The motors that were chosen to be used for the construction of the pumps and the air blowers LCI have a lifetime of 15 years, according to the available scientific literature (Environmental Product Declaration, 2006).
- It is assumed that the unplasticized polyvinyl chloride (UPVC) pipes used in this study have a lifetime of at least 50 years, and no replacement during the lifetime of the whole unit is needed (Sand, 2013).
- Extraordinary conditions (i.e. flooding of the pilot plant, unexpected stoppage of the units, etc.) were not considered (i.e. outside of the system boundaries).
- The transportation of the equipment needed for the installation of the MBR pilot unit is assumed to be delivered from the city where it was constructed to the city where it was installed (80 km distance). A truck (of approx. 7.5 tn) was considered for the equipment transportation and installation, while vans (<2.5 tn, light vehicles) were selected for the transportation of the chemicals and the maintenance of the normal function of the MBR pilot unit. The average lifetime of these vehicles was assumed to be equal to 8.3 years, according to the study of Erumban et al. (2008).

- The construction data (i.e. pieces of equipment of the plant, construction materials and manufacturing processes) and the operation and maintenance data have been taken from the Cypriot manufacturing company of the MBR pilot unit.
- The data regarding airborne emissions of MBR operation were taken from the available scientific literature (Ortiz et al., 2007; Foley et al., 2010).

3. Life Cycle Inventory (LCI) analysis

An inventory of all flows (e.g. energy, raw materials and releases to air, land and water) of the MBR system from and to nature was created. As part of this study, all relevant values were normalized as per the functional unit, in order to make the options considered comparable. Table 2 lists the Life Cycle Inventory (LCI) of the system under study. Data external to the system boundaries are not included in the analysis. The attributional LCI methodology was used, which by definition provides the set of total system-wide flows that are “associated with” or “attributed to” the delivery of a specified amount of the functional unit.

Experimental data regarding the MBR operation and treatment efficiency were collected and used from the system itself. Data on materials and energy consumption, as well as characterization of the wastewater entering and leaving the facilities were collected from the Cypriot manufacturer of the unit, and on-site experiments and lab analysis that were carried out. Also, the Ecoinvent 3.01 database was used to build the LCI of the MBR pilot unit. Moreover, the local electricity mix, the electric motors and the submerge membranes units were created from literature data, since they are not available in SimaPro’s LCI datasets.

The electricity mix of Cyprus consists of 92.5% from oil, 5.6% from wind power, 1.1% from photovoltaic systems and 0.8% from biomass (Electricity Authority of Cyprus, 2015). Data from SimaPro’s LCI databases were used to model the aforementioned mix.

The types of the pumps and the air blowers used for the operation of the MBR pilot unit are not available in the existing databases. For this reason a literature search was conducted, and the available LCI data identified were related to the main part of this equipment, namely to their motor. The motor that was chosen to be used in this LCA study was the

ABB Motor Type 90s (1.1 KW with a lifetime of 15 years) (Environmental Product Declaration, 2006). The MBR pilot unit utilizes Kubota’s submerged microporous membranes (average pore size: 0.4 μm) cartridges, whose main material is chlorinated polyethylene, which is not listed in existing LCI databases. Thus, it was compiled using its main inputs, as described in the literature (Quenum et al., 1975; Dow Chemical Company, 2015). A useful life of five years was assumed for the membranes (Kubota, 2012). In addition, the cleaning of the membranes is conducted with sodium hypochlorite (NaClO) (0.5%), and it was estimated that in the lifetime of the MBR pilot unit (i.e. 20 years) a quantity of 18.75 kg of NaClO is required.

4. Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) is the third phase of the LCA and consists of the assessment and evaluation of the environmental impact of the system under study. In this stage the data collected in the phase of LCI was assessed with the software package SimaPro 8.0.3.14. SimaPro is one of the most widely known LCA tools, used both by professionals and researchers (Foteinis et al., 2011). Two impact assessment methods were used in this work, namely IPCC 2013 version 1.00 and ReCiPe version 1.10.

IPCC (Intergovernmental Panel on Climate Change) 2013 is a single issue method that compares processes based on CO_2 emission equivalents ($CO_{2\text{-eq}}$), which are used to measure the Global Warming Potential (GWP), a standard indicator of environmental relevance that is easily understood by the public (Chatzisymeon et al., 2013). The standard timeframe of 100 years was used in this work.

ReCiPe takes into account a broad set of environmental issues, including the GWP indicator, and is a robust method that comprises two sets of impact categories (i.e. midpoint and endpoint) with associated sets of characterization factors. At the midpoint level, 18 impact categories are addressed, i.e. 'climate change' (CC), 'ozone depletion' (OD), 'terrestrial acidification' (TA), 'freshwater eutrophication' (FE), 'marine eutrophication' (MEP), 'human toxicity' (HT), 'photochemical oxidant formation' (POF), 'particulate matter formation' (PMF), 'terrestrial ecotoxicity' (TET), 'freshwater ecotoxicity' (FET), 'marine ecotoxicity' (MET), 'ionising radiation' (IR), 'agricultural land occupation' (ALO), 'urban land occupation' (ULO), 'natural land transformation' (NLT), 'water depletion' (WD), 'metal depletion' (MD) and 'fossil depletion' (FD). These midpoint impact categories can be multiplied by damage factors and aggregated into three endpoint categories (i.e. 'human health, 'ecosystems' and 'resource surplus costs'), which in turn can be normalized, weighted and aggregated into a single score (Chatzisymeon et al., 2013). ReCiPe, utilizes three different perspectives, namely individualist (I), hierarchist (H) and egalitarian (E). In this study, the H perspective was chosen for the evaluation of the results, since it is a consensus model based on the most common policy principles, with regard to timeframe and other issues.

5. Results and Discussion

For each of the two stages of the MBR pilot unit (i.e. pre-aeration stage and MBR stage), a thorough LCI was performed, followed by a full LCA, in order to assess the environmental impacts of each stage and identify their main hotspots. Finally, the two stages were modeled together, in order to assess the total environmental footprint of the entire MBR pilot unit.

5.1 IPCC 2013 results

The results of IPCC 2013 impact assessment method, for a timeframe of 100 years, are presented herein. For the functional unit chosen in this case study, which is the effective treatment of 1 m^3 of urban wastewater, the total $CO_{2\text{-eq}}$ emissions of the MBR pilot unit are amount to 4.65 kg $CO_{2\text{-eq}}/m^3$, while the contribution of each parameter (e.g. energy consumption, pumps, membranes, maintenance activities, etc.) of the system to the total GHG emissions is given in Figure 2.

