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Benchmarking industrial water purification systems with the aid of life cycle assessment

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ABSTRACT

Water is among the essential inputs of many industrial production processes. Substantial amounts of water with varying qualities is of importance in running quite a number of industrial sectors. The water quality requirements necessitate the application of different water purification systems. This study concentrates on comparing the environmental impacts of reverse osmosis and an ion exchange system that treat the water supplied from a well to a quality suitable for boiler water makeup. Life cycle assessment methodology is adopted for this evaluation. Purification system with the ion exchanger requires 18.6% less energy in comparison with the reverse osmosis system. However, substantially higher environmental impacts are obtained for the ion exchanger system when compared with the treatment scheme of reverse osmosis. Hence, the reverse osmosis system should be favored. Changing the source of energy from the grid mix to wind power is observed to further reduce abiotic depletion potential (fossil), human toxicity potential, acidification potential, eutrophication potential, and terrestric ecotoxicity potential for the reverse osmosis system.

Keywords: Water purification; Reverse osmosis; Ion exchange; Environmental impacts; Life cycle assessment

1. Introduction

Raw waters originating from various sources are passed through water purification systems to reach the required quality goals. Water inputs with different qualities are required in industrial facilities, ranging from potable water for workers to softened or deionized ones for production processes. Globally 22% of global freshwater withdrawal is rationed for industrial purposes [1].

Make up water for boilers is a type of non-process water input, very commonly used in almost every industrial premise. Depending on the source and therefore the quality of raw water, different purification alternatives arise to reach the required quality levels for the boiler make up water. Reverse osmosis (RO) and ion exchangers (IE) are the most commonly pertained water purification methods used to prepare boiler feed water. In RO systems, where pressure is applied, mechanisms such as oxidation, accumulation of pollutants, and precipitations on the membrane surface, are of importance in reaching the required functioning of the purification system. As especially precipitations on the membrane surface effects the system performance in an adverse manner, scaling must be avoided with a proper pretreatment [2,3]. For this purpose softening with lime or ion exchangers, acid dosing, and antiscalant dosing can be used [3]. Chlorination or other oxidation methods that prevent microbial growth have negative impacts on the membranes [4]. To avoid such unwanted results activated carbon, sodium bisulfide (SBS), or sodium meta-bisulfide (SMBS) can be introduced prior to RO [5,6]. In contrast to

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RO, application of additional pressure apart from head losses, is not required for IE systems. During the regeneration of IE, considerable amounts of acids and bases are added and a concentrated wastewater is obtained [7]. In general RO systems, sensitive to flowrate and pressure changes can be economically feasible for treating waters with high conductivity levels. On the other hand, IE yields economic benefits for purifying waters having smaller flowrates and lower conductivities [8]. The general approach is to conduct an economic feasibility in order to obtain the most proper treatment train. Such a methodology only considers the financial portrait and lacks the environmental impacts. However, environmental impacts along with financial ones are of importance in reaching a sustainable solution. In this respect, a methodological approach to point out diverse impacts on environment is required. Environmental impacts of processes/products/services can be quantified by adopting life cycle assessment (LCA) as an instrument [9]. Various LCA studies dealing with water treatment systems are presented in literature [10–15]. Some of these are on picking the appropriate purification sequences [14,15]. However, there isn't any study pointing out the comparative environmental impacts of treatment methods that convert well water quality into boiler make up water. Moreover, various phases of water treatment plants are examined in literature by adopting LCA methodology, such as construction [16], operation [10,17], construction and operation [18–20], or the whole life cycle covering also end of life [21]. Among others operation is the phase that generates majority of the environmental impacts, and electricity consumption cause most of the burdens in the operation phase [14]. To foresee the potential environmental impacts of alternate water treatment schemes during design stage, aids choosing the right treatment train.

The main objective of this study is to comparatively evaluate the environmental impacts generated during the operation and maintenance stages of two alternative industrial boiler water make up treatment systems, reverse osmosis (RO) and ion exchanger (IE), respectively. For this purpose LCA methodology is adopted. Furthermore, environmental hotspots within the mentioned purification methods are pinpointed. The data used is obtained from the design stage.

2. Materials and methods

LCA methodology as defined in ISO 14040–14044 standards [22,23], is used to get the environmental impacts. Thus, iterative steps of goal and scope definition, inventory analysis, impact assessment, and interpretation are pursued.

LCA modeling is used by adopting GaBi software version 7.3 with professional database version 7.3. Electricity source for both treatment options is Turkish grid. The used version of the database does not have the Turkish grid electricity as a process. Hence, the data presented by The Electricity Generation Corporation of Turkey on Turkish grid mix (24.7% hydraulic, 32.3% natural gas, 32.9% coal, 5.7% wind, 2.6% solar, geothermal, and biomass) [24] is used to establish a process for grid electricity.

