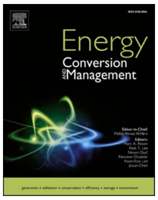
Energy Conversion and Management 251 (2022) 114971

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman



Reverse osmosis desalination systems powered by solar energy: Preheating techniques and brine disposal challenges – A detailed review

S.M. Shalaby [a,1], Swellam W. Sharshir [b,c,1], A.E. Kabeel [d,e,*], A.W. Kandeal [b,c], H. F. Abosheiasha [a], Mohamed Abdelgaied [d], Mofreh H. Hamed [b,f], Nuo Yang [c,*]

[a] Engineering Physics and Mathematics Department, Faculty of Engineering, Tanta University, Egypt
[b] Mechanical Engineering Department, Faculty of Engineering, Kafrelsheikh University, Kafrelsheikh 33516, Egypt
[c] State Key Laboratory of Coal Combustion, Huazhong University of Science and Technology, Wuhan 430074, China
[d] Mechanical Power Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt
[e] Faculty of Engineering, Delta University for Science and Technology, Gamasa, Egypt
[f] Higher Institute of Engineering and Technology, MNF-HIET, Menoufia, Egypt

ARTICLE INFO

Keywords:
Desalination
Reverse osmosis
Solar energy
Photovoltaic
Rankine cycle
Brine disposal
Specific power consumption

ABSTRACT

Globally, reverse osmosis desalination systems are widely utilized as they have the cheapest freshwater production cost. On the contrary, reverse osmosis systems have high specific energy consumption and membrane fouling that requires continuous chemical cleaning. Additionally, the plants' performance and their applicability can be stated via different terms: specific energy consumption, freshwater cost, thermal efficiencies, configurations, water recovery factors, and water quality. Therefore, many investigations have been conducted to enrich these indicators. Accordingly, the current review aimed to comprehensively merge most of these studies to give a complete picture of the recent developments of reverse osmosis plants considering all the aforementioned parameters. On the one hand, the current survey focused on solar-based reverse osmosis plants, which were established to decrease the specific energy consumption using photovoltaic or solar thermal power plants; especially, the organic Rankine cycle. Besides, various preheating techniques and relevant works were presented. The preheating boosts the plants' thermo-economic performance, and yield as the power consumption and productivity proportionally vary with the feedwater temperature. The preheating can be conducted by recovered heat from other systems, such as photovoltaic cooling unit, humidification-dehumidification process, organic Rankine cycle, and hybrid systems. Finally, the brine disposal methods were introduced, discussed, and compared to help in identifying the most appropriate economic technique, especially for the inland desalination plants. It is proposed that this review can help in the research continuity in the desalination field, especially reverse osmosis plants.

1. Introduction

The Egyptian government has an ambitious plan to reclaim 5 million acres in the western desert, Sinai in the west, the new valley in the south, and Elmaghrah in the north. These areas were selected based on the huge amount of underground water saved in their aquifers. Unfortunately, the underground water in most of the Egyptian aquifers, especially in the mentioned areas, has high salinity. There are many desalination processes that can be considered for freshwater production. On the one hand, thermal desalination systems are popular for simple designs and economic installation and operation, such as solar stills [1-4] and humidification-dehumidification (HDH) [5-8]. However, these processes are known for their low to moderate capacity, even with the efforts conducted to improve them [9-13]. Therefore, they may not be sufficient for the large demand in the aforementioned locations. On the other hand, membrane desalination (MD) units are known for their high capacity production; especially, reverse osmosis (RO) [14]. The RO desalination has some demerits, such as the high specific energy

---

* Corresponding authors at: Mechanical Power Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt (A.E. Kabeel); Huazhong University of Science and Technology, Wuhan 430074, China (N. Yang).

E-mail addresses: saleh.shalaby@f-eng.tanta.edu.eg (S.M. Shalaby), sharshir@eng.kfs.edu.eg (S.W. Sharshir), kabeel6@f-eng.tanta.edu.eg (A.E. Kabeel), mohamed_abdelgaied@f-eng.tanta.edu.eg (M. Abdelgaied), nuo@hust.edu.cn (N. Yang).

[1] These authors equally contributed in this work.

https://doi.org/10.1016/j.enconman.2021.114971
Received 14 August 2021; Received in revised form 13 October 2021; Accepted 30 October 2021

consumption (SEC) that reaches 4 kW/m^3 [15,16] and the membrane fouling that needs chemical cleaning [17-19]. However, it is the mostly-utilized desalination technology around the world so far [20-23] because it still has the cheapest production cost per freshwater volume (m^3). On the other side, there is a rapid growth of industrialization, energy shortages, and blackouts resulted in high energy demands. The research interest has gained considerable attention in utilizing low-grade heat sources to minimize energy losses. In addition, the priority in recovering waste heat is an initiative taken by worldwide governments to reduce fuel consumption and thereby achieve higher energy conversion efficiencies. So, it is planned to install an enormous number of high-capacity RO plants in the mentioned remote areas. So, the integration between the solar systems and RO is the perfect solution for an unreachable power grid. In this case, the energy recovery from solar systems can be used for feed water preheating [24] as the RO plant performance is improved by applying water preheating [25-27]. The expected huge brine of RO plants is considered an enormous challenge in this plan as it is a global problem, and its perfect solution is still in the research stage [28-32]. So, it is very important to comprehensively review the solar-driven RO desalination systems and discuss the different feed water preheating and brine disposal techniques.

The solar-driven RO desalination systems were reviewed by Shalaby [33]. The main conclusion extracted from this review was that the photovoltaic (PV) is the mostly-used renewable source for driving the RO as it is considerably cheap compared to the solar organic Rankine cycle (ORC). This superiority of PV is also supported by the results reported by Mito et al. [23,34]. Recommendations of solar ORC design used to drive the RO were introduced by Delgado-Torres et al. [27]. They found that the selection of organic working fluid and turbine used as prime mover depends on the solar collector type. They also concluded that using the heat transfer fluid (HTF) configuration could be more efficient than a direct steam generation.

The concentration of RO brine was reviewed by Subramani and Jacangelo [35], and Pramanik et al. [36]. From the reported results in these reviews, the forward osmosis (FO) showed promising results in concentrating the brine of RO. The superiority of FO compared to utilization of more stages of RO mainly occurs because it uses osmotic pressure as driving force and has lower fouling than RO [35]. The membrane desalination (MD) has also shown auspicious performance in concentrating the RO rejection [25,37-41].

According to the literature, there are many works considering the enhancement of the RO plants' performance. Three main topics can be extracted from the conducted efforts: reducing the specific energy consumption (SEC), boosting the freshwater yield, and selecting a proper brine disposal method. Despite the tied relation between these topics, they have been separately reviewed in previous review works. Therefore, the current review aimed to comprehensively merge the recent investigations of RO plants. The review focused on the solar-powered (PV and ORC-based) RO plants, which have low SEC:. Besides, different preheating techniques were presented, in which heat is recovered from various thermal processes: PV cooling unit, HDH, and ORC. Finally, the most crucial brine disposal topic was intensively handled through comprehensive discussions and comparisons between various conventional and developed methods. Accordingly, results and related comparisons were presented, figured out, and tabulated throughout the manuscript.

2. Solar-powered RO desalination plants

Throughout the literature study, it is found that the PV and solar thermal power systems are the most used technologies for driving the RO desalination plants. The solar-driven RO units are discussed in the following subsections:

2.1. PV-driven RO desalination systems

An experimental study on a low capacity PV-RO battery-based with a freshwater capacity of 0.8–3 m^3/day was conducted by Herold and Neskakis [42]. The SEC was 15 kWh/m^3 when feed pressure of 63 bar was applied. Their system also succeeded in producing freshwater with TDS less than 500 ppm that fulfilled the world health organization (WHO) quality recommendation. They recommended that feed water should be preheated up to 45 °C to increase the system yield. Although they introduced an interesting experimental study, their results were poor from the economic analysis side. The economic analysis was further analyzed in an experimental study presented by Mohamed et al. [43] for two cases of the PV-RO: with and without batteries. Although the SEC decreased when the system was tested with batteries, the cost increased from 7.5 to 8.3 €/m^3 due to the high capital and replacement cost. Table 1 summarizes the recently studied PV-RO desalination systems. As presented, for experimental works (the real reliable results), PV-RO systems have high SEC (2.6–4.6 kWh/m^3), whereas freshwater costs 7.8–8.3 €/m^3. This cost is considered very low compared to other solar desalination systems, such as humidification-dehumidification (HDH) (112$/m^3) [44] and solar still (166 $/m^3) [45], respectively.

Techno-economic analysis of a large-scale PV-RO desalination plant was introduced by Kettani and Bandelier [46]. They found that for a plant capacity of 275,000 m^3/day, the freshwater cost was about 1 $/m^3. According to Monnot et al. [47], the cost of produced water may drop from 2.9 to 0.6 $/m^3 when the plant capacity is increased from 1 to 20 m^3/day.