As can be seen in Figure 2(a), the pre-aeration stage of the MBR pilot unit is responsible for the 47.7% (i.e. 2.22 kg $CO_{2\text{-eq}}/m^3$) of the total GHG emissions, while the remaining 52.3% (i.e. 2.43 kg $CO_{2\text{-eq}}/m^3$) is attributed to the MBR stage of the unit. The majority of the $CO_{2\text{-eq}}$ emissions (i.e. 97% or 4.52 kg $CO_{2\text{-eq}}/m^3$) is traced back to the energy used by the lift pump and the air blower in the pre-aeration stage and the air feeding and the permeate pump in the MBR stage. This especially high contribution (i.e. 97%) can be attributed to two main reasons: (i) the local energy mix, which is heavily depended on fossil fuels, and (ii) the overall low contribution to the total $CO_{2\text{-eq}}$ emissions of the equipment and materials used for the construction of the unit. As far as the energy consumption is concerned, the use of oil accounts by itself for 95.5% of the total $CO_{2\text{-eq}}$ emissions, while wind power, biomass and solar energy are responsible for 0.1%, 0.4% and 1%, respectively (Figure 2(b)). The small contribution of the latter is attributed to the facts that these are renewable energy sources and as such have a minimal environmental impact, and they only contribute by a very small percentage to the local electricity mix. Moreover, 0.6% (or 0.029 kg $CO_{2\text{-eq}}/m^3$) is attributed to the submerge membrane units, 0.8% (or 0.038 kg $CO_{2\text{-eq}}/m^3$) to the pre-fabricated tank (manufacturing procedure and production material (i.e. stainless steel)), while the maintenance activities of the unit contribute 0.85% to the total $CO_{2\text{-eq}}$ emissions. It has to be noted that the airborne emissions and the land use of the MBR pilot unit have a few orders of magnitude lower $CO_{2\text{-eq}}$ emissions, compared to the energy consumption, and thus they are considered as negligible. This is attributed to the fact that airborne emissions, which are mainly direct $CO_{2\text{-eq}}$ emissions, were assumed to be biogenic, having thus a neutral impact on the environment. In addition, the use of chemicals for membrane cleaning and prevention of membrane fouling has a negligible contribution to the total environmental impact, due to the small amounts used and their low environmental impacts (e.g. NaOCl). Moreover, the pumps, the aeration diffuser, the air feeding and the pipes exhibit a very low contribution (<0.1%) to the total $CO_{2\text{-eq}}$ emissions. It is noted that the latter refers to the environmental impact of the material production of the above mentioned equipment.

It should be highlighted that the construction phase of the MBR unit has a minimal environmental impact (~3.5%), compared to the operational phase (~96.5%), mainly due to the fact that: (i) the materials used for the construction of the MBR pilot unit, except of the membrane units, are not associated with high environmental impacts, (ii) these materials exhibit an overall high life span, and (iii) recycling of the main materials (i.e. stainless steel and plastics), after the end of the lifespan of the pilot unit, was considered (i.e. a 70% recycling on metals/plastics was assumed). It should be noted though that the fossil fuel-depended grid, used in this study, contributes to the increase of the environmental impacts of the operational phase of the unit.

The mean daily $CO_{2\text{-eq}}$ emissions per capita in Cyprus are about 27.7 kg $CO_{2\text{-eq}}$ (data for 2013) (EEA, 2014), and the daily treated urban wastewater per capita in Cyprus is about 50 L (data for 2009) (AQUASTAT, 2013). Comparing the treatment of the wastewater effluent per capita in Cyprus by an MBR unit, it is obvious that its emissions would contribute less than 1.2% of the mean daily total $CO_{2\text{-eq}}$ emissions per capita. This low contribution illustrates the sustainability of the MBR technology for treating urban wastewater effluents.

5.2 ReCiPe results

The ReCiPe impact assessment method was employed, in order to identify the midpoint and endpoint impact categories that are affected by the MBR operation, as well as its total environmental footprint. Figure 3, shows the contribution of each parameter of the MBR pilot unit at each of the 18 midpoint impact categories mentioned above. It is shown that the majority of the environmental impacts is attributed to the lift pump, air blower (pre-aeration stage), air feeding and the permeate pump (MBR stage). Similarly to IPCC 2013, this is attributed to the consumption of energy, and specifically to the fossil fuel-depended electricity mix used herein. The submerge membrane unit contributes to a lower extent to the toxicity impact categories (i.e. 'terrestrial ecotoxicity', 'human toxicity' and 'marine ecotoxicity').

Figure 4, shows ReCiPes' 18 midpoint level normalized impact categories, using Europe's reference inventories. ReCiPes' score is expressed in Eco-Indicator points (Pt), where 1000 Pt is the yearly environmental load of an average European citizen. As shown, the impact categories that are affected the most, from the higher to the lower score, are: 'natural land transformation', 'marine ecotoxicity', 'human toxicity', 'freshwater ecotoxicity' and 'terrestrial acidification'. These impact categories are mainly affected by the energy consumption of the pumps and blowers of the MBR unit, and more specifically by the crude oil extraction and refining and from the combustion of oil, which is the main energy source of the local grid. For example, fossil fuel combustion release toxic materials, such as heavy metals, sulphurous compounds and polycyclic aromatic hydrocarbons (PAHs) to the environment, affecting thus the 'ecotoxicity' (e.g. marine and freshwater ecotoxicity) and 'toxicity' (e.g. human toxicity) impact categories (Atilgan and Azapagic, 2015).

Moreover, fossil fuel extraction, transportation and processing can require large areas, therefore affecting the impact category 'natural land transformation'. Furthermore, the impact categories 'fossil depletion', 'particulate matter formation', 'photochemical oxidant formation' and 'climate change' are affected to a lower extent, as shown in Figure 4. This is mainly due to the fossil fuel combustion. The impact categories 'freshwater eutrophication' and 'terrestrial ecotoxicity' are mainly affected by the extraction process (e.g. the impact on freshwater is due to phosphate emissions from fossil fuel extraction and nitrogen oxide emissions from combustion) (Atilgan and Azapagic, 2015). The remaining impact categories have a very low score and thus they are assumed to be negligible.

Moreover, as shown in the inset graph of Figure 4, the membrane units have a very low contribution, compared to the electricity consumption, and is mainly attributed to the impact categories 'terrestrial ecotoxicity' and 'human toxicity', while they also exhibit a smaller contribution to the impact categories 'fossil depletion', 'marine ecotoxicity', 'freshwater ecotoxicity', 'particulate matter formation', 'terrestrial acidification' and 'climate change'. The materials of the membranes (i.e. chlorinated polyethylene and ABS resin), which according to the study of DeMatteo, (2011) are suspected as carcinogenic, contributed to these impact categories. Specifically, the manufacturing procedure of chlorinated polyethylene, which is based on the chlorination of polyethylene by gaseous chlorine, contributes to these impact categories. According to the Material Safety Datasheet (MSDS) of chlorinated polyethylene resin, at temperatures exceeding melt temperatures, polymer fragments can be released, while its decomposition products can include among others aldehydes, alcohols, organic acids, hydrogen chloride, as well as trace amounts of hydrocarbons (Dow Chemical Company, 2014). The construction of the pre-fabricated tank contributes to a lower extent to the impact categories 'metal depletion' (mainly due to the raw material (i.e. stainless steel) that is constructed from), 'particulate matter formation', 'terrestrial acidification', 'fossil depletion' and 'climate change', while the air diffuser used in the pre-aeration stage of the MBR pilot unit contributes mainly to 'marine ecotoxicity', 'freshwater eutrophication', 'freshwater ecotoxicity' and 'human toxicity'. Moreover, the land use and the maintenance activities of this unit contribute mainly to the impact categories 'fossil depletion' and 'human toxicity'. Finally, the chemical cleaning of the MBR exhibits a very low, almost negligible score on all impact categories, as shown in Figure 4, which can be attributed to the small amounts of chemicals used for the cleaning of this unit and to the fact that the chemicals (i.e. NaOCl) used (i.e. production, application and disposal) are not associated with a high environmental footprint.

From all the above, it can be concluded that the aforementioned midpoint impact categories are mainly affected by indirect emissions from oil extraction and electricity production and are not the result of direct emissions from wastewater treatment by the MBR pilot unit. This is in line with the study of Slagstada and Brattebø, (2014). Therefore, if electricity is provided by an environmentally friendly renewable energy source, such as solar energy, different impact categories would be affected and lower normalized scores would be expected, highlighting thus the need for a sensitivity analysis.