CML (Center for Environmental Science – University of Leiden, The Netherlands) metodology is used for life cycle impact assessment [25]. The following environmental impact categories are examined: terrestric ecotoxicity potential (TETP), ozone depletion potential (ODP), human toxicity potential (HTP), global warming potential (GWP), freshwater aquatic ecotoxicity potential (FAETP), eutrophication potential (EP), acidification potential (AP), and abiotic depletion potential-fossil (ADP).

This study covers the operation and maintenance stage of two alternative water purification systems of RO and IE. Construction and demolition stages are excluded from the study due to their low contribution to the overall environmental impacts [14]. The use and disposal phases of the treated water is out of the scope of this study and therefore this is a cradle to gate study.

In this study, two different sort of comparison methodology is applied. The first evaluation is based on results obtained from the modeling. Furthermore, in order to ease the verdict of the decision-makers, normalization, and weighing is applied. By doing so, comparisons are performed on a total score. In this study, CML 2001 normalization and weighing factors are used as given in Table 1 [25].

The functional unit is selected as 1 m^3 treated water ready to use as boiler make up water.

The water is obtained from a well with an average quality given in Table 2.

A treatment to reach a water quality of less than 0.02 mg/L SiO_2, less than 0.2 μS/cm conductivity, and finally a pH higher than 9.2 is required.

For this purpose, the following water purifications systems are considered: case 1: dual media filters (DMF) followed by ultrafiltration (UF), then a reverse osmosis (RO); case 2: DMF followed by UF, then an ion exchange (IE).

The system boundaries of the cases are given in Figs. 1 and 2.

In both cases, the first parts of the treatment scheme are the same: Well water is introduced into a DMF system by feeding pumps. DMF system with a capacity of 50 m^3/h, has quartz and anthracite as packing material. NaOCl and $FeCl_3$ are added during this stage of treatment as disinfectant and coagulant, respectively. Water is then passed through cartridge filters of 150 μ and subsequently fed into a UF unit. For cleaning the UF membranes HCl, citric acid, NaOH, and NaOCl are used.

After the UF, case 1 has a RO unit. Whereas in case 2 an IE system composed of anion exchanger (CIX) and cation exchanger (AIX) is used.

Table 1
Adopted normalization and weighing factors [25]

Impact categories	Normalization factors	Weighing factors
ADP	2.85E-14	6.4
AP	5.95E-11	5.7
EP	5.41E-11	6.5
GWP	1.92E-13	8.8
HTP	2E-12	6.5
ODP	9.8E-08	5.4
TETP	8.62E-12	6.2
FAETP	4.78E-12	6.2

Table 2
Quality of water withdrawn from the well

Parameters	Unit	
NH_4^+	mg/L	0
K^+	mg/L	10
Na^+	mg/L	49.22
Mg^{+2}	mg/L	118
Ca^{+2}	mg/L	220
Sr^{+2}	mg/L	0
Ba^{+2}	mg/L	0
CO_3^{-2}	mg/L	7.60
HCO_3^-	mg/L	325
NO_3^-	mg/L	11
Cl^-	mg/L	118
F^-	mg/L	0
SO_4^{-2}	mg/L	67
SiO_2	mg/L	15
Boron	mg/L	0
CO_2	mg/L	1.97
TDS	mg/L	1,576
pH	–	8.3

In case 1, SMBS and antiscalant are added to condition the water. HCl, citric acid, NaOH, and NaOCl are used to clean the RO membranes.

In comparison with RO (case 1), CIX and AIX of case 2 operate under relatively lower pressures. In case 2, the outlet of UF unit first passes through CIX, then a degassing unit, and after that AIX. HCl is used to regenerate CIX and NaOH is added for the regeneration of AIX.

The last unit of treatment for both cases is a mixed bed (MB) ion exchanger. NaOH, HCl, and air is used to regenerate the resin in this unit.

The backwash water arising from DMF is discharged into a river for both of the cases. Other wastewaters originating from cleaning and regeneration operations are collected in a neutralization tank where NaOH and HCl are fed to meet the discharge standards.

In case 1, the water leaving the RO unit has a much higher ion concentration than the outlet water of IE unit in case 2. Because of this fact, the mixed bed system used after the RO unit in case 1, saturates quickly and requires frequent regeneration. The chemicals applied during regeneration on the other hand, have a negative impact on the lifetime of the resin. Therefore, a 3% (by weight) resin input and subsequent resin waste generation is applied to case 1. On the contrary, for case 2, no additional resin is required and thus no waste resin is generated from the mixed bed unit for a 5 y period of time.

