Evaluation of environmental indicators of RO seawater desalination: case study coastal strip of Hormozgan province, Iran

Somayeh Mohammadi Jouzdani, Mohammad Mahdi Zerafat, Peyman Daneshkar Arasteh and Hassan Vagharfard

ABSTRACT

In recent years, desalination has been turned into a fresh water supply as a solution in some areas which suffer from water shortage. Desalinated water as an industrial product causes environmental problems. The objectives of this study are investigating environmental sustainability indicators related to seawater desalination via reverse osmosis (SWRO) on the coastline of Hormozgan province to provide a better insight for current and future water and energy demands related to this alternative. The selected indicators are specific energy consumption, seawater withdrawal, and brine volume in desalination, fuel consumption, carbon emission and water withdrawal in electric power generation. Using a solution-diffusion model, the direct indicator of energy consumption was obtained as used to calculate indirect indicators from the energy generation sector. Analysis of results indicates that desalination can lead to out-of-area side effects resulting from fuel type consumed and the practical power of the power plant, in addition to the regional environmental effects that are mostly affected by total dissolved solids of feed water. Based on the results, the environmental issues should be considered for the regions where desalination was planned as the most feasible alternative for water supply. This result can help policymakers to manage water supply and demand for sustainable development appropriately.

Key words | environment, Iran, seawater desalination, sustainable, SWRO

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HIGHLIGHTS

- For assessment environmental sustainability production in water harvesting (SWRO desalination), the direct and indirect indicators were calculated.
- The direct indicator was used to calculate some indirect indicators so that minimum input of index was used.
- For calculating index, the theoretical and experimental models were used.
- Calculation of how much fresh water indirectly consume as cooling water, for, desalinating 1 unit freshwater via SWRO desalination.
- The research was aimed at creating a comprehensive insight into SWRO on its long-term environmental effects. This result can help policy makers to manage water supply and demand for sustainable development appropriately.

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INTRODUCTION

Population growth and enhancement of living standards coupled with inefficient consumption and contamination of water resource have led to the consideration of desalination technology as an alternative to obtain freshwater in some countries. According to IDA (2014), there are approximately 23,000 desalination plants in more than 150 countries producing ~85,000 m^3/day of water and 60% of these are located in the Middle East. The installed desalination plants are increasing in number, such that 564 new desalination plants were constructed from 2013 to 2014.

While other distillation technologies were dominant in 1997, currently, desalination with reverse osmosis (RO) has an approximately 65% growth in installed plants due to higher efficiency. Based on the Sixth Development Plan approved in February 2017 in Iran, the government is tasked to supply at least 30% of the drinking water for southern provinces via seawater desalination (Parliament of Iran 2016).

Environmental effects due to energy consumption and brine discharge are among the challenges in this industry. In fact, feed water is often a habitat and part of the ecosystem. Desalination by feed water withdrawal and discharge of saline water including a large amount of chemicals can disturb the ecosystem. Lior (2017) states that the associated saline feed water flow rate is 63% higher than that of the Nile River, and 83% higher than that of the Yellow River. Also, the rate of CO_2 emission from desalination was almost 0.8% of the world's total emissions in 2011. Emission of SO_2 and NO_x are also high. One of the key concerns of desalination projects is its potential effects on climate change. These values become much more significant where the regional amount of desalination becomes larger per unit area.

The Persian Gulf is a marginal and semi-enclosed area with special environmental conditions due to its geographical location, shallow depth, and high evaporation rate. Water desalination in regional countries of the Persian Gulf is an energy-intensive activity consuming non-renewable fossil fuels (Darwish *et al.* 2009). Due to the increased water consumption, governments' policy and wealth, cheap fuel and fragile environment and poor consumption laws, desalination can exert long-term adverse effects on the environment in the Persian Gulf and regional countries. Serious cooperation among these countries is required for this problem to be solved (Lior & Kim 2018).