Figure 5 shows the aggregated environmental impacts of the MBR pilot unit, using ReCiPes' three endpoint indicators (i.e. 'human health', 'resources' and 'ecosystems'). According to this figure, the total environmental footprint of the MBR pilot unit is 442 mPt per treated m^3 of urban wastewater with the damage category 'human health' exhibiting the highest score (195 mPt), followed by 'resources' (161 mPt), while 'ecosystems' damage category has the lowest score (85 mPt). Similarly, to the midpoint analysis the main contributor to these damage categories is the electricity consumption from the local energy mix, i.e. energy consumption being responsible for 0.4 Pt. 'Human health' damage category is affected by the extraction process and oil combustion (e.g. airborne emissions), while 'recourses' damage category is affected by the depletion of crude oil, a non-renewable energy source.

The results of this study are in agreement with Tangsubkul et al. (2005), Memon et al. (2007), Hospido et al. (2012) and Pretel et al. (2013), where the main contributor to all impact categories (e.g. global warming, eutrophication, freshwater aquatic ecotoxicity, terrestrial ecotoxicity, etc.) was also the energy consumption of the MBR unit. Also, Memon et al. (2007) and Ortiz et al. (2007) noted that the operational phase of an MBR contributes the most (about 95% and 79%, respectively) compared to the construction phase (about 5% and 21%, respectively) for the treatment of greywater and urban wastewater, respectively. These values are in line with the results of the present study (i.e. 96.5% operational and 3.5% construction phase).

6. Alternative Scenarios - Sensitivity analysis

In terms of the total environmental footprint, the MBR pilot unit was found to yield low, but still important, environmental impacts. Thus, alternative scenarios to improve its sustainability were examined.

A sensitivity analysis was conducted in order to determine how changes in the main environmental hotspots, i.e. energy mix and material of the membrane units, were affecting the overall sustainability of the MBR pilot unit. For this reason, four different energy mixes, namely Greek (Grid 2), Italian (Grid 3), French (Grid 4) and Norwegian (Grid 5) were compared to the Cypriot energy mix (Grid 1). Their effects on GHG emissions and on the overall environmental footprint of the MBR pilot unit were also examined. Grid 2 is heavily depended on fossil fuels (i.e. 54% provided by solid fuels (lignite), 11% on crude oil, 17% on natural gas, while 18% is provided by renewable energy sources) (Public Power Corporation S.A. Hellas, 2015). Although lignite is a 'cheap' energy source, the environmental impacts associated with its use are high, something that applies also for petroleum and in a lower extent for natural gas (Theodosiou at al., 2014). Grid 3 is also based on fossil fuels (51%), but in this case natural gas, a much cleaner fossil fuel compared to lignite and crude oil, which accounts for 39% of the energy mix, and a further 10% by renewable energy sources (European Union, 2013). In the case of Grid 4, 76% of electricity is provided by nuclear power, while the remaining 15% is provided by renewable energy sources and 9% by fossil fuels (French National Grid, 2015). Finally, Grid 5 is based on renewable energy sources (i.e. 97.9% hydroelectric, 1.5% thermal and 0.6% nuclear), exhibiting thus a very environmentally friendly footprint. Moreover, due to the fact that globally the energy mix is heavily depended on fossil fuels - and more specifically, according to the study of Theodosiou et al. (2014), 80% of the electricity needs worldwide are met by fossil fuels - a renewable energy source, namely solar energy, the most abundant renewable source in the country, was also examined. Finally, a more environmentally friendly membrane material, namely ethylene propylene diene monomer (EPDM), was examined, assuming that an EPDM membrane would have the same treatment performance as chlorinated polyethylene membrane, which was used in the conventional scenario.

6.1 Life Cycle Improvement Analysis of the MBR pilot unit using solar energy

The first and most critical improvement that can be made for the system under study is the diversification of the electricity mix, the main environmental hotspot. Usually, high energy consumption for the operation of a WWTP comes with the benefit of achieving high effluent quality, although this is accompanied by a high environmental cost (Ortiz et al. 2007). On this basis, if reducing the energy consumption is not possible, then the option of shifting to a cleaner energy source (i.e. solar) could be examined, as to improve the environmental performance of the applied technology.

In the first alternative scenario (S1), the energy needs of the MBR pilot unit are covered 100% by solar energy originating from a photovoltaic (PV) system that is connected to the electrical grid. It was shown that the use of solar energy can substantially reduce the total GHG emissions (IPPC 2013) of the MBR pilot unit, since the total $CO_{2\text{-eq}}$ emissions are reduced from 4.65 kg $CO_{2\text{-eq}}/m^3$ (conventional scenario) to 0.56 kg $CO_{2\text{-eq}}/m^3$, i.e. 88% reduction. Moreover, in S1 the contribution of electricity consumption to the total GHG emissions is 75.2%, the maintenance activities 7%, the submerge membrane units 5.2%, the pre-fabricated tank of the unit 6.85% and the pumps 1.7%. It is noted that the latter percentage (i.e. 1.7%) refers to the environmental impact of the material production of the pumps. Therefore, not only do the total GHG emissions of the MBR unit are substantially reduced (i.e. by 88%), but the contribution of the construction and the operation phase to the total GHG emissions, during the whole lifespan of the MBR pilot unit, is also significantly affected.

When ReCiPe impact assessment method is used, the environmental footprint of the MBR pilot unit is again significantly reduced through the use of solar energy. In this case, the most affected impact categories are the ecotoxicity/toxicity ones, which are attributed to the manufacturing procedure of the PV panels that results to airborne emissions, mainly copper, and to the high amounts of fossil fuels that are used during the manufacturing procedure of the PV, which also induce impacts onto the damage category 'human health'. Specifically, the high normalized scores on the impact categories 'freshwater ecotoxicity' and 'marine ecotoxicity' are largely attributed to the emissions of metals during PV panels manufacturing procedure. These emissions, can induce significant changes in metal concentrations on freshwater and marine ecosystems (Mohr et al., 2009).

When ReCiPe results are aggregated into a single score, the total environmental footprint of S1 is 74.7 mPt, instead of 442 mPt in the conventional scenario. Thus, a substantial reduction, about 83%, is achieved by adopting solar energy. Moreover, the damage category 'human health' is affected the most, followed by the 'resources' and 'ecosystems'. Life-cycle emissions could derive from fossil fuel-based energy consumption to produce the materials for solar cells, modules and systems, as well as directly from smelting, production and manufacturing facilities. Indirect emissions associated with the use of fossil fuels in the generation of energy required in the life cycle of photovoltaics can result to heavy metal, SOx, NOx, particulate matter (PM), CO_2, toxic gas and GHG emissions. Direct emissions include particulate matter and heavy metals from mining and smelting, whereas liquid and solid waste are, for the most part, being recycled according to the study of Fthenakis et al. (2008). These indirect emissions (e.g. heavy metal, SOx, NOx, PM, CO_2, toxic gas), as well as the direct heavy metal emissions mainly affect the damage category 'human health', whereas the damage category 'resources' is mainly affected by raw materials and fossil fuel consumption for the PV production. Finally, the damage category 'ecosystems' is mainly affected by heavy metal emissions.