The production of filter cartridges, UF membranes, anionic, and cationic resins are not covered during LCA. Furthermore, disposal of spent filter cartridges, UF membranes, and resins are not considered. On the other hand, the production of all the chemicals are within the scope of the study.

Aggregated inventory is tabulated in Table 3.

All the chemicals listed are obtained from the same supplier with a location of 100 km away and spent filters, membranes, and resins are sent to a landfill that is 55 km away. The mentioned transportations are performed by trucks using diesel. Information on the transportation of materials is tabulated in Table 4.

Among various antiscalants, phosphoric acid is chosen as indicated by Goga [26]. Apart from SMBS, all the background data is taken from GaBi professional database. A unit process, based on expert opinion, is established for SMBS.

3. Results and discussion

3.1. Energy requirement

The energy input of case 2 is approximately 18.6% less than that of case 1.

The total energy requirement of case 1 is 0.947 kWh per m^3 treated water. Within this total, around 45% is dedicated for RO unit (0.430 kWh/m^3 treated water) and approximately 27% is spent for UF unit (0.256 kWh/m^3 treated water). According to literature [27], UF units consume energy between 0.1 and 0.2 kWh/m^3 of purified water, whereas for RO units 0.4–0.5 kWh energy is needed per m^3 treated water. The findings of this study show higher level of energy consumption for UF unit. Such a result can be obtained due to the design, type of the membrane, or operation conditions. Some types of membranes are designed in a way not to require any blowers during backwashing, yielding a reduction in the necessary energy input. The results on energy consumption of RO unit obtained in this study are consistent with the literature [27]. Ras [18] states a lump sum energy input of 0.66 kWh/m^3 treated water for UF and RO units. Our study yields a total energy requirement of 0.686 kWh/m^3 purified water for UF and RO units. Such a result is in line with the findings of Ras [18].

On the other hand, CIX-AIX and UF units consume 34% and 33% of the total electricity input for case 2. In a similar literature study that deals with an IE system used for obtaining boiler water from well water, lower electricity requirement is presented due to the fact that only a low fraction of energy is provided from grid, and waste heat and low pressure steam are among the used energy sources [28].

3.2. Environmental impacts

The share of different units contributing to environmental impacts for both of the cases are invesigated.

For case 1, 42%, 37%, and 12% of the FAETP arise from DMF, MB, and RO units, respectively. More than 46% of TETP is of MB origin and after that RO comes with a 22% contribution. Again HTP mainly arises due to MB (33% of the total), RO (27%), and DMF (22%) units. Main source of ODP is MB (approximately 83% of the total). RO and MB both contribute about 32% of GWP, where UF has a share of 19%. Around 40% and 27% of EP is of neutralization and MB units, namely. DMF and MB have 39% and 27% shares in total AP, respectively. Around 30%, 29%, and 21% of the total ADP are originating from MB, RO, and DMF units, respectively.

CIX and AIX units together have significant contributions to all the impact categories in case 2. Around 98% of