Recently, a feasibility study was conducted by Rahimi et al. [48] for the PV-RO plant considering two cases of the PV were considered: on-grid and off-grid. The results revealed that the freshwater cost 0.76 and 4 $/m^3 for the on-grid, and off-grid cases, respectively. Ajiwiguna et al. [49] optimized a battery-less PV-RO desalination plant. The resulted freshwater cost, according to that analysis, ranged from 1.74 to 2.59 $/m^3 with cost superiority of the on-grid system.

2.2. Solar organic Rankine cycle (ORC)-driven RO plants

The working principle of a steam cycle and organic Rankine cycle (ORC) do not differ much except the working fluid used in the system. The ORC uses an organic fluid, while the steam cycle uses water as a working fluid. Commonly, the simple ORC consists of a proper heating system, followed by an expansion turbine to transform the low-grade energy to work. Then, the working fluid is condensed in a condenser, and finally, the condensed working fluid is pumped again to the solar heating system to repeat the cycle. The advancements in ORC are progressed through applications in the field of thermoelectric generators, fuel cells, microturbines, seawater desalination systems, Brayton cycles, and cascade systems. Particularly, the hybrid ORC-RO system is an economic and eco-friendly technique to produce freshwater depending on low-grade thermal energy sources. Therefore, many investigations were conducted on RO desalination plants powered via gained power from solar ORC's expansion turbine, as summarized in Table 2. As shown, the majority of the related works are theoretical, except for one experimental work Manolakos et al. [50], whose cost analysis was conducted by Manolakos et al. [51]. According to these experiments, at a low plant capacity of 0.3 m^3/day, the freshwater obtained from solar ORC-RO costed 7.77 €/m^3, whereas it costed 12.53 €/m^3 in the case of PV-RO (Table 1). For high-capacity plants, theoretical results showed that low costs could be achieved, as noticed in the table.

3. RO feed water preheating techniques

Preheating of brackish water increases the flux through the membrane leading to a decrement in the operating pressure. Subsequently, the energy consumption decreases, as shown in Fig. 1. As noticed, increasing inlet water temperature from 5 to 30 °C and from 25 to 35 °C

Table 1
Summary of some recent PV-RO systems.

Ref.	Type of study	Type of water	Use of batteries	Capacity	SECkWh/ m^3	Cost/m^3
Herold and Neskakis [42]	Experimental	Sea	Batteries were used	0.8–3 m^3/day	15–16.3	–
Alghoul et al. [52]	Theoretical	Brackish	Batteries were used	5.1 m^3/day	1.1	–
Mohamed et al. [43]	Experimental	Sea	Batteries were used	0.6 m^3/day	4.3	8.3 €/m^3
Mohamed et al. [43]	Experimental	Sea	Battery-less	0.35 m^3/day	4.6	7.8 €/m^3
Manolakos et al. [51]	Experimental	Sea	Battery-less	0.1 m^3/h	3.8–6	7.77 €/m^3
Thomson and Infield [53]	Theoretical	Sea	Battery-less	3 m^3/day	3.5	2.8 \$/m^3
Kumarasamy et al. [54]	Theoretical	Sea	Battery-less	2.4–6 m^3/day	–	–
Helal et al. [55]	Theoretical	Sea	Battery-less	20 m^3/day	7.33	7.34 \$/m^3
Jones et al. [56]	Theoretical	Sea, Brackish	Battery-less	13–63 m^3/day	6.9–10.5	0.7–1.55 \$/m^3
Soric et al. [57]	Experimental	Sea	Battery-less	0.84 (140 l/h)	2.6	–
Vyas et al. [58]	Experimental	Brackish	Battery-less	2.88 (480 l/h)	–	–
Kelley and Dubowsky [26]	Experimental	Sea	Battery-less, feedwater preheating	0.3–0.45 m^3/day	–	–
Alsheghri et al. [59]	Theoretical	Sea	PV connected to grid	200 m^3/day	6.99	0.825 \$/m^3
Kettani and Bandelier [46]	Theoretical	Sea	several cases including battery and on grid	275000 m^3/day		1 \$/m^3
Monnot et al. [47]	Theoretical	Sea	Battery-less	1–20 m^3/day	2.4–2.9	0.6–2.6 \$/m^3
Rahimi et al. [48]	Theoretical	Sea	On-grid Off-grid	2000 m^3/day	3.4–5.5	0.76 \$/m^3 4 \$/m^3
Ajiwiguna et al. [49]	Theoretical	Sea	Battery-less	1000 m^3/day	2.4	1.74 to 2.59 (\$/m^3)

Table 2
Summary of some recent solar ORC-RO plants.

Ref.	Typeof study	Type of water	Capacity	Cost/m^3
García-Rodríguez and Delgado-Torres [60]	Theoretical			–
Delgado-Torres et al. [61]	Theoretical		0.11 m^3/h	–
Nafey and Sharaf [62]	Theoretical	seawater (TDS = 45000 ppm)	145.8 m^3 /h	–
Bruno et al. [63]	Theoretical	Seawater	15 m^3/day	4.32–9.54 €/ m^3
		Brackish water		2.03–3.31 €/ m^3
Ibarra et al. [64]	Theoretical		7.2 (1.2 m^3/h)	
Kosmadakis et al. [65]	Theoretical			6.38 (\$/m^3)
Penate and Garcia-Rodriguez [66]	Theoretical	Seawater	2500 (m^3 /day)	–
Manolakos et al. [50]	Experimental	Seawater	280 l/h	–
Manolakos et al. [51]	Experimental	Seawater	0.3 m^3/h	12.53 €/m^3
Delgado-Torres and Garcia-Rodriguez [67]	Theoretical	Seawater Brackish water		– –

lead to a decrease in the RO consumed power by 21 and 4 %, respectively. On the other hand, the attained flux increment reduces effluent water quality; however, the TDS of the produced water still lays within the acceptable range for potable water quality. Herein, in the following subsections, the different techniques of brackish water preheating are presented, and related works are reviewed.

3.1. Preheating via organic Rankine cycle (ORC)

As previously mentioned, the first function of ORC is to drive the RO unit via the gained power from the expansion turbine. The second function is preheating the inlet water for the RO system through extracting heat by cooling the ORC working fluid in the condenser. Nafey and Sharaf [62] mathematically studied the energetic, exergetic, and cost-effectiveness of the ORC-RO unit at saturation and superheated operating conditions under Sharm El-Sheikh, Egypt conditions. Different solar heating systems were selected for different organic working fluids based on molecular weight, melting point, boiling temperature and thermal efficiency of the organic working fluid, and the capacity of the solar heating system. R134a, R152a, R245ca, R245fa, Propane, Butane, and Isobutane were tested by applying a flat plate solar collector (FPC) as the solar heating system. While R113, R123, Pentane, and Hexane were studied with a compound parabolic solar concentrator (CPC). In addition, Toluene, Octane, Nonane, and Dodecane were investigated with a parabolic trough solar collector (PTC). Within all collectors, water was used as a working fluid, too. All tested organic working fluids had a T-S diagram with a positive slope to ensure that the turbine outlet was in superheated condition to prevent any possible damage to the turbine due to the presence of liquid. All results were validated with previous literature studies and showed a fair agreement. The cost analysis showed that the cost per cubic meter of the produced water from the proposed system ranged between ~ 0.9 \$ for Toluene with PTC and ~ 0.94 \$ for Butane with FPC. Using water as a working fluid and PTC as a solar heating system showed the second-lowest cost after using Toluene with PTC. Using FPC and CPC, the saturated operating condition had a lower cost than the superheated operating condition because of the changes related to the generated power and the required condenser area. The best performance was achieved using Toluene with PTC at superheated operating conditions. The performance of the system in this best-case was optimized by Nafey et al. [68]. The optimization trials depended on integrating pressure exchanger or Pelton wheel

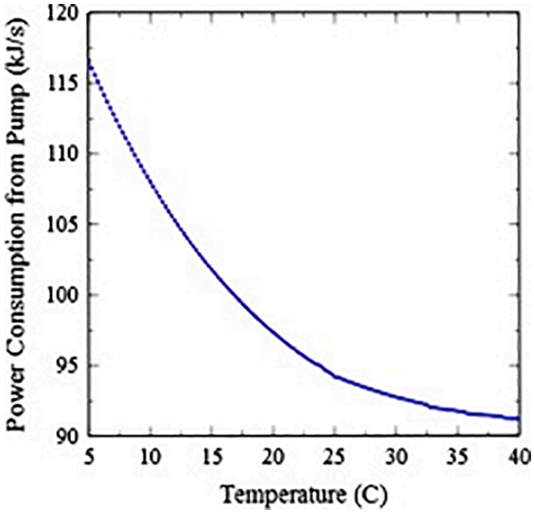


Fig. 1. Variation of power consumption rate with brackish water inlet temperature [24].