The environmental sustainability indicator is among the indicators presented by Krajnc & Glavic (2003). These indicators are categorized into seven groups according to whether entering or exiting the system. Energy use, materials' use, water use were introduced as input indices and product, solid and liquid waste, and air emission indicators as outputs.

In the case of desalination, most studies have evaluated sustainability indicators in energy generation (Torcellini *et al.* 2003; Rutberg 2012; Diehl & Harris 2014; Ansorge & Zeman 2016) and water supply (Ludwig 2010; Nazari *et al.* 2012; Mazlan *et al.* 2016; Voutchkov 2018). In recent years, many research activities have been performed, especially on environmental sustainability of the desalination industry, such as those reported by Lior (2017), Liu *et al.* (2013), Manju & Sagar (2017), Miller *et al.* (2015), Shahabi *et al.* (2014), Shemer & Semiat (2017), and Xevgenos *et al.* (2016). Darwish *et al.* (2009), as the first researchers, applied the environmental indicators of specific fuel-energy consumption for evaluating seawater desalination, using measured data. Then, Lior & Kim (2018) used emission and brine discharge as environmental indicators for quantitative sustainability analysis of RO desalination that were expressed by weights based on relative importance.

In this research, environmental sustainability indicators for RO, as the dominant desalination technology in the Persian Gulf, based on their priority and significance in the environment and also used in previous studies, were selected. The novelty of this study is utilization of the direct sustainability indicator (specific energy consumption) in the desalination sector to determine other indirect sustainability indicators in this technology related to energy generation sector (specific fuel consumption, specific water withdrawal, and specific carbon emission). The assumption was that the desalination plants were powered by thermal power plants with natural gas and fuel oil consumed by wet cooling tower systems. For calculating water desalination and energy generation sector indicators, theoretical and experimental models were used, respectively. The research was aimed at creating a comprehensive insight into seawater desalination via reverse osmosis (SWRO) on its long-term environmental effects.

MATERIALS AND METHODS

The location of the investigated desalination plants on the Persian Gulf is given in Figure 1.

The procedure is summarized in the following five steps:

1. The environmental sustainability indicators of RO desalination were considered as introduced by Krajnc & Glavic (2003) for assessment of sustainability production. The output indicators were selected based on their significance on the environment and previous studies (Lior & Kim 2018). Carbon is emitted during energy generation in power plants. Fuel consumption and water withdrawal of power plants are indirect indicators attributed to carbon emission. In addition, specific seawater withdrawal was selected due to the physical and geographical conditions of the Persian Gulf (Table 1).
2. In the SWRO desalination sector, indicators were calculated for producing 1 m^3 of desalinated water, using the physiochemical data of the Persian Gulf water. IMSDesign software was used for RO processing considering optimal energy consumption.
3. In electricity generation, indicators were calculated using the data from ten thermal power plants supplying 21% of the entire national grid of Iran. The S-GEM model considered the minimum consumed or withdrawn fuels and fresh water.
4. Based on the obtained specific energy consumption in step 2, the calculated indicators in step 3 were accounted.
5. The calculated indicators were evaluated according to daily drinking demands of the population of Hormozgan province.