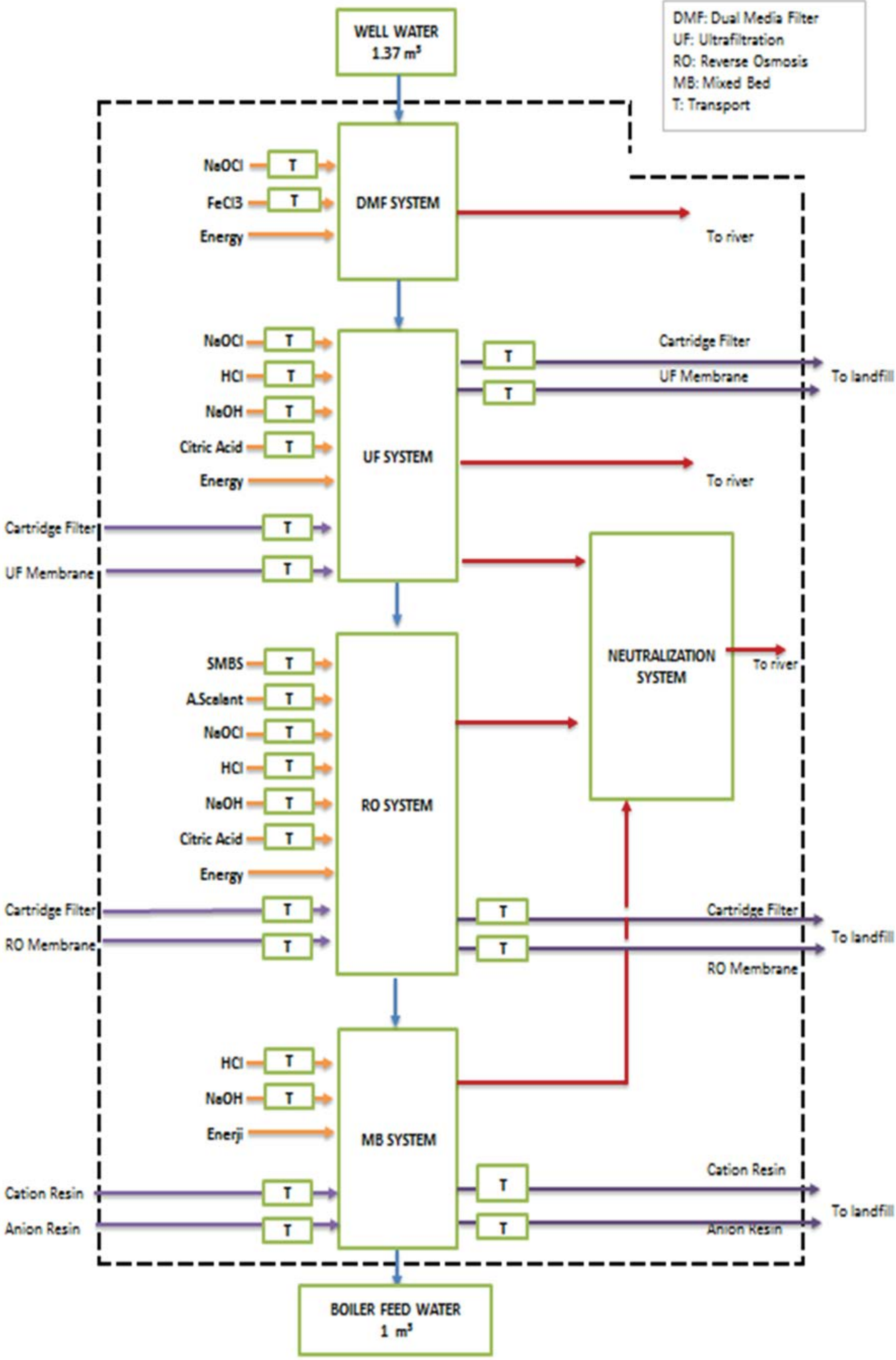

Fig. 1. System boundaries of case 1.