turbine to the RO system to recover the power of the rejected brine and reuse it for increasing the pressure of inlet seawater. The ORC-RO system performances using pressure exchanger and Pelton wheel turbine were numerically compared with that of basic RO unit under the same operating conditions exergy, economic, and thermo-economic points of view. The results revealed that integrating pressure exchanger and Pelton wheel turbine to RO system decreased the required PTC area by 65 and 43.5 % and reduced the exergy destruction by 47.6 and 26 %, respectively. The cubic meter of distilled water costed 0.89, 0.57, and 0.68 $ for basic RO, using pressure exchanger, and using Pelton wheel turbine, respectively. Moreover, the findings revealed that the system with a pressure exchanger has the lowest investment, operating, and maintenance costs. Tchanche et al. [69] mathematically studied the effect of changing some ORC parameters on the thermodynamic and exergy performance of the entire hybrid system. An evacuated tube solar collector was used as a heating system that was able to increase the water temperature up to 85 °C that was pumped to the heat exchanger of the ORC evaporator. Different systems were compared, namely: basic ORC and ORC with heat recuperator and regenerative feed liquid heaters (open and closed). In addition, various working fluids were considered within the ORC units: R134a, R245fa, and R600. Moreover, the RO system was integrated with the hydraulic turbine to recover the waste pressure of the rejected brine, and seawater at 25 °C was preheated in the ORC condenser. The obtained exergy efficiencies were 8.07, 8.07, 6.77, and 7 % for ORC, ORC with heat recuperator, ORC with regenerative open feed liquid heater, and ORC with regenerative closed feed liquid heater. Whereas, for the same order, the degrees of thermodynamic perfection were 79.34, 79.16, 83.69, and 83.18 %. Among all working fluids, R600 had the best performance with all investigated ORC systems, except for the exergy efficiency of basic ORC and ORC with heat recuperator that was slightly higher in case of using R134a. Li et al. [24] theoretically proposed and studied the system shown in Fig. 2. As shown, the ORC was driven by low-grade thermal energy sources (less than150 °C); namely: geothermal, solar thermal, and waste heat energies. The same operating conditions were considered for different cases: ORC, conventional ORC with recuperator, and supercritical ORC without recuperator. In addition, various working fluids were proposed: R245fa, R152a, R290, and R32. Within the ORC condenser, the RO feed (sea water) was heated from 25 to 32 °C. Subsequently, the required feed pressure and the pump consumed power were reduced by ~ 2.3 and 2.6 %, respectively. Moreover, the RO unit was integrated with energy recovery device to benefit from high pressure of the waste brine. As reported, using one-through energy source (waste heat or geothermal energies) with supercritical ORC operating by R152a without recuperator had better performance compared to that of recirculating energy source (solar thermal energy) with conventional ORC operating by R245fa and recuperator.

On the other hand, changing the properties of the ORC working fluid may have a vital influence on the performance of the ORC-RO system. Geng et al. [70] carried out a theoretical investigation to figure out the effect of changing the mole fraction of R600/R601 and R600/R601a ORC zeotropic working fluids on ORC performance. Besides, the effect of seawater temperature rise in the ORC condenser on both RO and ORC performances was considered. The ORC evaporator was assumed to be driven by geothermal water at 150 °C. As a result, uplifting the seawater temperature had different influence profiles on ORC output work and efficiency. In other words, the ORC obtained work enhanced with increment in seawater temperature rise till a specified temperature then declined, whereas ORC thermal efficiency continuously increased. The best performance was obtained via (0.9/0.1) R600/R601a as ORC working fluid and setting seawater temperature rise at 27 K, followed by using (0.9/0.1) R600/R601 and seawater temperature rise of 26 K.

In hybrid with Rankine vapor cycle (RVC) as waste recovery system, Lourenco and Carvalho [71] have presented a mathematical study for RO desalination system powered by an internal combustion engine (ICE). Hence, two power sources (ICE + RVC) and seawater preheating systems (ICE radiator + RVC condenser) were proposed. The system was studied from exergy, economic, exergoeconomic, and exergoenvironmental points of view using two different fuel tubes: fossil diesel and soybean biodiesel. The exergy efficiency of the plant reached 6.9 and 6.7 % using fossil diesel and soybean biodiesel fuels in ICE, respectively. Moreover, the estimated costs per one cubic meter of produced freshwater were 1.312 and 2.164 $, for the same order. In other words, the cost of the produced freshwater using soybean biodiesel fuel was higher than that using fossil diesel fuel by ~ 65 %; however, the soybean biodiesel-based system had a 75 % lower environmental impact. It could be claimed the higher environmental impacts might be associated with the production process of both fuels.

3.2. *Preheating via humidification-dehumidification (HDH)*

The traditional humidification-dehumidification (HDH) process consumes a lot of energy, so many improvements have been proposed to increase its effectiveness. One of the possible improvements is making benefit from the rejected brine by recirculating it again in the HDH system or by feeding it to another desalination unit, such as solar still [7] or RO desalination unit. In other meaning, the HDH can be considered as a provider of preheated high salinity brine water for the RO unit. Hence,

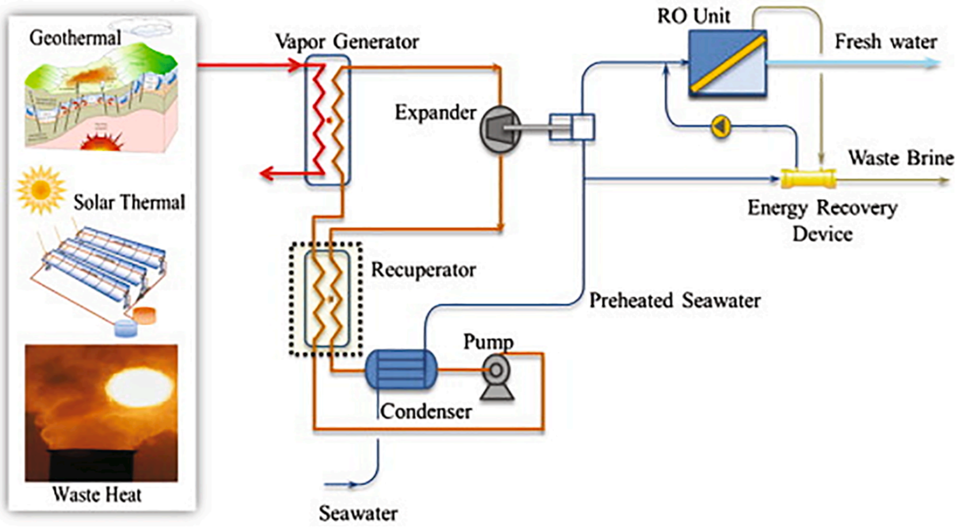


Fig. 2. An ORC-RO system with different thermal energy sources and having recuperator and energy recovery device [24].

besides increasing the freshwater production from the reused brine, the RO working pressure and consumed power can be reduced. Jamil et al. [72] compared the HDH system (with two different configurations of water and air loops) performance with that of HDH hybrid with RO unit (HDH-RO). Three different cases of HDH-RO were proposed: simple, with Pelton turbine, and with pressure exchanger. All systems powered by electrical and solar heaters were evaluated from thermal (energetic and exergetic), and economic points of view. The thermal analysis demonstrated that the best system is the HDH-RO unit having a pressure exchanger, followed by that with Pelton turbine, simple configuration, HDH (closed-water/open-air (CWOA)), and HDH (open-water/open-air (OWOA)). The economic analysis showed that the cubic meter of the produced freshwater costed (6.56 and 2.8 $), and (5.98 and 2.54 $) for HDH (OWOA), and HDH (CWOA), respectively, using (electrical and solar heaters). Whereas for all HDH-RO cases, the cost was approximately the same of 0.13 $/m^3 and 0.12 $/m^3 using electrical, and solar heaters, respectively. Abdelgaied et al. [73] conducted a simulation of a PV-powered HDH-RO system integrated with thermal recovery (PV cooling) units, solar collectors (air and water), and pressure exchanger, shown in Fig. 3. The collectors were used to enhance the performance of the HDH unit, whereas the PV cooling units had dual rules, namely, preheating the HDH water and boosting the PV power gain. The proposed system was able to gain a maximum hourly yield of 192–200 l with SEC ranging between 1.22 and 1.24 kWh/m^3. Narayan et al. [74] proposed an HDH-RO system having the humidifier and the dehumidifier at different pressures. The system was similar to that was described in [75] but by replacing the mechanical compressor with a thermal vapor one, as shown in Fig. 4. As presented, a closed air loop was proposed, which was compressed after the humidification process via propelling steam, then expanded in the expander after the domification process. The RO unit was powered by the work generated from the expander and was fed with the hot rejected brine from HDH. As illustrated in the figure, a small amount of water could be condensed after compression and expansion processes. Theoretical analysis of the proposed system proved its outperformance over the multi-stage flashing (MSF) desalination method in terms of electrical energy consumption and gained output ratio (GOR). The proposed system performance was compared with the MSF method as it is known for great potential for medium-scale seawater desalination using medium pressure steam. The studied system attained electrical energy consumption of 9.5 kWh/m^3 and GOR of 20. Furthermore, a parametric exergy analysis was conducted on this system by Al-Sulaiman et al. [76]. They reported that changing the propelling steam pressure from 1 to 10 MPa led to a decrement in the overall exergy efficiency (from 12 to 10%) and an increment in the total mass of desalinated water (from 6 to 8.8 kg/s). In addition, increasing the compressor pressure ratio (charged steam pressure divided by humid air pressure) from 1.1 to 1.8 led to an increase in overall exergy efficiency (from 9.4 to 11.8 %) and a reduction in productivity (from 8.4 to 7.4 kg/s). Moreover, the efficacy of compressor and expander efficiencies on the exergy efficiency and freshwater production was evaluated. Uplifting the compressor efficiency from 10 to 40% enhanced the overall exergy efficiency and the productivity by 25.6 and 281.5 %, respectively. Whereas increasing expander efficiency from 40 to 90 % could achieve an improvement in