6.2 Life Cycle Improvement Analysis of the MBR pilot unit using EPDM membranes

In the second alternative scenario (S2) the effect of the use of a more environmentally friendly membrane material (i.e. ethylene propylene diene monomer (EPDM)), compared to the material used in the conventional scenario, (i.e. chlorinated polyethylene) was examined. EPDM is an inert material with limited environmental impact during manufacturing, installation and use, while its excellent performance reflects to low life cycle costs and less impact on the environment. If the membrane material is to be substituted by EPDM, it is found that it can reduce the membrane unit contribution to the total GHG emissions (IPCC 2013) almost by half. Nonetheless, this reduction does not significantly affect the total GHG emissions of the MBR pilot unit, since the membrane units contribution is reduced from 0.81% to 0.44%. Moreover, as far as the total aggregated environmental impact (ReCiPe) is concerned, the substitution of the membrane material has a slight effect, less than 1% reduction, on the overall sustainability of the MBR pilot unit. It has to be noted again that it was assumed that EPDM membranes would have the same treatment performance as the membrane made by chlorinated polyethylene.

6.3 Sensitivity analysis of the MBR pilot unit using different energy mixes

The choice of the electricity mix is a key aspect when assessing the environmental sustainability of a wastewater treatment technology. Therefore a sensitivity analysis was conducted in order to determine the effect of energy mix diversification on the sustainability of the MBR unit. Apart from the Cypriot energy mix (Grid 1), the Greek (Grid 2), Italian (Grid 3), French (Grid 4), Norwegian (Grid 5) as well as solar energy (Grid 6) utilization, were examined.

When solar energy is utilized (Grid 6), then the GHG emissions are significantly reduced to 0.556 kg $CO_{2\text{-eq}}/m^3$ (from 4.65 kg $CO_{2\text{-eq}}/m^3$ in the conventional scenario), as mentioned above. The reason is that PV technologies generate far less life-cycle air emissions per GWh than conventional fossil-fuel-based electricity generation technologies. Fthenakis et al. (2008), noted that at least 89% of air emissions associated with electricity generation could be prevented if electricity from photovoltaics displaces electricity from the grid, which is in accordance with the findings of this study (88% reduction of GHG emissions). When Grid 2 is used, the total GHG emissions are slightly elevated, compared to the conventional scenario, and amount to 5.70 kg $CO_{2\text{-eq}}/m^3$. This increase is attributed to the nature of this grid (Grid 2), which is depended on lignite, a less environmentally friendly choice compared to oil used in Grid 1 (Theodosiou at al., 2014). When Grid 3 is used, a reduction of about 26% compared to the conventional scenario (Grid 1), is observed, which is mainly attributed to the use of natural gas, a more environmentally friendly solution than oil (Theodosiou at al., 2014), and to the higher contribution of renewable energy sources. Moreover, the effect of nuclear power, which is not a renewable source, was examined by using Grid 4 as input. In this case, a sharp reduction (84%) on the total GHG emissions is observed, since only 0.73 kg $CO_{2\text{-eq}}/m^3$ are emitted, but this is still higher than that emitted in the case of Grid 6 (0.556 kg $CO_{2\text{-eq}}/m^3$). When Grid 5 is used, then the MBR pilot unit achieves the highest sustainability, since the total GHG emissions are only 0.25 kg $CO_{2\text{-eq}}/m^3$. Hydropower is the most environmentally friendly energy source and thus a reduction of about 94.5% is observed on the total GHG, compared to the conventional scenario (Grid

1), and 50% compared to Grid 6. A comprehensive overview of the total GHG emissions per energy mix for the treatment of 1 m^3 of urban wastewater by the MBR pilot unit is presented in Figure 6. As shown in Figure 6, the higher environmental footprint of solar energy, when compared to hydroelectricity, is attributed to the energy and materials required for PV system's module production (Fthenakis et al., 2008).

When the ReCiPe impact assessment method was used, then the results differed, since not only the total environmental footprint was found to be affected by the type of each energy mix but also the scores of the impact and the damage categories varied significantly. In Figure 7 (a) the normalized scores, at midpoint level, for the treatment of 1 m^3 of wastewater by means of the MBR pilot unit, using different energy mixes, are presented. As shown, each energy mix affects a different impact category, with the case of Grid 5 exhibiting overall lower scores and the case of Grid 2 overall higher scores. As noted above, most of the impact categories are mainly affected by indirect emissions that relate to the electricity generation, thus the differences in the energy mixes are reflected in the different scores on each impact category.

Moreover, in order to compare each energy mix at endpoint level, the results were aggregated into ReCiPe's three damage categories and then compared by using a single score. Specifically, in Figure 7 (b), ReCiPes' three damage categories (i.e. 'human health', 'ecosystems' and 'resources') and the contribution of each energy mix is presented. As observed, the damage category that is mainly affected by the MBR pilot unit is the category 'human health' followed by 'resources'. This is attributed mainly to the airborne emissions from fossil fuel extraction and electricity production by the different energy mixes used, while also air- and water-borne emissions from the same procedure mainly affect the damage category 'ecosystems'.

As far as the total aggregated environmental footprint is concerned, Grid 1, Grid 2, Grid 3, Grid 4 and Grid 5 amount to 0.42, 0.66, 0.31, 0.083 and 0.034 Pt/m^3, respectively. Therefore energy mixes that are heavily depended on fossil fuels, such as Grid 2 and Grid 1, highly affect the sustainability of the MBR system. For example, in the conventional scenario the total environmental footprint of the MBR pilot unit is 13-fold higher than those of Grid 5, where electricity is provided by renewable energies, and 5.4-fold higher than the case of nuclear power (i.e. Grid 4). Therefore, it is concluded that the progressive substitution of fossil fuels by renewable energies (i.e. Grid 5 and Grid 6), provokes an important reduction of the environmental load. The results of this study are also in agreement with the study of Ortiz et al. (2007), where the airborne emissions of an immersed and an external MBR system were found to significantly depend on the different origins of electricity.

7. Conclusions

Results indicate that the majority of the environmental impacts of the MBR pilot unit were attributed to indirect emissions, tracing back to electricity consumption. This is in line with existing literature. The second main contributor to the total environmental footprint was identified to be the membrane units. Nonetheless, due to their high life expectancy, they have only a low contribution to the total environmental footprint. It should be highlighted that the total GHG emissions of this unit operated for the treatment of 1 m^3 of urban wastewater correspond to approximately 1% of the daily GHG emissions per capita, demonstrating thus the systems' environmental sustainability. A sensitivity analysis revealed that when fossil fuel depended electricity mixes, such as oil and/or lignite, were used for the MBR pilot unit operation, high life-cycle footprints were observed, due to the extraction and burning of fossil fuels, which releases pollutants and carbon dioxide to the environment. If electricity from renewable energy sources, such as solar (which is an abundant energy resource in the Mediterranean countries) and/or hydroelectricity, replaces fossil fuels, the environmental footprint of the MBR pilot unit could be significantly reduced even up to 13-fold compared to the conventional scenario. Therefore, the environmental impact and the overall sustainability of the MBR system are highly depended on the different origins of the electricity consumed. However, in all cases examined the life-cycle emissions of the MBR pilot unit were not the result of direct emissions from the wastewater treatment applied, but from indirect emissions attributed to the energy production and/or material production.