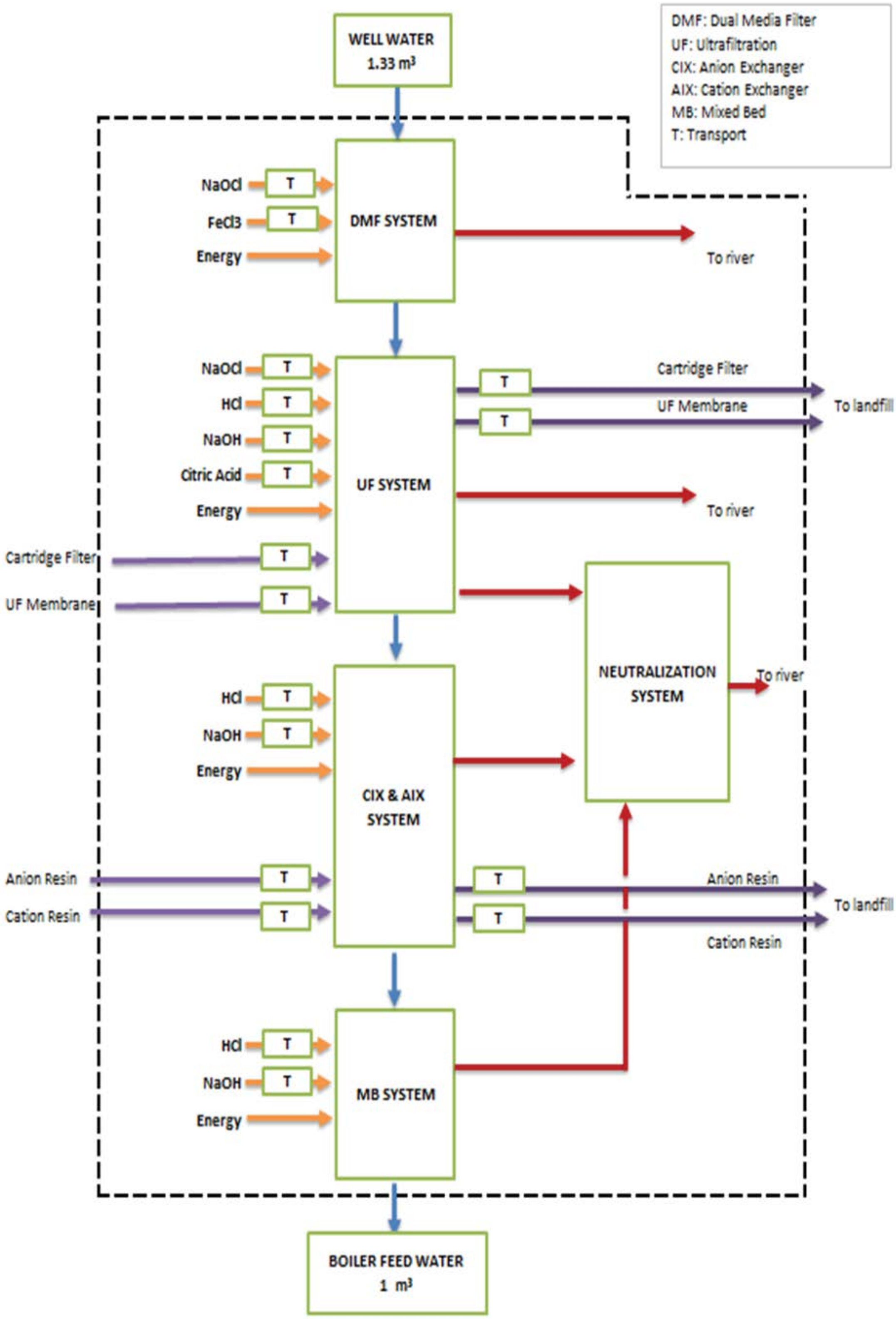

Fig. 2. System boundaries of case 2.

ODP is due to CIX and AIX units. About 92% of TETP and EP are of CIX and AIX units. These IE units contribute 89% to FAETP. Approximately 86% of HTP, GWP, and ADP arise from these units as well. Main source of AP is also IE units with a contribution of 82% to the total.

Fig. 3 summarizes the comparison of environmental impacts obtained for case 1 and 2 together with contribution of various factors on environmental impact categories.

It is clearly evident from Fig. 3 that, case 1 with an RO unit has substantially lower environmental impacts than case 2 involving an IE System for all the categories under investigation. For ODP, the results obtained for case 1 (RO) is 86% less than that of case 2. For TETP and FAETP around 77% lower impact levels are obtained for case 1, in comparison with case 2. For other impact categories, reductions ranging from 65% to 70% are achieved when case 1 is used instead of case 2. Therefore, case 1 with a RO unit must be chosen to treat the well water to the required quality level when the environmental impacts are considered.

Table 3
Aggregated inventory

	Unit	Case 1	Case 2
Inputs			
Raw water	m^3/m^3	1.37E+00	1.33E+00
Electrical energy	kWh/m^3	9.47E-01	7.71E-01
NaOCl	kg/m^3	5.10E-02	4.70E-02
Coagulant ($FeCl_3$)	kg/m^3	1.25E-01	1.14E-01
HCl	kg/m^3	1.74E-01	2.30E+00
Citric acid	kg/m^3	7.00E-03	2.00E-04
NaOH	kg/m^3	2.23E-01	1.51E+00
SMBS	kg/m^3	4.00E-03	–
Antiscalant	kg/m^3	5.00E-03	–
Outputs			
Treated water	m^3/m^3	1.00E+00	1.00E+00
Wastewater	m^3/m^3	3.70E-01	3.30E-01

Furthermore, different factors are contributing to environmental impacts. The highest contribution to ADP, AP, GWP, HTP, and TETP comes from the electricity input in case 1. NaOH is the main contributor to ODP by 80% in case 1. Approximately 34%, 32%, and 17% of AP arise from electricity requirement, coagulant, and NaOH inputs, respectively. Coagulant, electricity, and NaOH usages contribute 35%, 20%, and 19% to the FAETP, namely. TETP is of electricity requirement (41% of the total) and NaOH (31% of the total). For case 1, about 37%, 25%, and 15% of EP is due to wastewater discharge, electricity, and NaOH inputs, namely.

On the other hand, for case 2 a different profile than case 1 is obtained in terms of the contribution of various factors to environmental impacts. Similar to case 1, NaOH is the main contributor to ODP for case 2. HCl and NaOH inputs have 50% and 31% shares in the total FAETP for case 2, respectively. Around 48% and 38% of TETP come from NaOH and HCl, namely. About 43%, 38%, and 13% of HTP are of HCl, NaOH, and electricity origin, respectively. HCl, NaOH, and electricity usage have 44%, 33%, and 17% contributions to GWP, namely. These factors are contributing to ADP by 47%, 31%, and 16%, namely. HCl input has 43% and 35% shares on EP and AP, respectively. Furthermore, NaOH contributes 37% and 39% to EP and AP categories, namely. In general, the effect of electricity on environmental impacts is not prominent in case 2. HCl and NaOH inputs altogether are generally the main reason behind the environmental impacts of case 2.