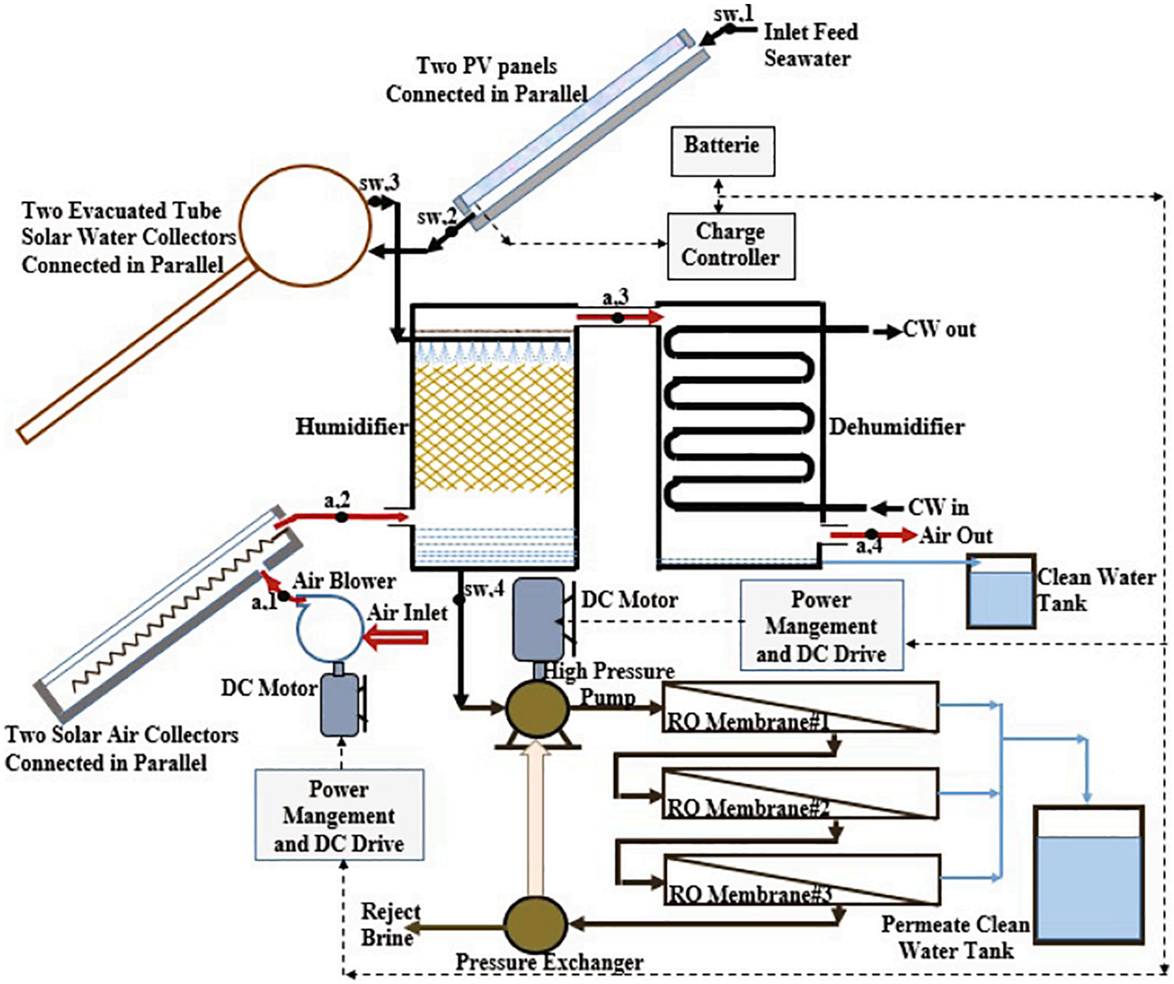


Fig. 3. An PV-powered HDH-RO integrated with thermal recovery units, solar collectors (air and water), and pressure exchanger [73].

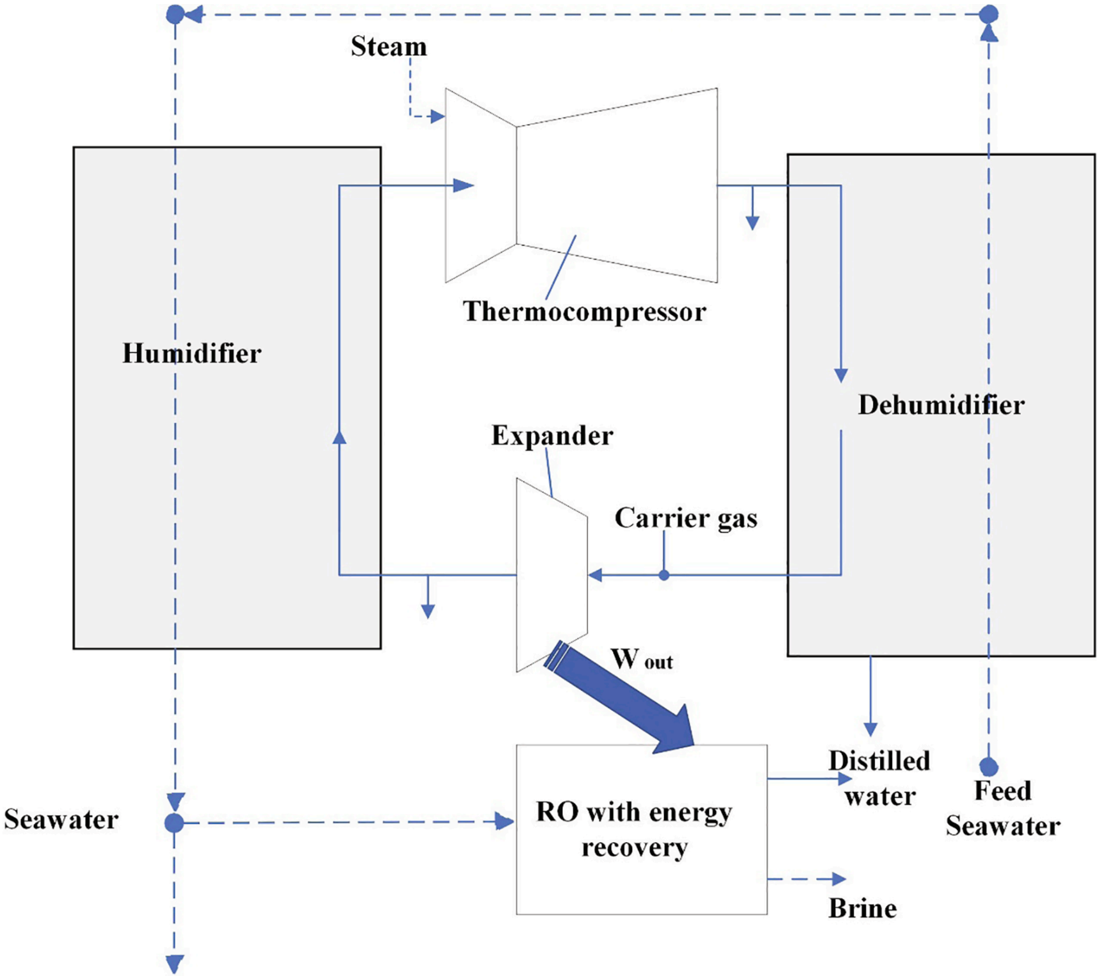


Fig. 4. Hybrid HDH-RO with humidifier/dehumidifier pressure via thermal vapor compressor [74].

exergy from 9.5 to 13.5 % and an enhancement in the production rate by 127.4 %. According to the exergy destruction analysis, the thermal vapor compressor and the dehumidifier were the most exergy destructive components in the system, hence, their design improvement is required.

Kumar et al. [77] introduced a multifunctional (power generation and desalination) hybrid system (ORC + HDH + RO) based on the waste heat from Naval ship engine exhausts, shown in Fig. 5. As noticed, the ORC working fluid (R245fa) was evaporated by the ship engine exhaust (process 5–6 ↔ process 1–2), then expended in the turbine (process 2–3). Some of R245fa was bled from the ORC turbine to heat the seawater before being sprayed in the humidifier of HDH (process 7–8 ↔ process 13–14), then it returned to the ORC condenser through a throttle valve (process 8–9) to be mixed with the remaining part (at state 4). Within the ORC condenser, the seawater is preheated before entering the RO unit (process 3–4 ↔ process 10–11), which was driven by the ORC turbine. The theoretical energy analysis showed that increasing the extraction ratio from the turbine led to a decline in ORC output work and an increase in freshwater yield. Whereas the lower extraction pressure, the higher ORC output work, and yield was obtained. Overall, the proposed system was able to produce output power and yield of 16.74 kW and 75.18 kg/h, respectively, with an efficiency of 42.1 %.