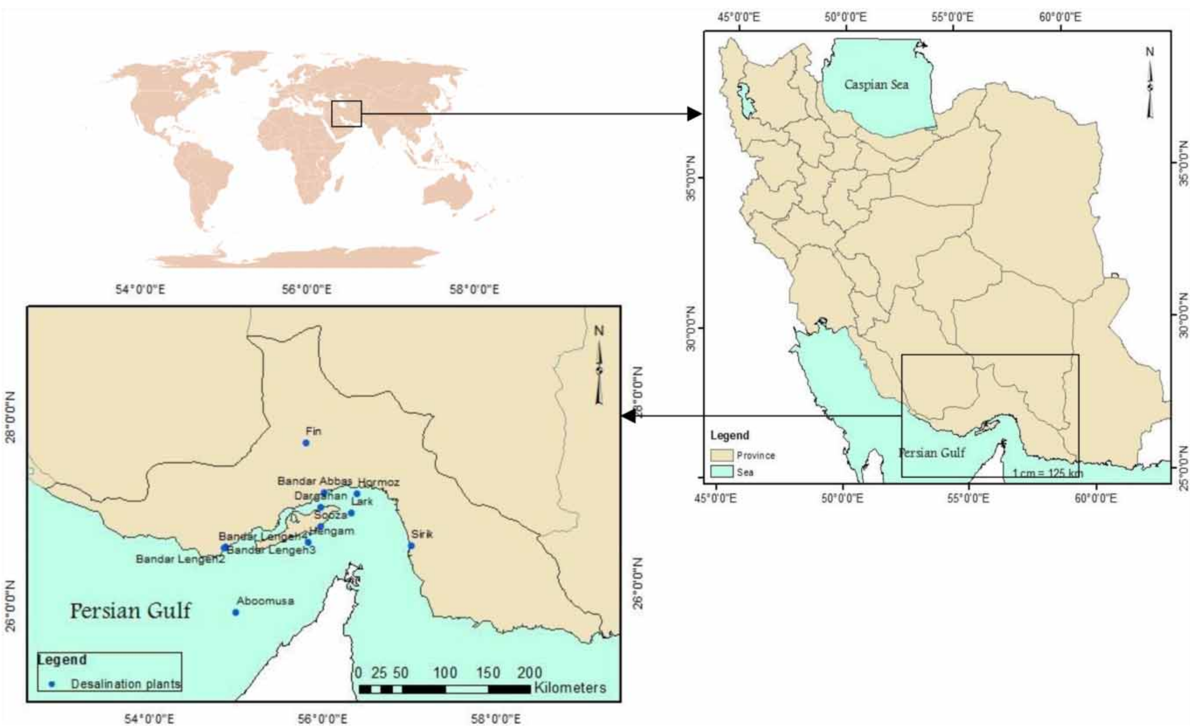

Figure 1 | The investigated RO seawater desalination plants in Hormozgan province.

Table 1 | The environmental sustainability indicators under study

Production unit	Input indicators	Output indicators
Desalination plant	Specific energy consumption	Specific brine volume
	Specific seawater withdrawal	
Power plant	Specific fuel consumption	Specific carbon emission
	Specific water withdrawal	

Environmental indicators for RO processing

Specific energy consumption

Specific energy consumption is the energy consumed per unit volume of freshwater produced. RO desalination consists of: (1) feed water intake, (2) pre-treatment, (3) high-pressure pumps (with or without ERD equipment), (4) membranes and modules, and (5) product transferring. As a result, the required energy for the total process can be expressed as follows:

$$E_T = E_{in} + E_{pt} + E_{hp} + E_A - E_{ERD} \quad (1)$$

where, E_T is the total energy consumption; E_{in} the energy requirement to obtain feed water from the source; E_{pt} the required energy for pre- and post-treatment (microfiltration and pumping) stages; E_{hp} the required energy for high-pressure pumps; E_a the required energy for other auxiliary equipment (chemical, filter washing and water pumping) and E_{ERD} the recovered energy by ERD (Gude 2011). In reverse osmosis, salt transmembrane permeation is a function of salt concentration:

$$N_s = B(C_{feed} - C_{permeat}) \quad (2)$$

where, N_S is salt permeation across the membrane; B a constant for salt permeation describing physical characteristics of the membrane; C_{feed}, salt concentration in feed water; and $C_{permeate}$, salt concentration in the permeate (Sagle & Freeman 2004). The IMSDesign software (Hydranautics Company) was utilized to design RO based on the solution-diffusion model.

The physio-chemical data of the Persian Gulf seawater were supplied by Hormozgan Province Water and Wastewater Company. The input information was determined according to AWWA guidelines (AWWA 1999) (Table 2).

