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Environmental Impact Assessment of Emerging MLD Desalination Plants

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Abstract—**With regard to sustainable development goals (SDG) 6, access to reliable water is an important and vital challenge in the world. In this study, 4 desalination plants based on reverse osmosis (RO), nanofiltration (NF), and membrane distillation (MD) were investigated with a life cycle assessment (LCA) approach to be implemented in Persian Gulf region. The individual RO, hybrid RO-RO, hybrid NF-RO, and hybrid RO-MD systems were evaluated from the perspective of freshwater recovery rate, climate change potential (global warming), eutrophication potential, ecotoxicity potential, and fossil depletion potential. It has been found the RO-MD and RO-RO were able to achieve the aim of minimal or minimum liquid discharge (MLD) strategy. Although the NF-RO is able to be used in MLD and ZLD technologies for seawater desalination, it is not appropriate approach for brackish water desalination to achieve the MLD strategy**.

Life cycle assement (LCA); desalination; minimum liquid discharge (MLD); Reverse Osmosis (RO); Nanofiltration (NF); Membrane distillation (MD)

1. Introduction

Water have an important role in our life of all living species [1]. With regard to sustainable development goals (SDGs), the SDG 6 (entitled clean water and sanitation) emphasizes on ensure access to water and sanitation for all [2-4]. According to reports, less than 0.5% of water sources are potable and it is estimated that it will increase by more than 50% until 2050 [5, 6]. Most of the water sources are not suitable for proper use due to pollutants or disturbing solutes such as salinity, biological organisms, etc. In addition, industries and agriculture play a significant role in water resources [7]. Therefore, desalination and the use of conventional resources such as brackish water is an approach to supply freshwater. Furthermore, although, brine flow is it has been found brine streams has been neglected in environmental assessments.

Several desalination technologies have been designed heretofore. Hybrid technologies are emerging methods to aim the zero liquid discharge (ZLD) and minimal or minimum liquid discharge (MLD) these days [5]. A hybrid water treatment system is a combination of two or more treatment systems to increase efficiency or lower costs. Since hybrid systems require significant investment, optimizing configurations makes a challenge to develop processes [5]. The ZLD strategy aimed to recover the feed more than 99 percent and the MLD is defined to recover up to 95 percent of freshwater [8]. By integrating different technologies and processes such as reverse osmosis (RO), nanofiltration (NF), membrane distillation (MD), ion-exchange (IEX), etc., it is possible to convert up to 90% of the brine stream into freshwater [9].

Various aspects of water treatment and desalination technologies, including their effects on the environment and human life, have been evaluated in numerous studies around the world. Khosravi et al. [10] compared these studies in terms of environmental, economic, and societal impacts. They found the energy supply source has significant role in the most environmental impacts [10]. In addition it has been found the equipment is influential parameter in human toxicity and ecotoxicity impacts [10]. Lundie et al. [11] compared the environmental effects of the RO plant. In this study, indicators of energy consumption, climate change, human toxicity, ecotoxicity, eutrophication, and photochemical oxidant formation have been evaluated [11]. Raluy et al. [12-16] assessed the impacts of RO, MSF and MED systems with integration with renewable energy sources. It was found that the environmental effects of RO system can be 94.6% less than MSF and 93.1% less than MED [13]. Stokes and Horvath [17] assessed an RO desalination plant in the United States in environmental aspects. In this research, it was observed that the energy source accounted for 56 to 90% of the share of environmental impacts in all investigated indicators [17]. In their study, the effects in the operational phase (gate to gate) have been investigated and the effects related to equipment and brine flow have not been investigated [18]. The results showed that the environmental effects in the case of using the national electricity network are 1.5 times the use of renewable resources [18].

In the last 2000s, two studies by Vince et al. [19, 20] compared the midpoint effects of RO and UF plants in France. In these studies, it was observed that although the operating pressure is reduced, the energy consumption is also reduced, but to achieve the same separation efficiency, the membrane surface should be increased, which will lead to an increase in cost [19, 20]. Muñoz et al. [21-23] compared effects of RO plants in Spain in three projects. The results showed that the environmental effects of desalination of underground sources are 50% less than desalination of sea water [21]. In addition, in these studies, the effect of brine stream was also evaluated and it was observed that chemical and metal compounds play a role in toxic emissions up to 90% [23].