4. RO brine disposal techniques

Generally, the discharged brine from a desalination process should be reused, treated or disposed due to its environmental impact [78,79]. Especially, the brine rejected from the RO desalination plant is high salinity water containing 85–98 % of total dissolved solids (TDS) [80]. The amount of TDS in the RO brine reaches 70,000 and (6000–20000) ppm in the case of sea [81] and brackish [82] water desalination plants, respectively. Several heavy metals are found in RO brine, such as that reported in Table 3, which represents an analysis of a water desalination plant located in an arid area of Texas, USA [83]. In order to identify the brine disposal technique, the chemical compositions of the brine should be firstly determined. Based on the TDS, calcium, and sulfate contents that cause scaling, the disposal option can be identified as desalination [83,84]. For example, the disposal of the aforementioned Texas plant brine (332 m^3/h) can be considered as an enormous problem, where the conventional methods such as deep well injection and evaporative pond cannot deal with it. So, in similar cases, looking for a novel technology to concentrate the brine is put in the top priorities of the researchers in this field. The following parts introduce and review the related literature of the different brine disposal techniques: conventional and membrane technologies.

4.1. Conventional RO brine disposal techniques

There are many traditional methods of brine disposal, as summarized in Fig. 6; namely, sea or surface bodies of water discharging, deep well injection, land application, evaporation ponds, and conventional crystallizers. The selection of the brine disposal technique mainly depends on the location; for example, discharging into the sea is used for all seawater desalination, while deep well injection is mostly used for inland desalination plants. Besides the location, the quality and volume are also of great importance when selecting the disposal technology.

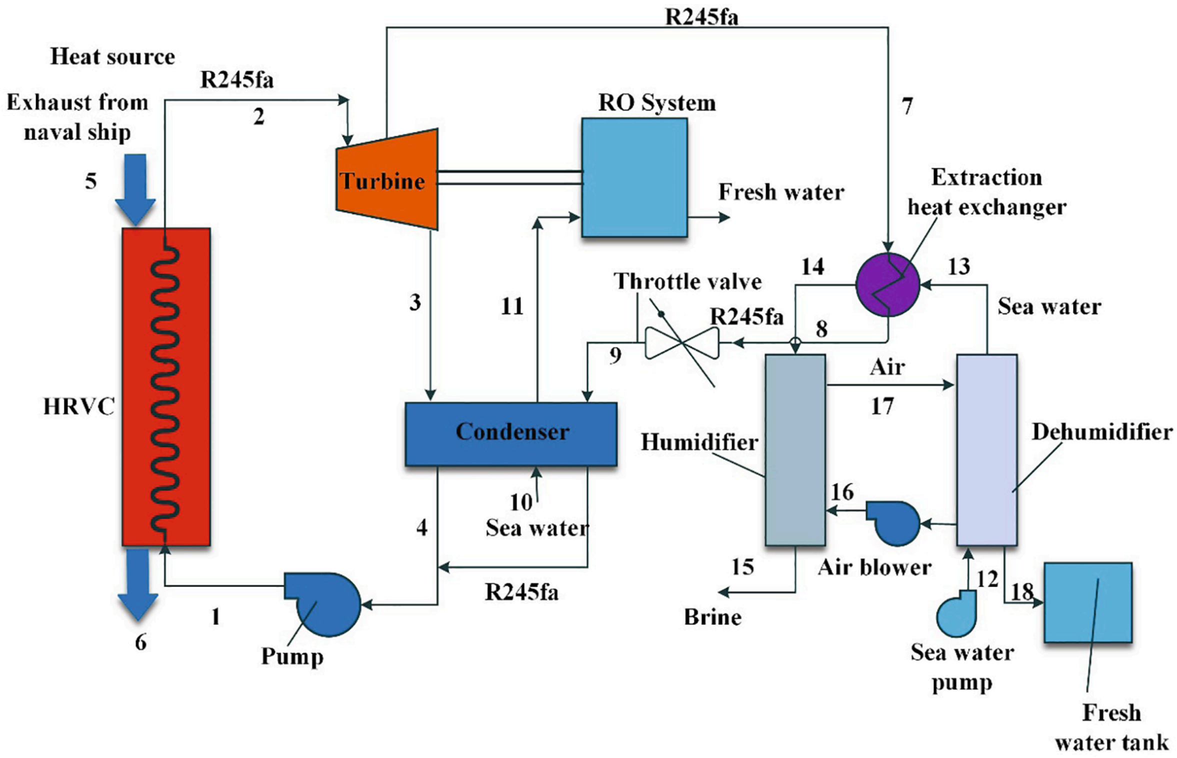


Fig. 5. A multifunctional hybrid system (ORC + HDH + RO) based on the waste heat from Naval ship engine exhausts [77].

Table 3
RO feed water and brine compositions [83]

Component	Feedwater	RO brine
Calcium (mg/l)	**74.6**	497.3
Magnesium (mg/l)	25	166.7
Sodium (mg/l)	279	1860
Potassium (mg/l)	14.7	98
Barium (mg/l)	**0.13**	0.9
Strontium (mg/l)	2.38	15.9
Manganese (mg/l)	0.02	0.1
Bicarbonate (mg/l)	94.4	627
Sulfate (mg/l)	**517**	507
Chloride (mg/l)	517	3447
Fluoride (mg/l)	0.67	4.5
Nitrate (mg/l)	0.6	3.3
Silica (mg/l)	30	200
pH	0.8	8.8
TDS (mg/l)	1120	7465

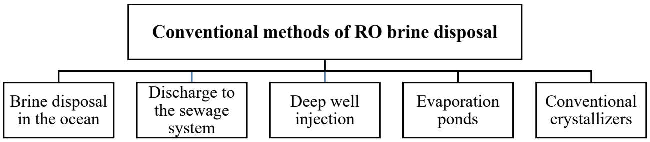


Fig. 6. Conventional methods of RO brine disposal.

Moreover, the cost of brine disposal is also considered; especially, in developing countries.

4.1.1. Brine disposal in the ocean

The brine of most seawater RO desalination plants is directly discharged into the sea, as reported in [85]. This method is considered the cheapest among the available technologies so far. It is used for plants in coastal areas, such as all desalination plants located on the sea in UAE [28] and all medium and high capacity plants located on the Mediterranean and Red seas in Egypt [86,87]. It is very important to evaluate brine composition to identify their impact on the marine ecosystem, which is affected by the high salinity bottom layer. This impact may be avoided by selecting the perfect discharge location, brine dilution and conducting careful monitoring programs [88,89]. These monitoring programs apply repeated observations of discharging location to detect any changes and identify the spatial distribution of brine. Therefore, it is required at least two annual visits to collect samples: the first in summer when low dilution of the brine is expected, and the second in winter at high brine dilution [90]. Torquemada and Lizaso [91] introduced some strategies for monitoring the brine disposal into the sea from the three RO desalination plants located in Spain. They selected seagrasses and echinoderms as bio-indicators due to their high sensitivity to salinity changes. They concluded that no significant effects on the organisms in the area of discharge were detected.

For inland brackish water desalination, discharging the brine to surface water like lakes or rivers is limited by environmental restrictions due to its pollutant components [92].

4.1.2. Discharge to a sewage collection system

Sewage collection system is commonly used for brine disposal of low capacity brackish water RO desalination plants. This technique costs 0.32–0.66$ per cubic meter of RO brine [50]. In this method, the negative impacts of brine TDS on the wastewater treatment plant should be considered [47].

4.1.3. Deep well injection

In the case of remote areas where the sewage collection system is not existing, the RO brine is usually injected into a deep well. This technique is used for some inland RO plants, such as in most inland plants in Egypt [93]. This injection requires reaching the aquifer under the used groundwater layer, and hydraulic isolation should be used to avoid leakage to the used groundwater. So, the geological study of the area should be conducted to identify the perfect well location and depth before drilling [52]. For example, the distance between the suction and injection depth level ranges from 40 to 60 m based on the actual results obtained from several water desalination plants operating in the Western desert, Egypt [94]. This technique faces many limitations, which lead to an increase in the cost; therefore, it is only used when there is no suitable alternative.

4.1.4. RO brine disposal in evaporation ponds

The evaporation ponds are commonly used when the temperature and dryness are high enough for water evaporation during a specific time [55]. In this method, the RO brine is discharged in a shallow evaporation pond, where the brine is directly exposed to solar radiation. The rate of water evaporation, in this case, depends on the ambient temperature and the solar intensity. The residual salts that remain in the pond should be periodically removed. Besides, the ponds should be coated to protect the underground water [56]. The weather conditions, the price of land in the plant location are the key points of selecting this method. The cost of using the evaporation pond for RO brine disposal ranges from 3.28 to 10.04 $ per cubic meter of brine [43]. So, it is considered the highest costly method compared to others.

4.1.5. RO brine disposal via conventional crystallizers

The Conventional crystallizer method is used to recover the valuable components of the RO brine. It is mostly used, in some cases, when the evaporation pond and deep well injection are very expensive regarding the land cost and geographical nature [40]. The mineral recovery from RO brine using crystallization technique was evaluated by Mohammadesmaeili et al. [95,96]. They found that high pure $Mg(OH)_2$, $CaCO_3$, and $CaSO_4$ could be gained. Zero liquid discharging can be achieved by combining evaporation and crystallization [97]. It has also been found that NaCl, $CaCO_3$, Na_2SO_4, and CaCl can be recovered at a fair cost [98]. In the USA, 45 million tons of salts can be recovered via the crystallization method [81]. Finally, in some cases, the RO brine can be appropriate to some land applications such as vegetation in parks and grass irrigation [94].