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Table 1: Quantitative characteristics of MBR influent and effluent

Parameters	MBR influent	MBR effluent
pH	7±0.5	6.7±0.4
Conductivity (μS cm^{-1})	1322±100	1003±95
DO (mg/L)	5.6±0.4	4.3±0.5
COD (mg/L)	120±12	40±7
TOC (mg/L)	42.7±5	8.8±0.9
TSS (mg/L)	42000±553	10±0.8
SMX (μg/L)	18.2±2	3.3±0.2

Table 2: Life Cycle Inventory (LCI) of the MBR pilot unit.

Experimental setup configuration		**Useful lifetime (years)**
Prefabricated tank *(material: stainless steel, $Fe/Cr_{18}/Ni_{10}$)*	800 kg	20
Two pumps (feed and permeate) _ 0.75 kW *(material: cast iron GG25 with flake graphite)*	35 kg each one	15
Basket screen *(material: stainless steel, $Fe/Cr_{18}/Ni_{10}$)*	6 kg	20
Two air blowers _ 1.1 kW *(material: aluminum alloy)*	32 kg each one	30
Four air diffusers *(material: membrane high grade EPDM)*	2 kg each one	8
Four support discs *(material: PVC (polyvinyl chloride))*	2 kg each one	8
Submerge membrane unit (25 membrane cartridges) *(material: chlorinated polyethylene; ABS resin membrane)*	3 kg each one	5
Flow indicator *(material: polysulphone)*	3 kg	30
Membrane case *(material: stainless steel, $Fe/Cr_{18}/Ni_{10}$)*	65 kg	20
Pipes *(material: UPVC PE)*	13.44 kg	50
Chemical cleaning (0.5% sodium hypochlorite (NaClO))	18.75 kg during the lifetime of the MBR unit (i.e. 20 yr)	-
Energy requirements		
Energy from the Cypriot grid (medium voltage)	92.5% oil, 5.6% wind power, 1.1% photovoltaic systems and 0.8% biomass	-
kWh for the treatment of 1 m^3 of urban wastewater per day	5.36 kWh m^{-3}	-
Local transportation		
Delivery and installation (by truck 8.8 tn)	5632 km	8.3
Maintenance (by van 2.7 tn)	25920 km	8.3
Outputs to nature (per functional unit)		
Airborne emissions MBR (Data provided from: Ortiz et al., (2007) and Foley et al., (2010)		
CO_2	0.77 Kg CO_2 m^{-3}	-
SO_x	2.79 g SO_x m^{-3}	-
NO_x	1.40 g NO_x m^{-3}	-
NMVOC	0.46 g NMVOC m^{-3}	-
Dust	0.72 g dust m^{-3}	-

Figure Captions

Schematic 1: Flow diagram of the MBR pilot unit.

Figure 1: System boundaries of the MBR pilot unit LCA.

Figure 2: (a) Dendrogram of the main parameters and their contribution to the total CO_{2-eq} emissions of the MBR pilot unit, using the IPCC 2013 methodology for a timeframe of 100 years and 0.5% cut-off; and (b) circular statistical graphic illustrating the contribution of each parameter of the MBR pilot unit to the total environmental footprint. The arc length of each slice is proportional to the percentage (%) it represents.

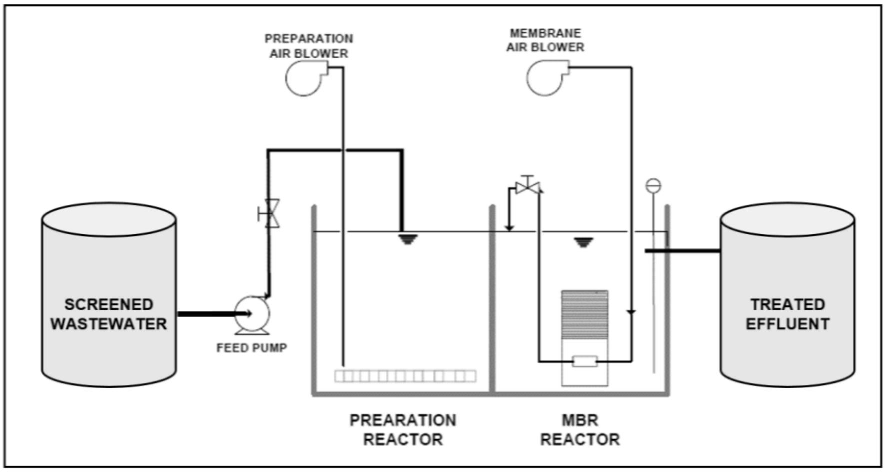
Figure 3: %Contribution of each parameter of the MBR pilot unit to the midpoint impact categories, according to the ReCiPe methodology.

Figure 4: ReCiPe's normalized results for the treatment of 1 m^3 of urban wastewater by means of the MBR pilot unit.

Figure 5: ReCiPe's aggregated endpoint impact categories for the treatment of 1 m^3 of urban wastewater by the MBR pilot unit.

Figure 6: Total GHG emissions (IPCC 2013) of the MBR pilot unit using the different energy mixes examined in this study.

Figure 7: ReCiPe's (a) normalized midpoint level impact categories and (b) aggregated environmental endpoint level impacts of the MBR pilot unit for the different energy mixes examined in this study.