The model was run using constants at various ranges of temperature and capacity, which are expected to have a significant effect on energy consumption (Demichele 2014). Three scenarios were performed to examine the capacity variations and effect of ERD on energy consumption; Test (0) without using ERD, Test (1) using Pressure Work Exchanger, and Test (2) using TURBO.

Specific seawater withdrawal

Specific seawater withdrawal is the volume of withdrawal feed water used for producing a unit volume of desalinated water. According to the AWWA manual for designing RO systems, a 50% permeate recovery was considered for feed water with total dissolved solids (TDS) = 39,142 mg/L. Therefore, specific water withdrawal is twice the permeate volume, theoretically.

Specific brine volume

Based on the level of recovery (50%), the theoretical specific brine volume is equal to 1 m^3/m^3.

Table 2 | The input parameters in the IMSDesign software for planning the SWRO system

Parameter	Value or type
pH	8.18
Permeate recovery	50%
Temperature	20–34 °C
Average flux	13.5 L/m^2 h
Membrane age	1 day
Element type/vessel	Spiral wound configuration: 8.6
ERD	Pressure Work Exchanger, TURBO
Total plant product flow	10,000–100,000 m^3/day
Chemical	According to model default

ENVIRONMENTAL INDICATORS IN ENERGY PRODUCTION

Specific water withdrawal

Specific water withdrawal is the amount of water used per unit electrical energy produced. Water is used as cooling in the wet tower of the thermal power plants in the recirculating loop. Hot water from the condenser and any other heating load flow into the top of the tower. Evaporation from the cooling tower is the principal mechanism through which water is consumed (Rutberg 2012). A system-level generic model (S-GEM) of water consumption was introduced by Rutberg (2012), for estimating water withdrawal in the cooling system in wet tower-cooled power plants:

$$I_{ww} = 3600 \frac{(1-\eta_{net}-k_{os})}{\eta_{net}} \frac{(1-k_{sens})}{\rho_w h_{fg}} \left(1+\frac{1}{n_{cc}-1}\right) + I_{proc} \quad (3)$$

where, I_{ww} is water withdrawal intensity; η_{net} net efficiency of power plant; k_{os} dimensionless coefficient representing the fraction of heat loss to sinks other than the cooling system; *ncc* number of concentration cycles: describing the concentration of impurities in the circulating water relative to that of the makeup water. The purer the input stream, the more cycles of concentration can be tolerated before mineral impurities reach the unacceptable level. Typical values for *ncc* in the US fall between 2 and 10. I_{proc} is the non-cooling process intensity coefficient for boiler feed water makeup and miscellaneous uses. In this case, 10 L/MWh was considered based on the type of consumed fuel. ρ_w is water intensity (0.998 kg/L); k_{sene} fraction of heat load rejected through sensible heat transfer, which is determined by the following equation:

$$y = (-0.000279 \times x^3) + (0.00109 \times x^2) - (0.345 \times x) + 26.7 \quad (4)$$

where, x is the mean annual normal air temperature and y is k_{sens}.

In this study, the required data were provided by Tavanir organization (see Supplementary Material). Ten power plants with wet cooling tower systems were selected (Table 3). Then, k_{sens} was estimated using mean annual air temperature for all power plants using synoptic stations' data prepared from IRIMO website (see Supplementary Material), and applying the inverse distance method for those that are not within the station range.