In the last decade, more researchers around the world began to investigate the environmental and economic life cycle impacts of desalination. Beery et al. [24-26] evaluated the environmental emissions of several RO and hybrid RO-UF plants in Germany. In these studies, the effects of the equipment used were also investigated. Furthermore, it was observed that the change in the source of energy supply can reduce the effect of the carbon footprint by 94% [24]. Recently, most studies have focused on examining and comparing emerging technologies. Hancock et al. [27], Al-Sarkal and Arafat [28], Linares et al. [29] studied the environmental effects of hybrid technologies and compared them with individual processes. Linares et al. [29] observed that the hybrid FO-RO system has 56% higher investment cost and 21% lower operating cost than the RO system [174]. In addition, the results showed that the hybrid FO-RO system requires 7% less investment and 9% more operating cost than the MBR-RO system [29]. In addition, Antipova et al. [30] and Cherif et al. [31] investigated the role of renewable energies in providing energy for water treatment. Antipova et al. [30] evaluated an RO system benefiting from solar thermal energy from the perspective of 12 indicators [30]. In addition, Cherif et al. [31] investigated the effects of using a renewable energy source for an RO system over a 20-year life cycle [31]. In this study, the environmental effects of wind turbines and types of photovoltaic cells were investigated in order to provide energy for the water purification process. The results showed that monocrystalline photovoltaic cells (mono-Si) have the most environmental effects [31]. Ronquim et al. [32] compared the midpoint effects of global warming, energy resource depletion, land use, and mineral resource depletion for RO and ZLD processes. Furthermore, Tsalidis et al. [33, 34] investigated ZLD desalination plants in some European countries. It has been found applying ZLD technology is a great approach to decrease the environmental impacts but the economic issues should be considered [34]. Recently, Bordbar et al. [35] investigated the environmental impacts of five desalination plants based on the impacts on climate change, ozone depletion, fossil depletion, human toxicity, and marine eutrophication. They compared the environmental impacts of multi-stage flash (MSF), hybrid RO–MSF, hybrid NF–MSF, RO, and hybrid NF–RO plants in the Persian Gulf region [35]. They found that NF-RO and RO have the least environmental impacts among others [35]. Although the studies have grown significantly these years, the impacts of brine streams have been neglected in the most studies.

In this study, the life cycle assessment (LCA) of four up-to-date real hybrid desalination plants in the Persian Gulf region, including RO, hybrid RO-RO, hybrid NF-RO, and hybrid RO-MD with a cradle-to-gate approach were assessed, and their environmental impacts were compared. The contribution of the all effective parameters including electrical energy, thermal energy, brine streams, and applied chemicals and materials during process and equipment on the impacts were also took account. This investigation was done by the midpoint approach with a long-term point of view. The studied impacts were freshwater recovery, climate change, eutrophication, ecotoxicity, and fossil depletion.

2. Theoretical methodology

2.1. Methodology

The cradle-to-gate LCA approach was used to assess the impacts of energy, materials, and chemical substances used in the case studies on the environment during manufacturing and operation. Ecoinvent 3.8 cut-off database [36-38] was used to determine inventories during the manufacturing and operation. The life cycle impact assessment (LCIA) was done by ReCipe 1.13 midpoint method [39] with global characterization factors in a long-term approach using SimaPro 9.3 software. The functional unit in this study was 1 cubic meter freshwater. Furthermore, the operational lifetime of the devices was considered in calculations regarding the real case studies. In addition ROSA simulation software was applied for simulation of desalination plants. ROSA software is provided by DuPont. This software is a tool for designing and simulating nanofiltration and reverse osmosis systems using membranes manufactured by this company. This software is capable of simulating the purification system of brackish and brackish water (sea water, wastewater, surface water and well water). The simulation is following the steps described in flowchart depicted in Figure 1.