Schematic 1

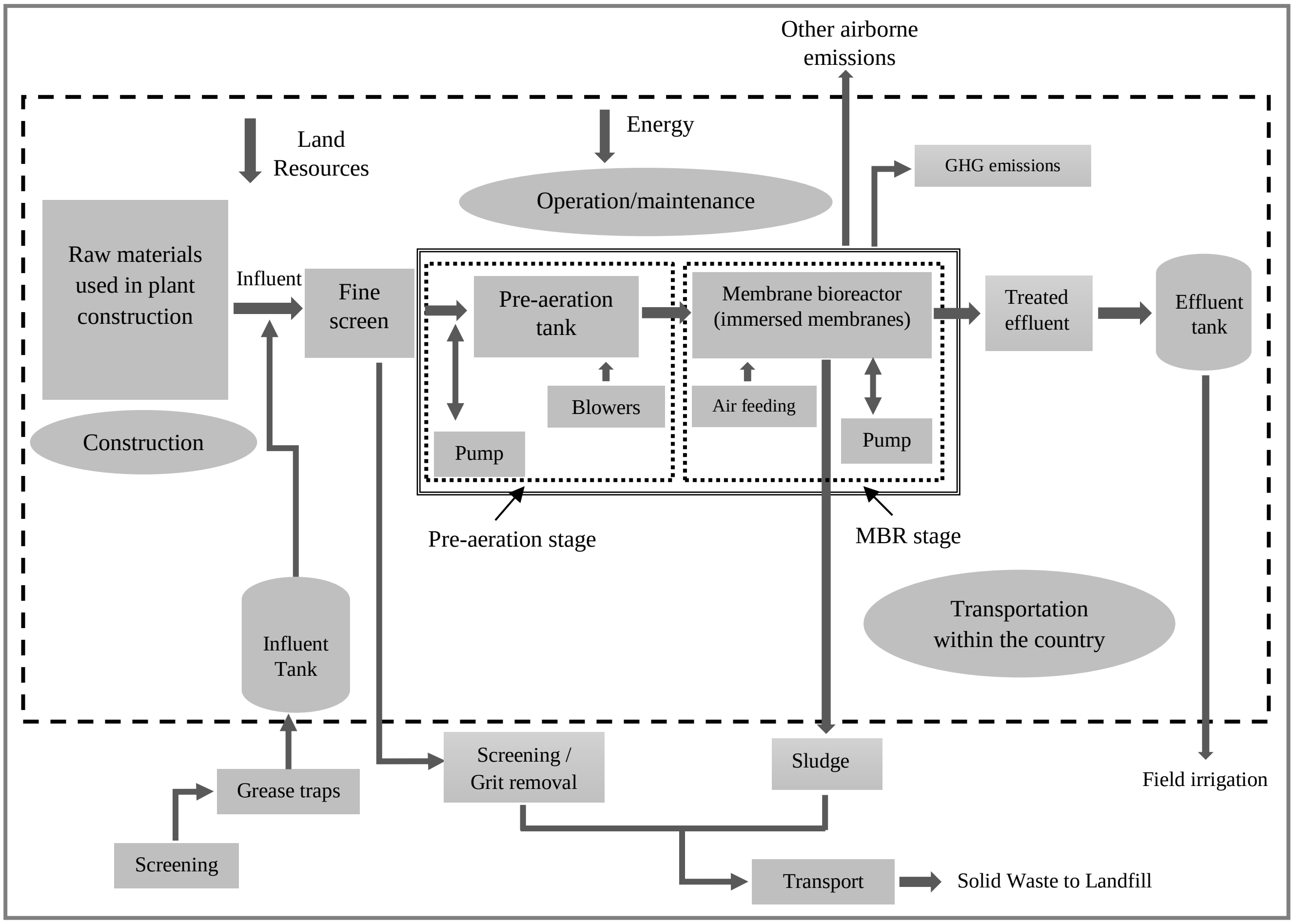


Figure 1

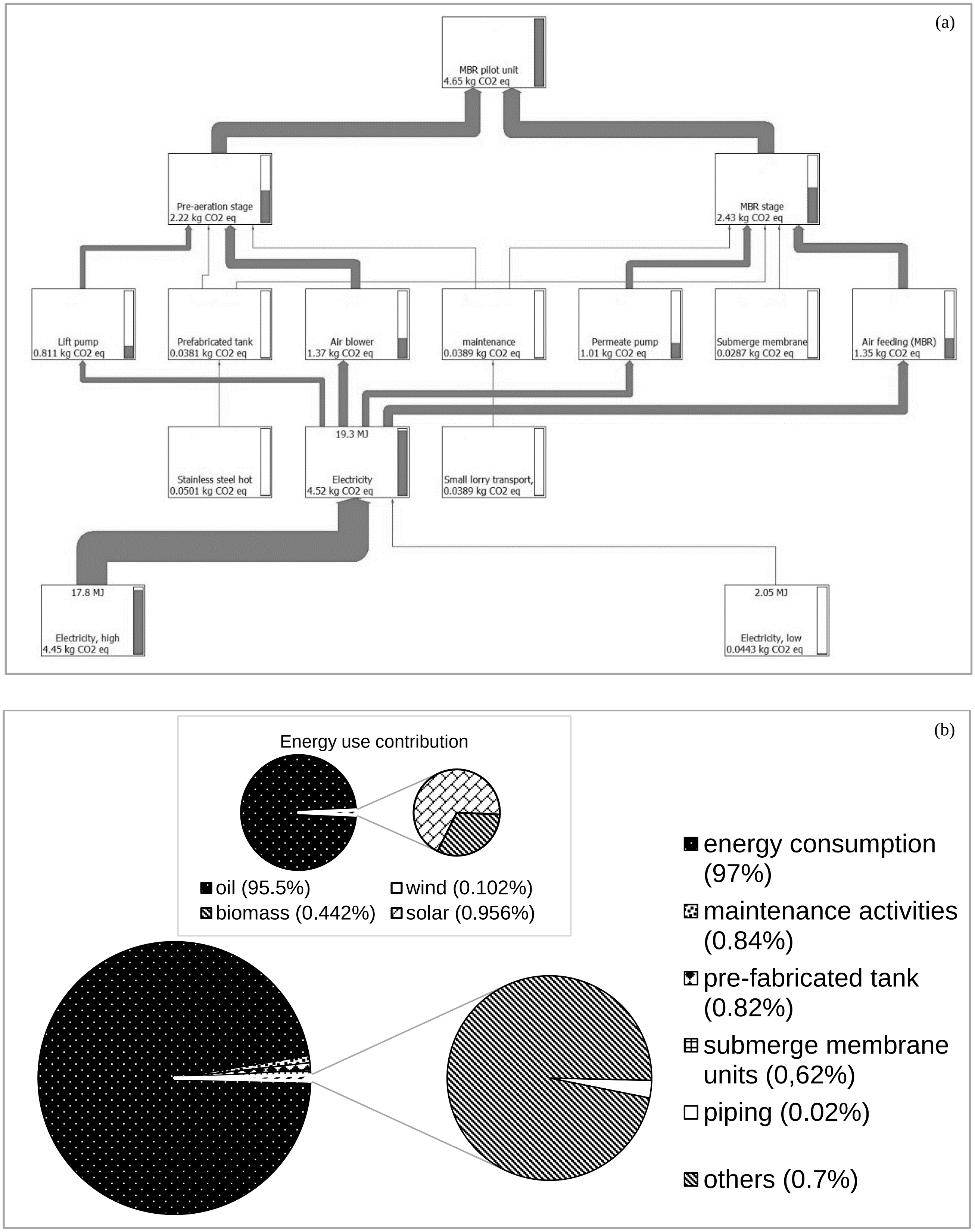

(a)
MBR pilot unit
4.65 kg CO2 eq
Pre-aeration stage
2.22 kg CO2 eq
MBR stage
2.43 kg CO2 eq
Lift pump
0.811 kg CO2 eq
Prefabricated tank
0.0381 kg CO2 eq
Air blower
1.37 kg CO2 eq
maintenance
0.0389 kg CO2 eq
Permeate pump
1.01 kg CO2 eq
Submerge membrane
0.0287 kg CO2 eq
Air feeding (MBR)
1.35 kg CO2 eq
Stainless steel hot
0.0501 kg CO2 eq
19.3 MJ
Electricity
4.52 kg CO2 eq
Small lorry transport,
0.0389 kg CO2 eq
17.8 MJ
Electricity, high
4.45 kg CO2 eq
2.05 MJ
Electricity, low
0.0443 kg CO2 eq
(b)
Energy use contribution
oil (95.5%)
wind (0.102%)
biomass (0.442%)
solar (0.956%)
energy consumption (97%)
maintenance activities (0.84%)
pre-fabricated tank (0.82%)
submerge membrane units (0,62%)
piping (0.02%)
others (0.7%)