For both of the alternatives, the transportation does not have significant contribution to the impact categories.

The normalized and weighed results are illustrated in Fig. 4.

According to the data shown in Fig. 4, ADP, GWP, and AP are the most important environmental categories for both of the cases. Besides ODP is not among the crucial impact categories.

The distribution of factors for weighed results are given in Fig. 5.

As evident from Fig. 5, the important impact factors for case 1 are electricity, coagulant, NaOH and HCl by

Table 4
Information on transportation

	Case-1	Case-2
	(amount and mode of transportation)	
Inputs		
Chemicals	0.6 kg/m^3; 100 km (Truck)	3.9 kg/m^3; 100 km (Truck)
Cartridge filter	9.7E-06 kg/m^3; 200 km (Truck) + 10,175 km (Ship)	5.5E-06 kg/m^3; 200 km (Truck) + 10,175 km (Ship)
UF membrane	2.5E-04 kg/m^3; 200 km (Truck) + 10,175 km (Ship)	2.5E-04 kg/m^3; 200 km (Truck) + 10,175 km (Ship)
TO membrane	3.2E-05 kg/m^3; 200 km (Truck) + 10,175 km (Ship)	–
Anionic resin	2.6E-06kg/m^3; 200 km (Truck) + 10,175 km (Ship)	1.7E-03 kg/m^3; 200 km (Truck) + 10,175 km (Ship)
Cationic resin	1.3E-05 kg/m^3; 200 km (Truck) + 10,175 km (Ship)	1.6E-03 kg/m^3; 200 km (Truck) + 10,175 km (Ship)
Outputs		
Spent filters, membranes, and resins	3.1E-04 kg/m^3; 55 km (Truck)	3.5E-03 kg/m^3; 55 km (Truck)

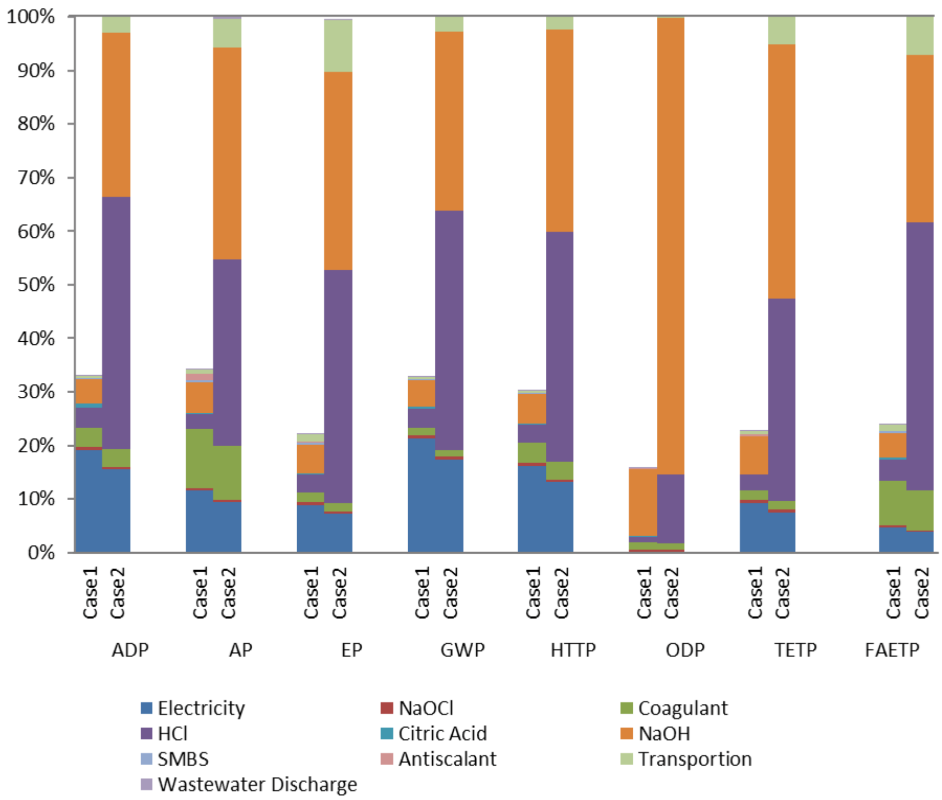

Fig. 3. Comparison of environmental impacts and contribution of various factors on environmental impact categories.