Table 3 | The studied thermal power plants

Power plant	Number of units	Practical power (MW)
Ramin (Ahvaz)	6	1,823
Shahid Mofateh Hamedan	4	1,000
Esfahan (Eslam Abad)	5	830
Bokhari Tabriz	2	650
Montazerolghaem	4	548
Zarghan (Shahid Modhej)	1	255
Shahid Beheshti (Loshan)	2	240
Besat	3	216
Mashhad	3	133
Shahid Firoozi (Tarasht)	4	40

In order to determine and apply the most appropriate *ncc* in Equation (3), the following procedure was taken. According to the allowable TDS for cooling water (1,850 ppm) (Guideline WG-2 2009), the acceptable TDS was calculated for each *ncc* (1,850/*ncc*, Figure 2). Specific water withdrawal (I_{ww}), for $ncc = 2$–10, was calculated for each power plant. Then, the amount of water saving variation vs the increasing *ncc* was computed using Equation (5) (Figure 2):

$$((\Delta I_{i-(i+1)})/(\Delta I_{2-10})) * 100 \quad (5)$$

where, the difference between specific water withdrawal of $ncc = i$ and $ncc = i + 1$, = the difference between specific water withdrawal of $ncc = 2$ and $ncc = 10$.

The variations of water saving for $ncc > 6$ is <0.01, so the specific water withdrawal was calculated for each power plant considering $ncc = 6$.

Specific fossil fuel consumption

The thermal power plants under study use different fossil fuels for producing thermal energy at different proportions. These fuels are natural gas, fuel oil, and gasoil with the following proportions: natural gas, 64 to 100%; fuel oil 0 to

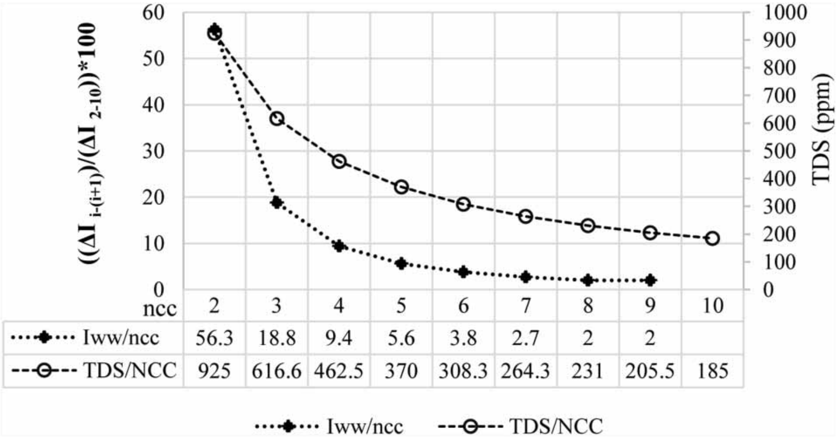

Figure 2 | Withdrawal water rate and the maximum allowable TDS due to *ncc* variations.

34%; and gasoil on average 1% supplied thermal energy. Two scenarios were supposed: (1) only natural gas supplied the total energy, (2) only fuel oil supplied the total energy. The specific volume of fuels for producing unit thermal energy were calculated using the volume of annual consumed fuels, the annual production, density, and higher heating value of all the fuels (Table 4). Then, the consumed volume of each fuel for producing unit electrical energy using the heating rate of the fuel was calculated.

Specific carbon emission

Specific carbon emission was estimated using Equation (6) and Table 4 (Van Harmelen & Koch 2002):

$$C_r = Q \times NCV \times EF \times (1 - S_f) \times F \quad (6)$$

where, C_r is the quantity of carbon released and attributed to fuel combustion; Q, the quantity of fuel delivered to or consumed by the activity sector expressed in natural units; *NCV*, the net calorific value of fuel = higher and lower heating value (TJ/natural unit): *EF* the emission factor (the specific carbon content, tC/TJ); S_f, carbon storage factor (the fraction of carbon delivered, which remains unoxidized after fuel consumption); and *F* the oxidation factor, the fraction of carbon which is oxidized during combustion. Specific carbon emission was calculated using Equation (6) supposing $S_f = 0$ for natural gas and fuel oil.