Figure 2

Figure 3

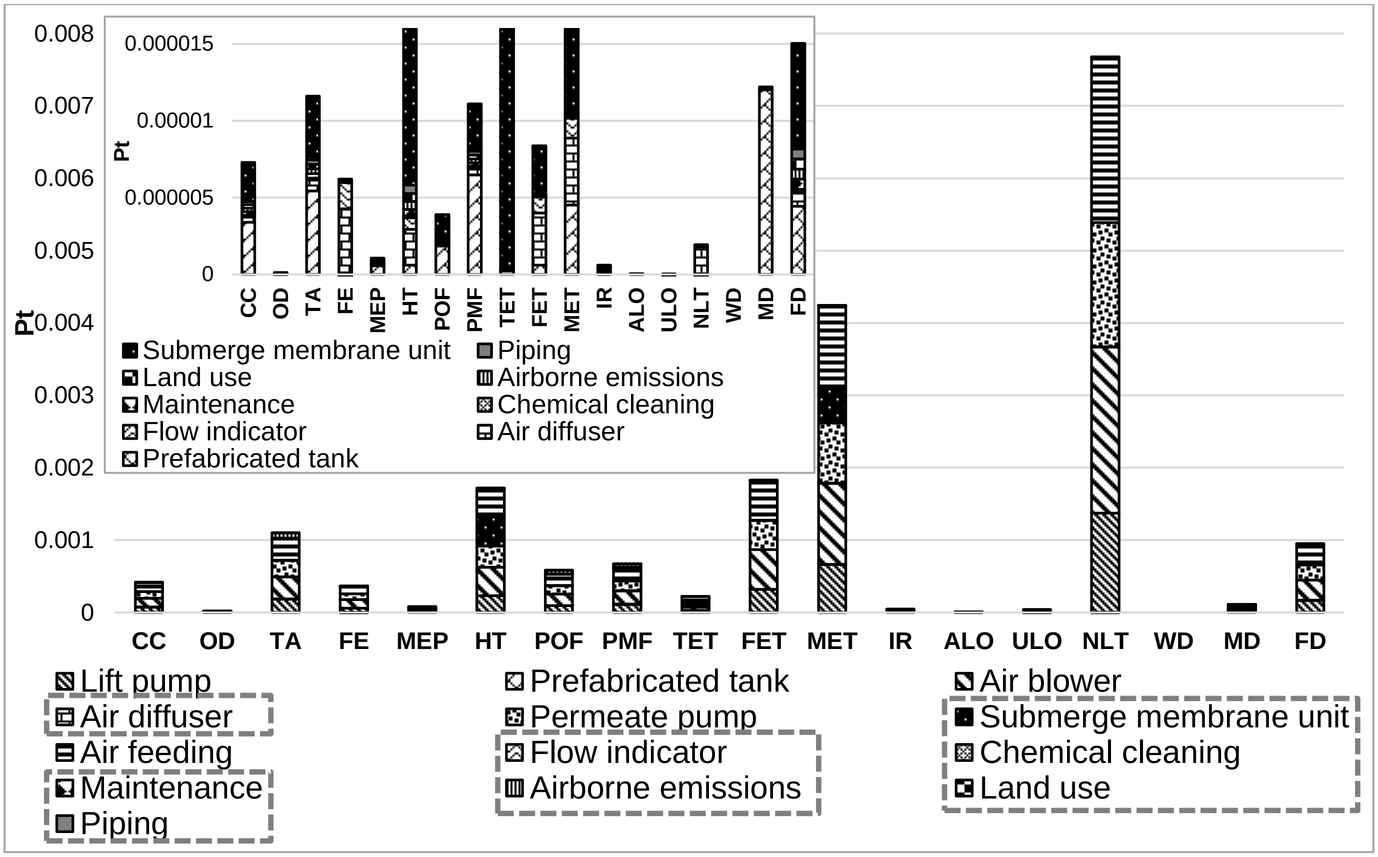


Figure 4

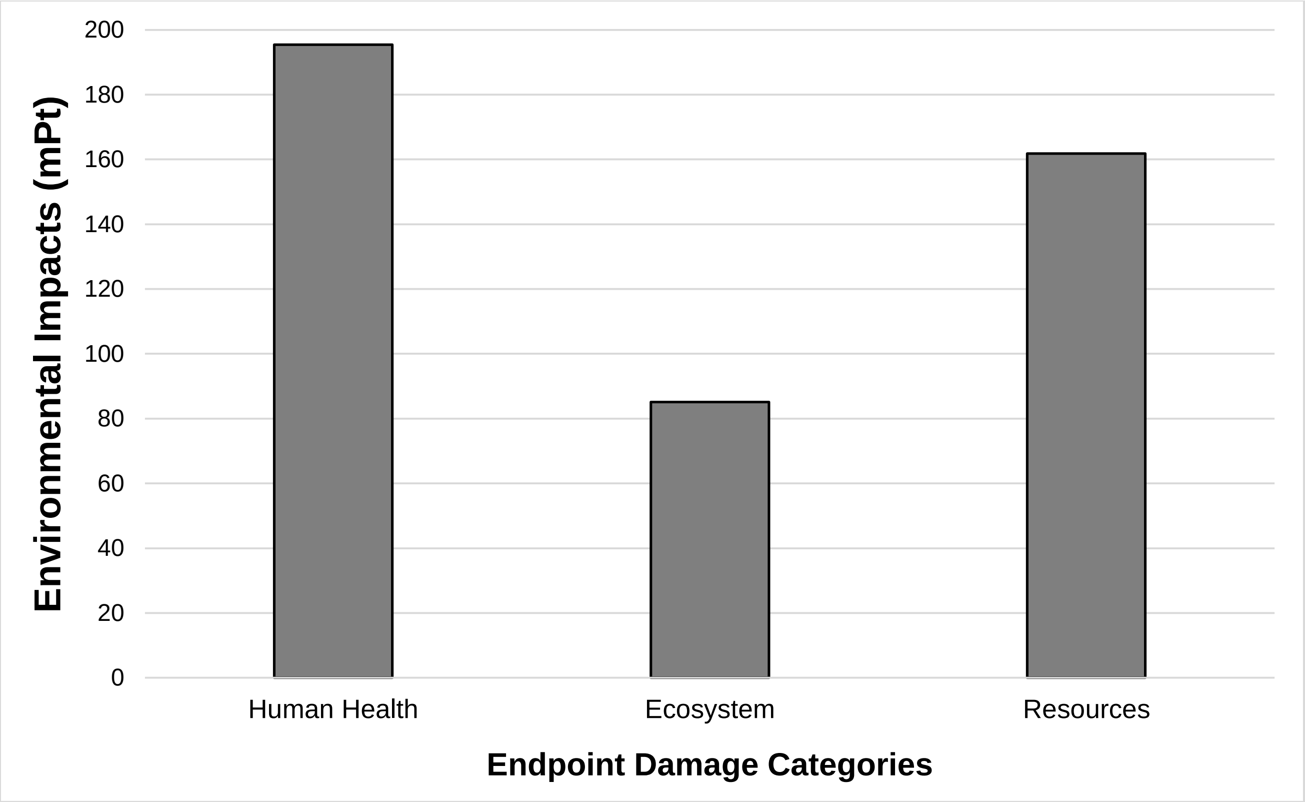

Environmental Impacts (mPt)
200
180
160
140
120
100
80
60
40
20
0
Human Health
Ecosystem
Resources
Endpoint Damage Categories