4.2. RO brine disposal using membrane technologies

4.2.1. Forward osmosis (FO)

Forward osmosis (FO) technology can be a dual-function technique: desalination and brine disposal. It contains a high concentration solution (draw solution) on one side of a semipermeable membrane, which generates an osmotic pressure gradient across the membrane; therefore, freshwater can be extracted from the other side solution (such as seawater or brine). The FO features cost-effective and low power consumption compared to conventional technologies as it depends on natural osmosis [35,99]. In addition, it has lower fouling effects than that of pressure-driven processes, such as RO, and ultra, micro, and nanofiltration (NF) [100-103]. FO has shown good potential for RO brine disposal, as proved by many investigations [104-106]. It can achieve water recovery of 90% from RO brine, as reported by Martinetti et al. [107]. It also has good treatment ability with water recovery factor reaches 60% from high salinity water of TDS ranging from 70,000 to 225,000 mg/L [108]. On the other hand, the recovery factor may depend on the draw solution and membrane type. McGinnis et al. [109] experimentally achieved a recovery factor of $> 60\%$ using NH_3/ CO_2, as a draw solution in FO unit, to treat the high salinity water such as produced water from shale gas exploration and RO brine. Additionally, using cellulose triacetate membrane and draw solution consists of 26% NaCl can obtain a recovery factor of 50% [110]. Nevertheless, despite all advantages of FO-based RO brine disposal, scaling is still an enormous problem facing this technology [106], and its applicability in large-scale plants is still limited [35].

4.2.2. Membrane distillation (MD)

The overview of the membrane distillation (MD) principle and operation is presented in [111]. As reported, MD is a process that follows the vapor–liquid equilibrium principle, in which only volatile elements can be transferred across a membrane with hydrophobic nature [112,113]. It works based on the presence of a partial pressure difference of a solution contacting one side of a porous hydrophobic membrane [114]. The evaporation process occurs in case of a positive pressure difference between the solution and condensate sides. Subsequently, the vapor crosses the membrane to the cold side and condensates [35,107,113,115]. There are many MD techniques that can be defined according to the media across the membrane sides. On the one hand, if hot brine flows on one side and a colder distillate stream flows on the other side, the technique is called direct contact MD (DCMD). In this type, the vapor diffuses through the membrane, which repels the liquid, then the vapor condenses [114], and the vapor pressure can be increased, and the vapor generation can be enhanced by increasing the feedwater temperature [116]. On the other hand, when the pressure difference is obtained via applying vacuum or low pressure on the other side of a microporous membrane, the technology is called vacuum MD (VMD). In VMD, the salt of a salty feed solution remains in the feed side, whereas the vapor passes through the membrane pores [117]. Generally, the RO brine concentration via MD features for the need of medium operating temperature 60–90 °C [118], hence, it can be powered by solar or geothermal energy [119]. Unfortunately, MD yield is low compared to RO, and this is the main drawback [119]. Therefore, many investigations have been conducted to enhance the MD yield besides enhancing its ability to concentrate RO brine. These attempts include trying different types and configurations of the membrane, integrating nanomaterials, and using hybrid systems. On the one hand, MD permeate can be enhanced via many polymers used in membranes manufacturing, such as polypropylene (PP), polytetrafluoroethylene (PTFE), polyacrylonitrile (PAN), and polyvinylidene fluoride (PVDF) [120,121]. In addition, the RO brine volume can be reduced via a spiral-wound MD, as reported by Duong et al. [31]. In this study, the RO brine was firstly heated to 55 °C using solar heaters before it flowed through the MD. The utilized MD had the characteristics presented in Table 4. The required thermal energy was provided to MD via one ha of flat plate solar collectors to treat 118 m^3/day of RO brine. The RO brine composition is compared with that after MD treatment and presented in Table 5. From the ion concentration analyses, the TDS was concentrated by 6.1 times. The concentrations of sodium, bicarbonate, and chloride were concentrated by 5, 6.9, and 5.8 times, respectively. These high concentration factors show the efficacy of using the MD for reducing the RO brine volume. Moreover, the integration of nanomaterials can enhance the MD characteristics, such as carbon nanotubes, which increase the MD polymer porosity up to 90% and reduce the thermal conductivity [122]. On the other hand, MD can be hybridized with other systems to enhance the water recovery and RO brine concentration. MD can be integrated with crystallization to concentrate the RO brine [118], obtaining high water recovery reaching 90% [39] and up to 95% [123]. Additionally, MD can be hybridized with NF and RO, and the hybrid system can reduce the SEC using low-grade thermal energy was from 13 to 2.6 kWh/m^3 as reported by Criscuoli and Drioli [124]. In addition, the

Table 4
Characteristics of the MD [31].

Type	Spiral wound air gap membrane distillation
Total net membrane surface area (m^2)	7.2
Diameter of the module (m)	0.4
Height of the module (m)	0.5
Length of the envelope (m)	1.5
Width of envelope (m)	0.4
Thickness of flow channels (mm)	2
Membrane material	Low-density polyethylene
Pore size (μm)	0.3
Thickness (μm)	76
Porosity (%)	85

Table 5
The characteristics of RO, MD brines [31].

Parameter	RO brine	MD brine	Concentration factor
Conductivity (mS/cm)	21.8	82.1	4
TDS (ppm)	14,100	86,100	6.1
PH	8.2	8.2	–
Sodium (mg/l)	6840	34,200	5
Bicarbonate	4740	32,800	6.9
Chloride	5540	31,800	5.8
Magnesium	17	74	4.4
Potassium	32	146	4.6
Calcium	14	34	2.4
Silica	75	170	2

NF water recovery can be increased from 64% to 95% when MD integrated with crystallizer was used [125].

Furthermore, the VMD can be used to reduce the RO brine volume with a high recovery factor reaching 89% [117]. Moreover, the vacuum-enhanced DCMD has the ability to enhance the yield and reduce the RO brine with water recovery up to 81% [107]. Additionally, a multi-effect VMD technique was studied by Janson et al. [126] to concentrate the RO brine and improve the productivity, as shown in Fig. 7. The presented series connection of membranes reduced the overall energy consumption benefits from the heat released from the condensation and transferred back to the feed within the modules.

4.3. RO brine disposal via second RO stage

The RO brine concentrating can be accomplished via a second RO stage [127-130], in which water recovery (>95%) can be achieved [35]. In addition, zero liquid discharge desalination can be achieved by treating the second RO brine using thermal technologies. In this technique, ion exchange and degasification of the first stage RO brine is used before the second stage RO. The degasification allows the buffering effect removal from CO_2 to reduce caustic demand in the second stage of RO. As reported by Cob et al. [131], the overall water recovery of 98% was achieved when ion exchange was used. As mentioned by Thiel et al. [132], two obstacles appeared when the second stage of RO was used. On the one hand, very high pressure was required as the applied pressure must be over the brine's osmotic pressure. However, it should be kept in mind that the RO membranes rated endurable pressure range is 69–83 bar [133-135]. On the other hand, the pretreatment required a high cost.

4.4. RO brine disposal via HDH

Recently, an HDH unit was experimentally studied by Shalaby et al. [44] to concentrate the extremely saline water such as RO brine. The water of extreme salinity with TDS equals 100000 ppm was prepared and warmed up via both solar and electrical heaters of total power 8 kW. In this investigation, the system could produce a freshwater amount of 72 kg/day when the feedwater was heated to 85 °C. They expected that their system could be commercialized for concentrating the RO brine with some improvements in the solar field. These improvements include using a PTC and a suitable energy storage system. Finally, Thiel et al. [132] compared the SEC of the different techniques (FO, MD, HDH, two stages of RO) used for the treatment of high salinity water, such as RO brine and the obtained water from shale oil and gas extraction. They found that the FO could operate at high salinities [109] with lower fouling compared to RO [102]. On the other hand, the SEC of FO was very high (25–150 kWh/m^3) compared to that of two stages RO (4–16 kWh/m^3) [132]. Moreover, high efficiency of evaporative systems, such as HDH, can be achieved at higher feed salinities [44,132].