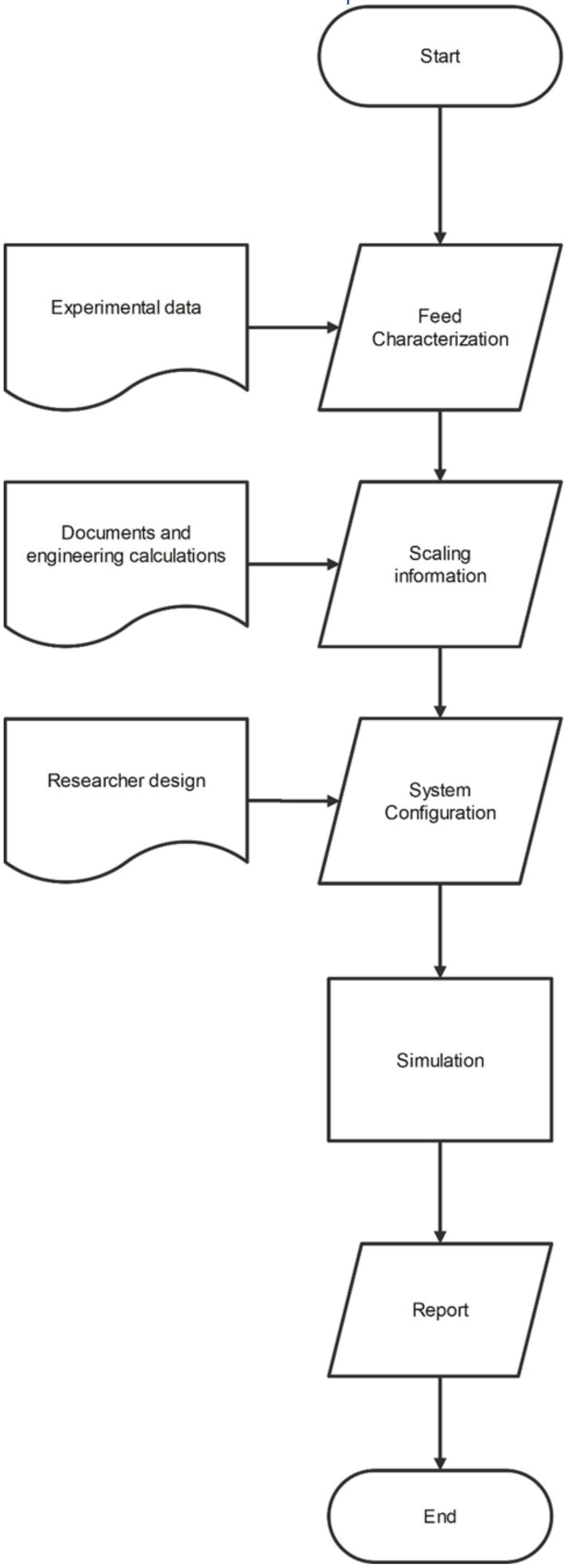

Figure 1. The flowchart of simulation process.

2.2. Systems description

The studied case (first scenario) is a brackish water desalination plant located in Dashtestan county, about 11 km from Borazjan city in Bushehr province, which applied RO technology to treat well water. Relatively salty well water is the feed of the process. According to the analysis, the process feed is relatively salty water with the presence of high amounts of divalent calcium and magnesium ions as well as monovalent sodium ions. The operational system includes two 8-inch reverse osmosis membrane modules, two carbon and sand filter columns, five-micron cartridge filters, a centrifugal pump, and two horizontal pumps. Figure 2a showed the schematic of system. The operational data of plant is presented in Table 1.

The second scenario is the hybrid RO-RO scenario that follows the MLD strategy. In this process, the output from the RO system is fed to a membrane module similar to the previous step. With regard to the pressure at the outlet of the first stage is high, there is no need to increase the pressure in the second stage; But considering that the amount of freshwater recovery will be higher, the amount of specific energy consumption will be lower. Figure 2b showed the schematic of system. The operational data of plant is presented in Table 1.