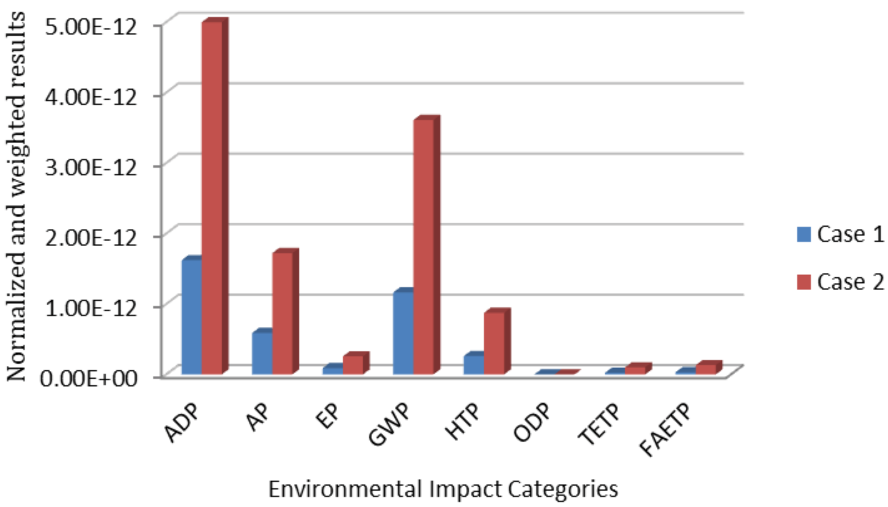

Fig. 4. Normalized and weighed results.

order. Whereas for case 2, HCl, NaOH and electricity are of importance when weighed results are assessed.

3.3. Sensitivity analysis on energy sources

The effect of using certain renewable energy sources such as solar panels and wind farms, instead of Turkish grid mix on environmental impacts is investigated. The results obtained are illustrated in Fig. 6. For both of the cases, elevations in TETP, ODP, HTP, and FAETP categories are observed when solar energy is used rather than grid. On the other hand, wind power reduced all the environmental impacts both for case 1 and 2.

For case 1, obtaining energy from solar panels rather than grid mix lowers the negative environmental impacts for ADP, AP, EP, and GWP, by 50%, 20%, 19%, and 57%,

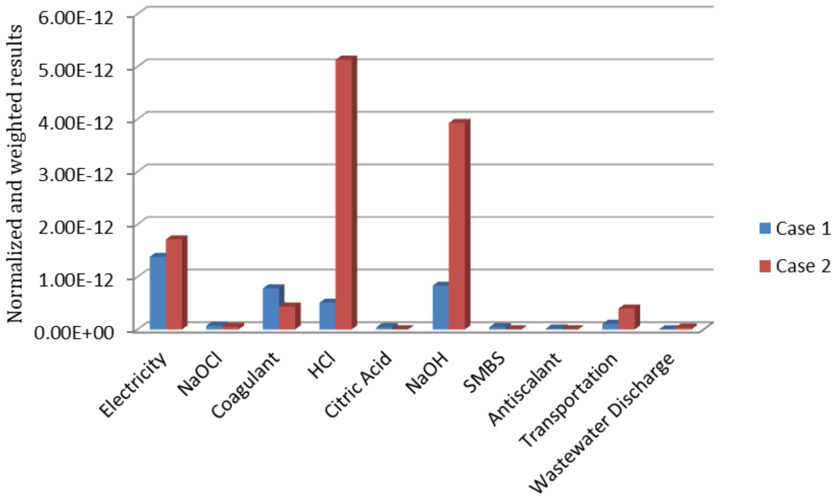

Fig. 5. Distribution of factors for weighed results.