5. Conclusions

Along with the importance of reverse osmosis (RO) desalination plants, this paper aimed to comprehensively review recent studies conducted on and RO plants performance enhancement. The reported studies were categorized according to three related topics: solar-based driving power, feedwater preheating systems, and brine disposal and concentration. The survey focuses on different performance evaluation parameters, namely: the SEC, produced water cost, energy and exergy efficiencies, system design, water recovery ratios, and water quality. According to the literature review, the following outlines can be drawn:

- Compared to thermal solar-based desalination units, the PV-RO plants have low production costs (7.8–8.3 €/m^3), despite their high SEC (2.6–4.6 kWh/m^3). In addition, for large-capacity plants, the freshwater cost can be reduced to 0.6 – 1$/$m^3$.
- For the same plant capacity, the solar ORC-RO system has low production cost than that of PV-RO.
- Increasing the feedwater temperature by about 25 °C can reduce the power consumption by ~ 21%.
- For ORC-RO systems, the selection of low-grade thermal energy sources depends on the type of organic working fluid. Besides, the

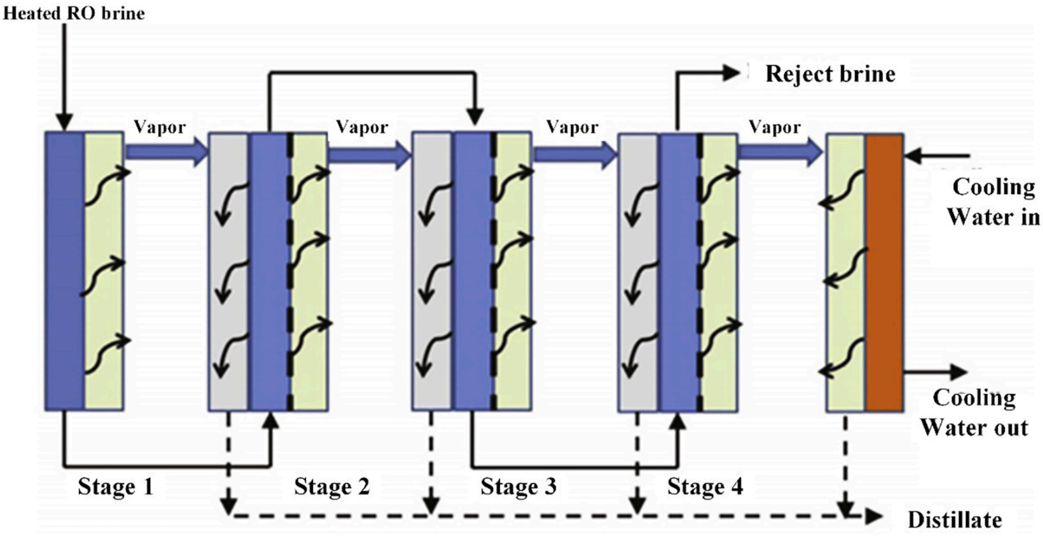


Fig. 7. Schematic diagram of RO brine disposal using multi-effect VMD [126].

integration of pressure exchanger and Pelton wheel turbine help on reducing the energy source area and the exergy destruction.

- For HDH-RO systems, integrating pressure exchangers may be more preferred than Pelton wheel turbine from the thermal analysis point of view. However, the produced freshwater cost may be in close range for all HDH-RO systems. In addition, utilization of variable pressure-subjected HDH unit can enhance the overall performance of the HDH-RO system, especially with improved compressor and expander efficiencies.
- A Hybrid (RO + ORC + HDH) plant can obtain output work and yield of 16.74 kW and 75.18 kg/h, respectively, with an efficiency of 42.1 %.
- The selection of proper brine disposal method mainly depends on the location and also the feed water type. Besides, periodic monitoring programs should be designed, especially for the techniques that have a negative impact on the ecosystem.
- The forward osmosis (FO) has good potential for RO brine disposal with a high water recovery of up to 90%. In addition, in the case of RO brine with extreme salinity (70,000 to 225,000 mg/L), the recovery ratio can reach 60%.
- Using a second RO stage has the lowest SEC compared with other water desalination technology used for concentrating the RO brine; nevertheless, it is limited by the rated pressure of the membrane. In addition, the FO and MD showed promising potential in concentrating the RO brine. But these technologies still in the research stage and have not been implemented on a large scale yet.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This paper is based upon work supported by Science, Technology & Innovation Funding Authority (STIFA), Egypt and China, under grant (40517). Also, the work was sponsored by National Natural Science Foundation of China (51950410592), National Key Research and Development Project of China (2018YFE0127800) and Fundamental Research Funds for the Central Universities (2019kfyRCPY045). The authors thank the National Supercomputing Center in Tianjin (NSCC-TJ) and China Scientific Computing Grid (ScGrid) for providing assistance in computations.

References

[1] Kandeal AW, An M, Chen X, Algazzar AM, Kumar Thakur A, Guan X, et al. Productivity Modeling Enhancement of a Solar Desalination Unit with Nanofluids Using Machine Learning Algorithms Integrated with Bayesian. Optimization 2021;9:2100189.

[2] Sharshir SW, Hamada MA, Kandeal AW, El-Said EMS, Mimi Elsaid A, Rashad M, et al. Augmented performance of tubular solar still integrated with cost-effective nano-based mushrooms. Sol Energy 2021;228:27–37.

[3] Sharshir SW, Ismail M, Kandeal AW, Baz FB, Eldesoukey A, Younes MM. Improving thermal, economic, and environmental performance of solar still using floating coal, cotton fabric, and carbon black nanoparticles. Sustainable Energy Technol Assess 2021;48:101563.

[4] Abdelaziz GB, Algazzar AM, El-Said EMS, Elsaid AM, Sharshir SW, Kabeel AE, et al. Performance enhancement of tubular solar still using nano-enhanced energy storage material integrated with v-corrugated aluminum basin, wick, and nanofluid. J Storage Mater 2021;41:102933.

[5] Sharshir SW, Peng G, Yang N, El-Samadony MOA, Kabeel AE. A continuous desalination system using humidification – dehumidification and a solar still with an evacuated solar water heater. Appl Therm Eng 2016;104:734–42.

[6] Kabeel AE, Hamed MH, Omara ZM, Sharshir SW. Experimental study of a humidification-dehumidification solar technique by natural and forced air circulation. Energy 2014;68:218–28.

[7] Sharshir SW, Peng G, Yang N, Eltawil MA, Ali MKA, Kabeel AE. A hybrid desalination system using humidification-dehumidification and solar stills integrated with evacuated solar water heater. Energy Convers Manage 2016;124:287–96.

[8] Hamed MH, Kabeel AE, Omara ZM, Sharshir SW. Mathematical and experimental investigation of a solar humidification–dehumidification desalination unit. Desalination 2015;358:9–17.

[9] Sharshir SW, Salman M, El-Behery SM, Halim MA, Abdelaziz GB. Enhancement of solar still performance via wet wick, different aspect ratios, cover cooling, and reflectors. Int J Energy Environ Eng 2021;12:517–30.

[10] Kandeal AW, El-Shafai NM, Abdo MR, Thakur AK, El-Mehasseb IM, Maher I, et al. Improved thermo-economic performance of solar desalination via copper chips, nanofluid, and nano-based phase change material. Sol Energy 2021;224:1313–25.

[11] Peng G, Sharshir SW, Wang Y, An M, Ma D, Zang J, et al. Potential and challenges of improving solar still by micro/nano-particles and porous materials - A review. J Cleaner Prod 2021;311:127432.

[12] Sharshir SW, Ellakany YM, Algazzar AM, Elsheikh AH, Elkadeem MR, Edreis EMA, et al. A mini review of techniques used to improve the tubular solar still performance for solar water desalination. Process Saf Environ Prot 2019;124:204–12.

[13] Kabeel, A.E. Hamed, M.H. Omara, Z.M. Sharshir, S.W. Water Desalination Using a Humidification-Dehumidification Technique¡ªA Detailed Review %. J Nat Resour, Vol.04, No.03; 2013. 20.

[14] Honarparvar, S. Zhang, X. Chen, T. Alborzi, A. Afroz, K. Reible, D. Frontiers of Membrane Desalination Processes for Brackish Water Treatment: A Review, 11; 2021, 246.

[15] Greenlee LF, Lawler DF, Freeman BD, Marrot B, Moulin P. Reverse osmosis desalination: water sources, technology, and today's challenges. Water Res 2009;43:2317–48.

[16] R.F. Service. Desalination Freshens Up. Science 2006;313:1088–90.

[17] Suo Y, Ren Y. Research on the mechanism of nanofiltration membrane fouling in zero discharge process of high salty wastewater from coal chemical industry. Chem Eng Sci 2021;245:116810.

[18] Matshetshe K, Sikhwivhilu K, Ndlovu G, Tetyana P, Moloto N, Tetana Z. Antifouling and antibacterial β-cyclodextrin decorated graphene oxide/polyamide thin-film nanocomposite reverse osmosis membranes for desalination applications. Sep Purif Technol 2022;278:119594.

[19] Yang H, He C, Fu L, Huo J, Zhao C, Li X, et al. Capture and separation of CO2 on BC3 nanosheets: A DFT study. Chin Chem Lett 2021.

[20] Wang J, Li S-L, Guan Y, Zhu C, Gong G, Hu Y. Novel RO membranes fabricated by grafting sulfonamide group: Improving water permeability, fouling resistance and chlorine resistant performance. J Membr Sci 2022;641:119919.

[21] Burn S, Hoang M, Zarzo D, Olewniak F, Campos E, Bolto B, et al. Desalination techniques — A review of the opportunities for desalination in agriculture. Desalination 2015;364:2–16.

[22] Ahmed FE, Hashaikeh R, Hilal N. Solar powered desalination – Technology, energy and future outlook. Desalination 2019;453:54–76.