Table 4 | The characteristics of studied fossil fuels

Fuel	HHV (MJ/kg)[a]	Density (kg/m$_3$)[a]	Emission factor (tC/TJ)[b]	Fraction of carbon oxidized[b]
Fuel oil	43.3	968	20–21	0.99
Natural gas	43.9	0.777	17.2–19	0.995

[a]Mekonnen *et al.* (2015), IGS-M-CH-033(1) (2014).
[b]Van Harmelen & Koch (2002).
(tC/TJ) = ton C/Tera Joule.

RESULTS AND DISCUSSION

This case study was conducted to evaluate the main environmental sustainability indicators of SWRO desalination. Indicators were selected based on their significance to the environment including direct indicators: (1) indicators in the desalination process (specific energy consumption, specific seawater withdrawal, and specific brine volume) and (2) indirect indicators in energy production (specific water withdrawal, specific fuel consumption, and specific carbon emission).

In order to calculate direct indicators, IMSDesign software was utilized to design RO based on the solution-diffusion model. The model was run using constants at various ranges of temperature (Figure 3(a)) and capacity variations with or without ERDs (Figure 3(b)).

The results indicated that the minimum specific energy consumed at 34 °C (of feed water) according to Gude

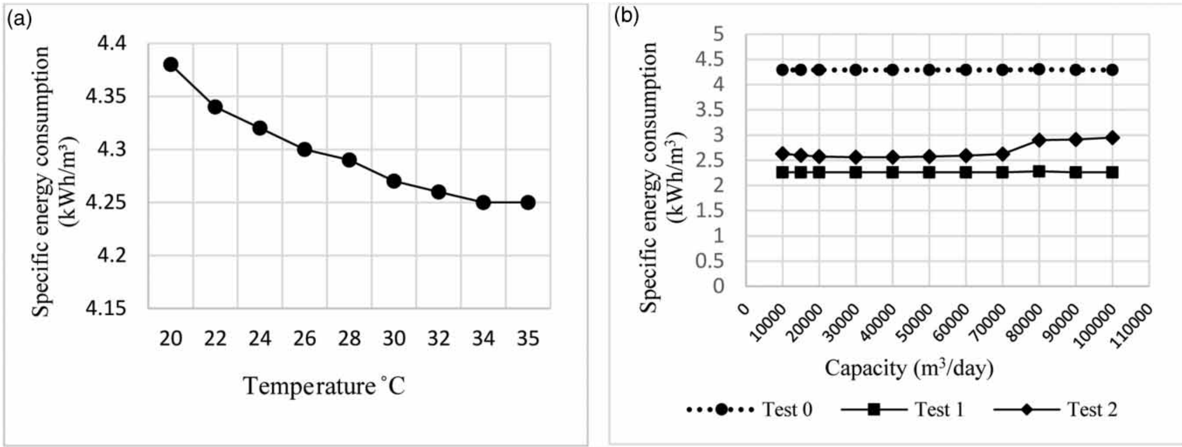

Figure 3 | (a) The effect of temperature and (b) the effect of capacity on specific energy consumption.

(2011) and the change in capacity does not have a noticeable effect on energy consumption. In addition, the use of the Pressure Work Exchanger as the ERD consumes less specific energy.

Considering the above, the minimum specific energy consumption was determined to be 2.26 kWh/m^3 (Table 5). Specific energy consumption is reported between 2.2 and 5.6 kWh in other studies (Ludwig 2010; Gude 2011, 2016; Mazlan *et al.* 2016; Lior & Kim 2018; Voutchkov 2018). If pH and dissolved cations-anions in water samples are considered constant for the coastline of Hormozgan province, this result can be generalized to other SWRO desalination units in this region.

Theoretically, specific seawater withdrawal and specific brine volume would be 2 and 1 m^3, respectively, according to 50% recovery in designing the SWRO system. However, these values are higher in practice as Pars Geometry Consulting Engineers Company (see Supplementary Material) reported 3.3 m^3 of water withdrawal for producing 1 m^3 desalination water in Bandar Abbas desalination plant.