Figure 5

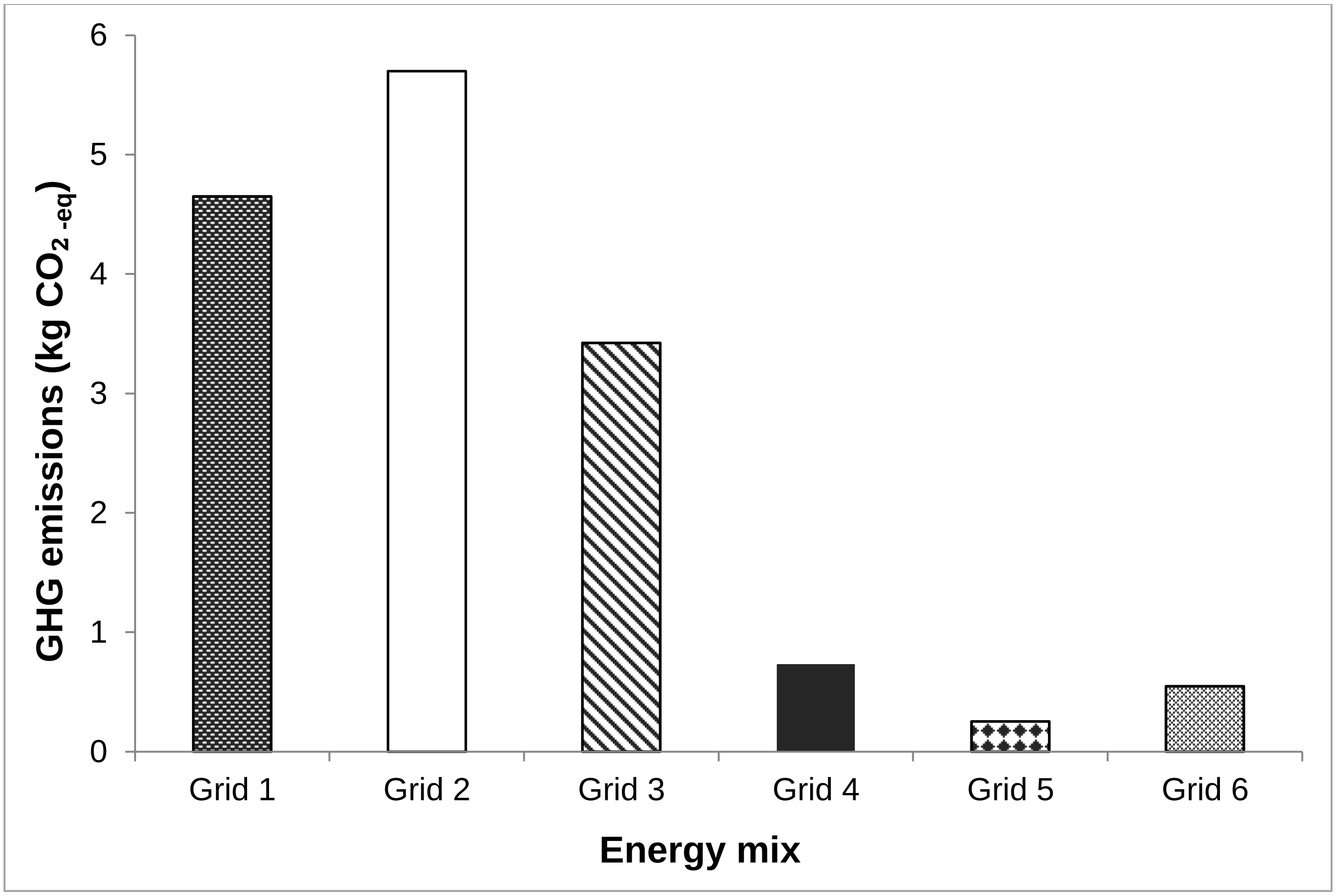

GHG emissions (kg CO2 -eq)
0
1
2
3
4
5
6
Grid 1
Grid 2
Grid 3
Grid 4
Grid 5
Grid 6
Energy mix

Figure 6

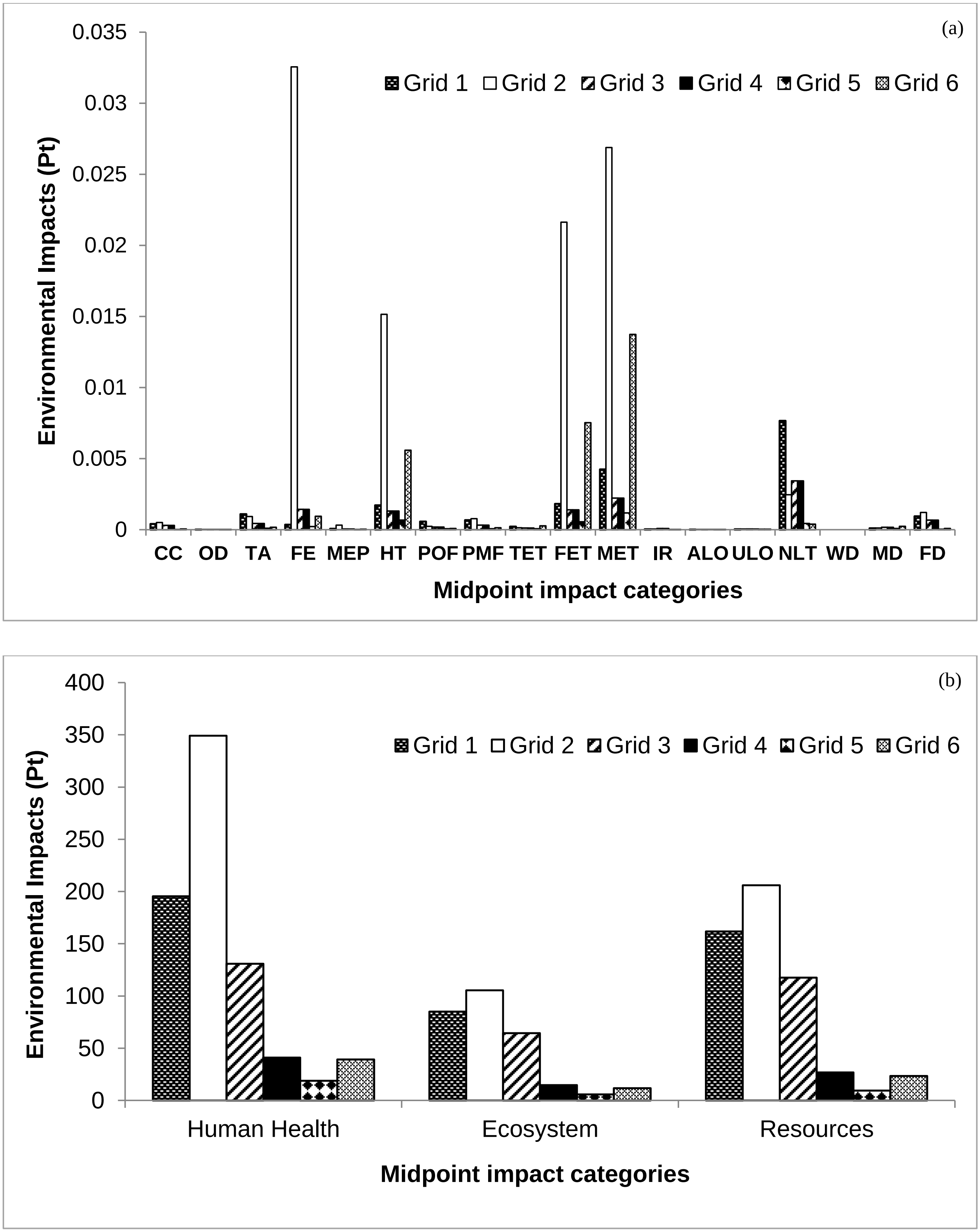

(a)
Grid 1
Grid 2
Grid 3
Grid 4
Grid 5
Grid 6
Environmental Impacts (Pt)
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
CC
OD
TA
FE
MEP
HT
POF
PMF
TET
FET
MET
IR
ALO
ULO
NLT
WD
MD
FD
Midpoint impact categories
(b)
Grid 1
Grid 2
Grid 3
Grid 4
Grid 5
Grid 6
Environmental Impacts (Pt)
400
350
300
250
200
150
100
50
0
Human Health
Ecosystem
Resources
Midpoint impact categories

Figure 7