The third scenario is the hybrid NF-RO system. In this scenario, NF technology is used before the RO process to remove divalent ions and reduce the concentration of pollutants in the feed of the reverse osmosis system. In the NF system membrane module, three membranes made by Dupont company were used. Figure 2c showed the schematic of system. The operational data of plant is presented in Table 1.

The fourth scenario is the combined RO-MD scenario. In this scenario, the RO unit is fed into an MD module [40]. In order to use the capacity of solar energy and reduce the environmental effects caused by the combustion of fossil fuels for energy supply, MD feed heating is done using a solar collector. In addition the electrical energy consumption for all scenarios were obtained from Iran grid network [41]. Figure 2d showed the schematic of system. The operational data of plant is presented in Table 1.

Table 1. Operational data of scenarios 1 to 4.

	RO	RO-RO	NF-RO	RO-MD
Feed flowrate (m^3/day)	50	50	50	50
Freshwater flowrate (m^3/day)	32.48	41.91	29.46	47.59
Brine flowrate (m^3/day)	17.52	8.09	20.53	2.41
Freshwater recovery (%)	64.96	83.82	58.92	95.18
Electrical energy consumption (kWh)	17.21	17.21	21.21	17.21
Required solar thermal energy (MJ)	-	-	-	47.15

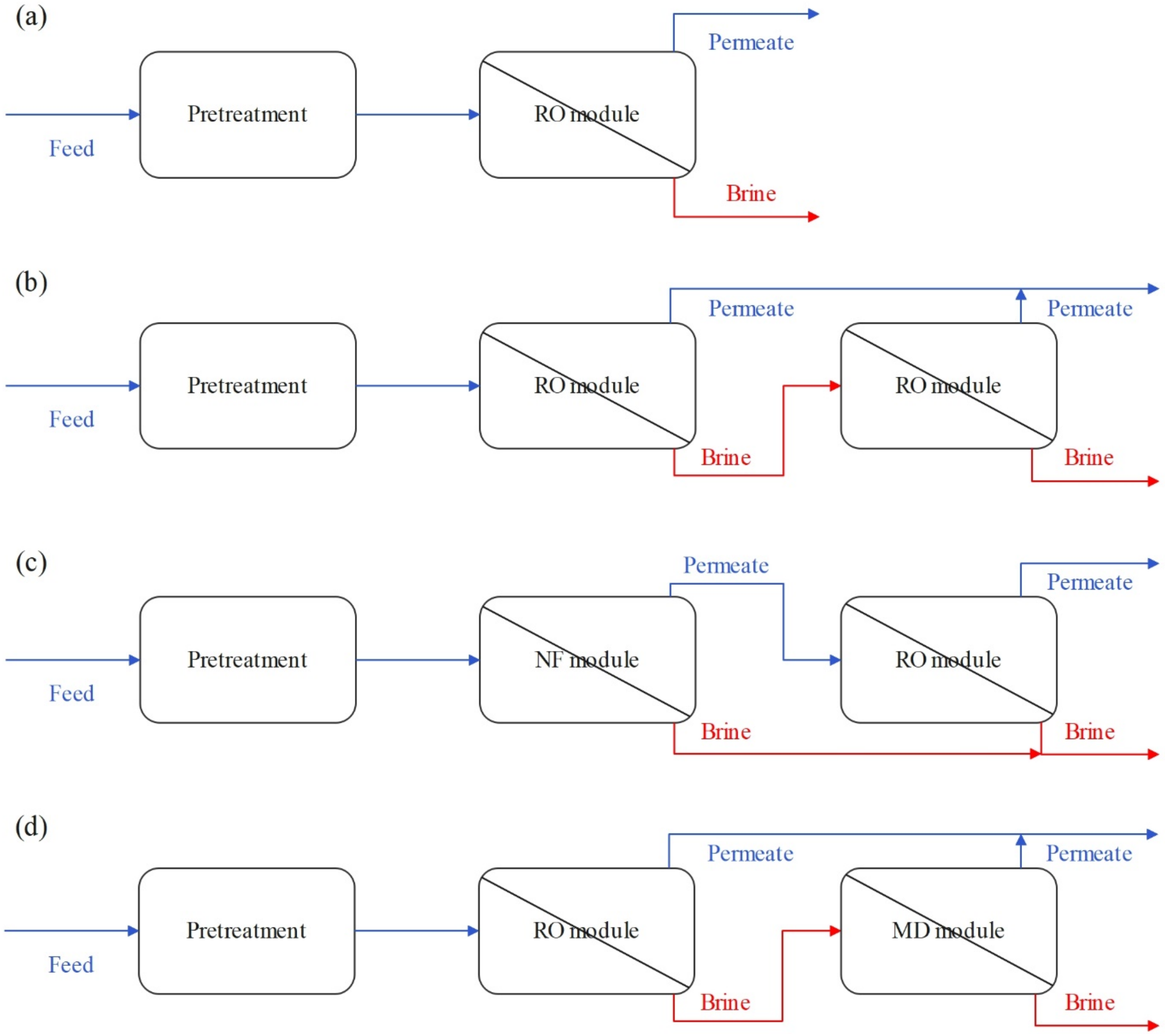

Figure 2. Schematic of scenarios: a) RO, b) RO-RO, c) NF-RO, and d) RO-MD.

3. Results and discussion

3.1. Freshwater recovery

One of the technical characteristics of water treatment and desalination systems is the freshwater recovery rate, which is defined as the ratio of obtained freshwater to the input feed. Higher freshwater recovery rate means the better the system performance. The freshwater recovery rate of scenarios 1 to 4 is presented in Table 1. The RO-MD scenario is presented as an excellent option as the MLD system by achieving a recovery rate of 95.18%. In addition, the RO-RO scenario with a recovery rate of 83.82% is a desirable system in line with the MLD strategy. However, the NF-RO scenario has failed to achieve the MLD strategy with a recovery rate of 58.92%. Although this system in saline and hyper saline feeds can be a suitable option to convert to ZLD technology to achieve added value. Furthermore, the recovery rate for the current operating system (scenario 1) was 64.96%.

3.2. Climate change