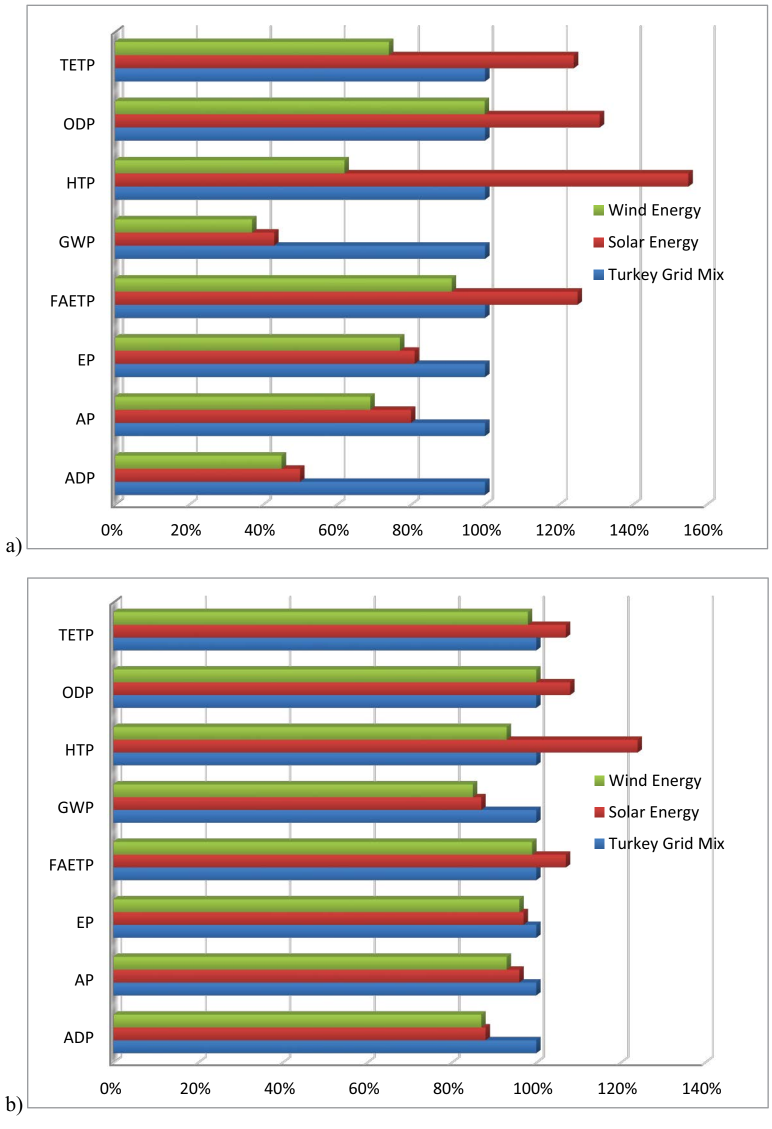

Fig. 6. Relative impact of renewable energy sources compared to grid mix for (a) case 1 and (b) case 2.

Table 5
Weighed results of grid mix vs. renewable energy sources

	Grid mix (Turkey)	Solar energy	Wind energy
Case 1	1.06E-08	2.35E-08	6.57E-09
Case 2	3.56E-08	4.67E-08	3.3E-08

respectively, as shown in Fig. 4a. Whereas elevations on environmental impacts are observed for FAETP, HTP, TETP, and ODP, by 25%, 55%, 24%, and 31%, namely. A similar increase in HTP is stated in literature due to the fact that using cadmium (Cd), silicon (Si), and copper (Cu) while manufacturing the solar panels [10]. Using wind energy instead of grid electricity has beneficial effects of different levels on impact categories other than ODP where no change is noted for case 1. The highest positive effect is obtained for GWP, with a 63% reduction. Reduction levels of 55%, 38%, 31%, 26%, 23%, and 9% in ADP, HTP, AP, TETP, EP, and FAETP are attained by supplying energy from wind farms, respectively for case 1.

As indicated earlier, the role of electricity input on environmental impacts are not significant for case 2. Therefore, changing the source of energy does not have substantial impact on the environmental categories for this case. Practically no change is obtained for AP and EP when solar panels are used instead of grid mix. Approximately 13% reductions are observed for ADP and GWP by using solar energy. An increase by 24% is noted for HTP when solar panels are used. Altering grid to solar energy yields minor elevations of less than 8% for FAETP, TETP, and ODP. When wind energy is used instead of grid mix, TETP, ODP, FAETP, and EP practically remain the same. GWP and ADP are reduced by 15% and 13%, respectively. Slight reductions in HTP and AP are obtained for case 2.

The weighed results obtained for alternative energy sources are tabulated in Table 5.

The data presented in Table 5 shows that the usage of wind energy rather than grid mix lowers the total environmental score. On contrary to this finding, solar energy usage instead of grid, elevates the total environmental score.

4. Conclusions

The following conclusions are driven from this study that focuses on environmental impacts of two industrial boiler make-up water purification systems: Although the energy input of the IE alternative is about 18.6% less than the RO one, substantially higher environmental impacts are obtained. Therefore, final decision must be made in favor of the RO unit. It is possible to further reduce certain environmental impacts such as ADP, HTP, AP, TETP, and EP by using wind energy instead of grid mix for this alternative water purification system.

It is recommended to run an extensive study on the production and disposal of filter cartridges, UF membranes, and resins, separately.

Financial feasibility studies must be supported with comparative evaluations based on environmental impacts before deciding on the proper type of purification alternatives.

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