Specific water withdrawal (I_{ww}), for $ncc = 2–10$, was calculated for each power plant. Then, the amount of water saving variation vs increasing *ncc* was computed. The variations of water saving for $ncc > 6$ was <0.01, so the specific water withdrawal was calculated for each power plant unit considering $ncc = 6$. Another two indirect

Table 5 | The calculated direct and indirect indicators for the production 1 m^3 of desalinated water

	Desalination plants			**Power plant units**				
					Carbon emission		**Fuel consumption**	
	Energy consumption	**Brine volume**	**Seawater withdrawal**	**Water withdrawal**	**Fuel oil**	**Natural gas**	**Fuel oil**	**Natural gas**
For producing 1 MWh electrical energy in power plant	–	–	–	1.898 (m^3/MWh)	257.885 (kg/MWh)	183.945 (kg/MWh)	0.265 (m^3/MWh)	268.94 (m^3/MWh)
Producing 1 m^3 desalinated water	2.26×10^{-3} (MW/m^3)	1 (m^3/m^3)	2 (m^3/m^3)	0.00423 (m^3/m^3)	0.583 (kg/m^3)	0.416 (kg/m^3)	0.000599 (m^3/m^3)	0.607 (m^3/m^3)
Supplying 30% drinking water for Hormozgan province	413.56 (MW/day)	155,475.453 (m^3/day)	310,950.906 (m^3/day)	666.909 (m^3/day)	90,614.219 (kg/day)	64,633.586 (kg/day)	93.114 (m^3/day)	94,498.664 (m^3/day)

indicators, specific fuel consumption and specific carbon emission, were calculated for each of the 34 power plant units.

The relevant graphs were drawn between each calculated indirect indicator and practical power in power plant units (Figure 4). It was found that the minimum fuel was consumed, water was withdrawn, and carbon was emitted in 250 MW practical power. Therefore, the practical power = 250, was selected as the base power.

Based on the obtained regression equation, each indirect indicator for 250 MW was calculated. The results are presented in Table 5.

Regarding specific energy consumption for desalination (2.26 kWh), each indirect indicator for producing 1 m^3 desalinated water was calculated and presented (Table 5).

Based on the calculated specific fuel consumption and carbon emission, 607 m^3 of natural gas or 0.6 L of fuel oil is required to supply electrical energy to produce 1 m^3 of SWRO desalinated water. Despite the fact that the natural gas was almost 1,000 times larger than that of the fuel oil, natural gas specific carbon emission is 0.7% of that for fuel oil.

Several studies calculated or reported carbon emission for electricity production between 100 to 275.2 kg C/MWh for natural gas combustion and 58.89 to 333.3 kg C/MWh for combustion of oil, including McIntyre et al. (2011), Mousavi et al. (2017), and Shrestha et al. (2011). In the literature, the estimated carbon emission associated with RO desalination varies in the 0.110 to 1.861 kg C/m^3 range (Cornejo et al. 2014), which can be multiplied by a factor of 3.6 to obtain the amount of CO_2 emission (Van Harmelen & Koch 2002).

The results show that to produce 1 m^3 of desalinated water, 4.23 L of fresh water is needed indirectly. This water is used for cooling systems in power plant units and 2 m^3 of seawater that is a part of the marine ecosystem. The population of Hormozgan province is 2,307,442 (in 2019) and daily drinking water consumption for Iranians is estimated as 0.225 m^3 (Center for Statistics of Iran, see Supplementary Material). The indicators were estimated for 30% of the volume of the population drinking water of