The climate change impact (or global warming potential) is one of the most common indicators in LCA reports that equates greenhouse gas emissions by CO_2 equivalent emissions. Figure 3 compares this index for scenarios 1 to 4. It should be noted that LCA indicators are reported based on a functional unit and the environmental indicators of this research are reported based on one cubic meter of desalinated water; Hence, the amount of life cycle indicators is related to the amount of freshwater recovery rate. Furthermore, the results of the analysis showed that the source of energy supply has the greatest impact on the climate change index, so it was observed that the share of the source of energy supply in this index was up to 94.7%. As can be seen, the lowest climate change index is reported for the RO-MD scenario. In the next place are RO-RO scenario. Finally, the highest amount of emissions is related to the NF-RO based scenarios due to the more energy consumption.

3.3. Eutrophication potential

The eutrophication potential index refers to the release of limiting nutrients (nitrogen-containing compounds) into water sources and soil, which causes excessive growth of algae. These emissions play an effective role in swamping and destroying the land around the sewage disposal site. The results of the study showed that the output of the process has a great role in this index. The analysis showed that share of brine stream in this index is more than 93.4%. Figure 3 presents a comparison of the eutrophication index of scenarios 1 to 4. The freshwater recovery rate has an effective role in this index. As can be seen, the NF-RO process, which had the highest amount of brine, shows the highest amount in this index. This amount is 84.38 kg equivalent of nitrogen per cubic meter of freshwater per day. In the next place is the current operating RO system with a rate of 22.92 kg of nitrogen equivalent per cubic meter of fresh water per day. The RO-RO scenario is in the next position with a slight difference of 14.15 kg. The lowest amount among the MLD scenarios corresponds to the RO-MD scenario, which shows the amount of 15.64 kg of nitrogen equivalent per cubic meter of fresh water per day.

3.4. Ecotoxicity potential

The ecotoxicity index examines the release of toxic substances caused by metals and chemicals in the environment. The results have shown that the chemicals used in the process and the materials used in the equipment have the greatest impact on this index. According to the equipment used in the solar thermal system in the RO-MD scenario, this scenario has the highest amount of this index. The RO-RO and NF-RO scenarios show the lowest emissions, which have lower emissions due to less equipment. In these scenarios, the materials used have a share between 74 and 79 percent. Figure 3 shows the environmental toxicity index for scenarios 1 to 4.