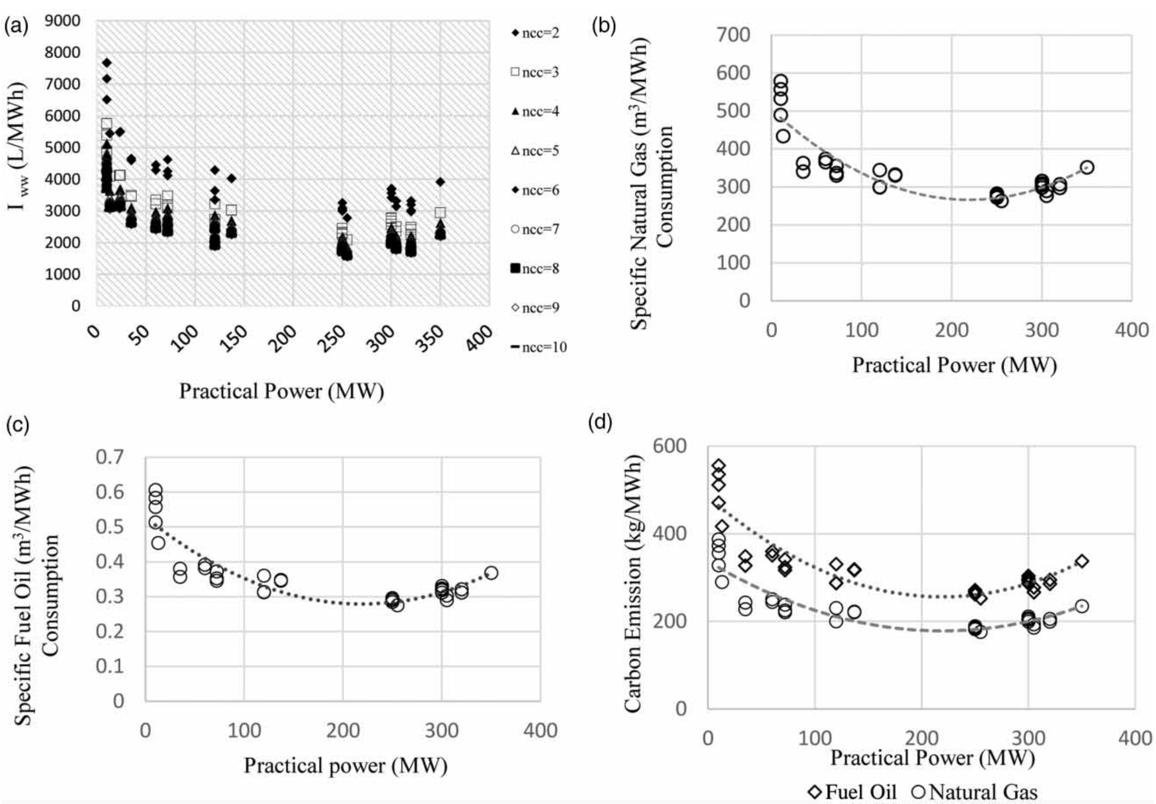

Figure 4 | The effect of practical power on: (a) specific water withdrawal, (b) specific natural gas consumption, (c) specific fuel oil consumption, and (d) specific carbon emission indicator.

Hormozgan province (based on the Sixth Five-Year Development Plan of Iran). The results are presented in Table 5. These results are for daily drinking water consumption. Long-term consumption and population growth can lead to serious effects on the environment, both in terms of consumption and pollution. Uddin (2014) revealed that the increased salinity in the Persian Gulf was attributed to desalination. Lior (2017) reported that the rate of CO_2 emissions of desalination was almost 0.8% of the world's total in 2011.

CONCLUSIONS

Desalination not only affects the environment regionally but also has out-of-area effects such as carbon emissions that can result in global warming. The minimum fuel is consumed, the minimum water is withdrawn, and minimum carbon emitted in power plant units that operate on a 250 MW practical power. By changing the type of fossil fuel for energy generation (natural gas instead of fuel oil), carbon emission can be reduced to 16%. Considering the positive rate of population growth in Hormozgan province, attention to environmental issues associated with desalination industry is necessary. Cooperation between the desalination industry and water research centers can help predict the long-term effects of this industry and its decline. Seawater desalination industries depend on the availability of sea or brackish water that may be a part of the ecosystem, thus, this system cannot be considered as a new water resource.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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