3.5. Fossil depletion potential

Energy resource depletion potential (also known as cumulative energy demand (CED)) refers to the total energy applied to the process. This index can be divided into fossil and renewable energy sources, which are called fossil energy demand or fossil resource destruction and renewable energy demand, respectively. As shown in Figure 3 the most fossil depletion indicator is for NF-RO system due to the more energy consumption. The next place is individual RO plant with about 26% less impact in comparison to NF-RO. RO-MD and RO-RO are close to each other. The RO-MD showed 5.1% less impact in comparison to the RO-RO and the least fossil depletion among all scenarios. Figure 3 shows the fossil depletion impact of scenarios 1 to 4.

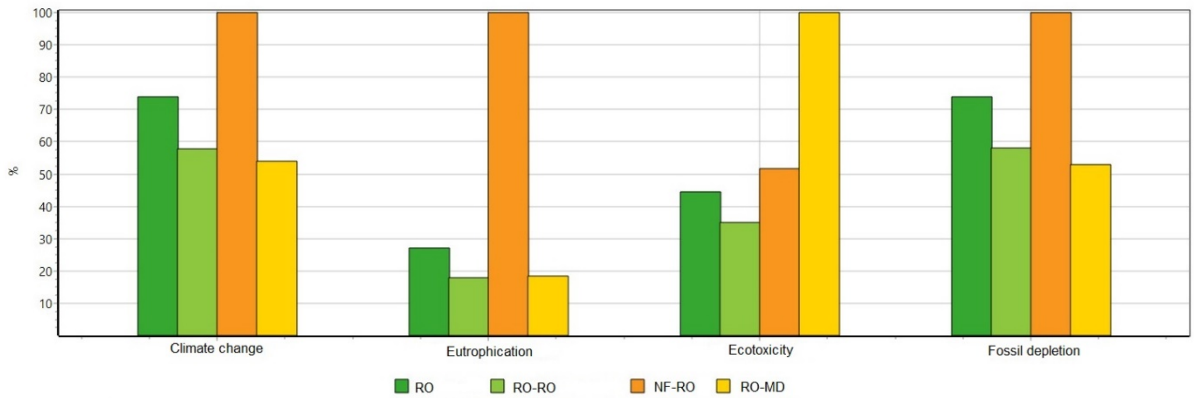

Figure 3. Comparison of environmental impacts of scenarios 1 to 4.

4. Conclusion

In this study, 4 brackish water desalination scenarios were investigated with a life cycle assessment approach to be implemented in Persian Gulf region. Considering the vital need to access water sources and the increasing importance of developing desalination and water treatment technologies, the results of this study can be used to reduce environmental effects and explain a sustainable policy for the development of water treatment and desalination projects in the country and especially in the province. In this study, the selected scenarios for implementation were evaluated from the perspective of freshwater recovery rate, climate change potential (global warming), eutrophication potential, ecotoxicity potential, and fossil depletion potential. It was observed that RO-MD showed the most freshwater recovery. It has been found the RO-MD and RO-RO were able to achieve the aim of MLD strategy. In addition, environmental assessment showed that energy consumption is a key parameter in climate change impact. It was found that the RO-MD had the least climate change impact. With regard to the eutrophication impact, it has been found that brine streams had a significant role in eutrophication potential. The NF-RO system had the most eutrophication index due to the more brine flowrate. In addition, the RO-RO and RO-MD were too close to each other. The analysis showed that chemical and materials of equipment have significant role in ecotoxicity potential. Due to the solar thermal facilities applied in the RO-MD system, it had the most ecotoxicity impact. Furthermore, the RO-RO scenario had the least ecotoxicity due to less equipment among hybrid systems and more freshwater recovery in comparison to individual RO. At last, the fossil depletion impact of scenarios had been compared. It was observed that the NF-RO showed the most fossil depletion impact due the higher energy consumption among other scenarios. The results of this study can make a guideline to make a policy for development of desalination plants in Persian Gulf region.

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