[23] Abdelkareem MA, El Haj Assad M, Sayed ET, Soudan B. Recent progress in the use of renewable energy sources to power water desalination plants. Desalination 2018;435:97–113.

[24] Li C, Besarati S, Goswami Y, Stefanakos E, Chen H. Reverse osmosis desalination driven by low temperature supercritical organic rankine cycle. Appl Energy 2013;102:1071–80.

[25] Lin S, Yip NY, Elimelech M. Direct contact membrane distillation with heat recovery: Thermodynamic insights from module scale modeling. J Membr Sci 2014;453:498–515.

[26] Kelley LC, Dubowsky S. Thermal control to maximize photovoltaic powered reverse osmosis desalination systems productivity. Desalination 2013;314:10–9.

[27] Delgado-Torres AM, García-Rodríguez L. Design recommendations for solar organic Rankine cycle (ORC)–powered reverse osmosis (RO) desalination. Renew Sustain Energy Rev 2012;16:44–53.

[28] Ahmed M, Shayya WH, Hoey D, Al-Handaly J. Brine disposal from reverse osmosis desalination plants in Oman and the United Arab Emirates. Desalination 2001;133:135–47.

[29] Arnal JM, Sancho M, Iborra I, Gozálvez JM, Santafé A, Lora J. Concentration of brines from RO desalination plants by natural evaporation. Desalination 2005;182:435–9.

[30] Malaeb L, Ayoub GM. Reverse osmosis technology for water treatment: State of the art review. Desalination 2011;267(1):1–8.

[31] Duong HC, Chivas AR, Nelemans B, Duke M, Gray S, Cath TY, et al. Treatment of RO brine from CSG produced water by spiral-wound air gap membrane distillation — A pilot study. Desalination 2015;366:121–9.

[32] Fu L, Wang R, Zhao C, Huo J, He C, Kim K-H, et al. Construction of Cr-embedded graphyne electrocatalyst for highly selective reduction of CO2 to CH4: A DFT study. Chem Eng J 2021;414:128857. https://doi.org/10.1016/j.cej.2021.128857.

[33] Shalaby SM. Reverse osmosis desalination powered by photovoltaic and solar Rankine cycle power systems: A review. Renew Sustain Energy Rev 2017;73:789–97.

[34] Mito MT, Ma X, Albuflasa H, Davies PA. Reverse osmosis (RO) membrane desalination driven by wind and solar photovoltaic (PV) energy: State of the art and challenges for large-scale implementation. Renew Sustain Energy Rev 2019;112:669–85.

[35] Subramani A, Jacangelo JG. Treatment technologies for reverse osmosis concentrate volume minimization: A review. Sep Purif Technol 2014;122:472–89.

[36] Pramanik B, Shu L, Jegatheesan V. A review on the management and treatment of brine solutions. Environ Sci Water Res Technol 2017;3.

[37] Drioli E, Laganà F, Criscuoli A, Barbieri G. Integrated membrane operations in desalination processes. Desalination 1999;122(2-3):141–5.

[38] Adham S, Hussain A, Matar JM, Dores R, Janson A. Application of Membrane Distillation for desalting brines from thermal desalination plants. Desalination 2013;314:101–8.

[39] Ji X, Curcio E, Al Obaidani S, Di Profio G, Fontananova E, Drioli E. Membrane distillation-crystallization of seawater reverse osmosis brines. Sep Purif Technol 2010;71(1):76–82.

[40] Mericq J-P, Laborie S, Cabassud C. Vacuum membrane distillation for an integrated seawater desalination process. Desalin Water Treat 2009;9(1-3):287–96.

[41] Li X-M, Zhao B, Wang Z, Xie M, Song J, Nghiem LD, et al. Water reclamation from shale gas drilling flow-back fluid using a novel forward osmosis–vacuum membrane distillation hybrid system. Water Sci Technol 2014;69:1036–44.

[42] Herold D, Neskakis A. A small PV-driven reverse osmosis desalination plant on the island of Gran Canaria. Desalination 2001;137:285–92.

[43] Mohamed ES, Papadakis G, Mathioulakis E, Belessiotis V. A direct coupled photovoltaic seawater reverse osmosis desalination system toward battery based systems — a technical and economical experimental comparative study. Desalination 2008;221:17–22.

[44] Shalaby SM, Kabeel AE, Moharram BM, Fleafl AH. Experimental study of hybrid solar humidification dehumidification system for extremely saline water desalination. Energy Convers Manage 2021;235:114021.

[45] El-Bialy E, Shalaby S, Kabeel A, Fathy A. Cost analysis for several solar desalination systems. Desalination 2016;384:12–30.

[46] Kettani M, Bandelier P. Techno-economic assessment of solar energy coupling with large-scale desalination plant: The case of Morocco. Desalination 2020;494:114627. https://doi.org/10.1016/j.desal.2020.114627.

[47] Monnot M, Carvajal GDM, Laborie S, Cabassud C, Lebrun R. Integrated approach in eco-design strategy for small RO desalination plants powered by photovoltaic energy. Desalination 2018;435:246–58.

[48] Rahimi B, Shirvani H, Alamolhoda AA, Farhadi F, Karimi M. A feasibility study of solar-powered reverse osmosis processes. Desalination 2021;500:114885.

[49] Ajiwiguna TA, Lee G-R, Lim B-J, Cho S-H, Park C-D. Optimization of battery-less PV-RO system with seasonal water storage tank. Desalination 2021;503:114934.

[50] Manolakos D, Kosmadakis G, Kyritsis S, Papadakis G. On site experimental evaluation of a low-temperature solar organic Rankine cycle system for RO desalination. Sol Energy 2009;83:646–56.

[51] Manolakos D, Mohamed ES, Karagiannis I, Papadakis G. Technical and economic comparison between PV-RO system and RO-Solar Rankine system. Case study: Thirasia island. Desalination 2008;221(1-3):37–46.

[52] Alghoul MA, Poovanaesvaran P, Mohammed MH, Fadhil AM, Muftah AF, Alkilani MM, et al. Design and experimental performance of brackish water reverse osmosis desalination unit powered by 2 kW photovoltaic system. Renewable Energy 2016;93:101–14.

[53] Thomson M, Infield D. A photovoltaic-powered seawater reverse-osmosis system without batteries. Desalination 2003;153:1–8.

[54] Kumarasamy S, Narasimhan S, Narasimhan S. Optimal operation of battery-less solar powered reverse osmosis plant for desalination. Desalination 2015;375:89–99.

[55] Helal AM, Al-Malek SA, Al-Katheeri ES. Economic feasibility of alternative designs of a PV-RO desalination unit for remote areas in the United Arab Emirates. Desalination 2008;221:1–16.

[56] Jones MA, Odeh I, Haddad M, Mohammad AH, Quinn JC. Economic analysis of photovoltaic (PV) powered water pumping and desalination without energy storage for agriculture. Desalination 2016;387:35–45.

[57] Soric A, Cesaro R, Perez P, Guiol E, Moulin P. Eausmose project desalination by reverse osmosis and batteryless solar energy: Design for a 1m3 per day delivery. Desalination 2012;301:67–74.

[58] Vyas H, Suthar K, Chauhan M, Jani R, Bapat P, Patel P, et al. Modus operandi for maximizing energy efficiency and increasing permeate flux of community scale solar powered reverse osmosis systems. Energy Convers Manage 2015;103:94–103.

[59] Alsheghri A, Sharief SA, Rabbani S, Aitzhan NZ. Design and Cost Analysis of a Solar Photovoltaic Powered Reverse Osmosis Plant for Masdar Institute. Energy Procedia 2015;75:319–24.

[60] García-Rodríguez L, Delgado-Torres AM. Solar-powered Rankine cycles for fresh water production. Desalination 2007;212:319–27.

[61] Delgado-Torres AM, García-Rodríguez L, Romero-Ternero VJ. Preliminary design of a solar thermal-powered seawater reverse osmosis system. Desalination 2007;216:292–305.

[62] Nafey AS, Sharaf MA. Combined solar organic Rankine cycle with reverse osmosis desalination process: Energy, exergy, and cost evaluations. Renewable Energy 2010;35:2571–80.

[63] Bruno JC, López-Villada J, Letelier E, Romera S, Coronas A. Modelling and optimisation of solar organic rankine cycle engines for reverse osmosis desalination. Appl Therm Eng 2008;28:2212–26.

[64] Ibarra M, Rovira A, Alarcón-Padilla DC, Zaragoza G, Blanco J. Performance of a 5 kWe Solar-only Organic Rankine Unit Coupled to a Reverse Osmosis Plant. Energy Procedia 2014;49:2251–60.

[65] Kosmadakis G, Manolakos D, Papadakis G. Parametric theoretical study of a two-stage solar organic Rankine cycle for RO desalination. Renewable Energy 2010;35:989–96.

[66] Peñate B, García-Rodríguez L. Seawater reverse osmosis desalination driven by a solar Organic Rankine Cycle: Design and technology assessment for medium capacity range. Desalination 2012;284:86–91.

[67] Delgado-Torres AM, García-Rodríguez L. Preliminary design of seawater and brackish water reverse osmosis desalination systems driven by low-temperature solar organic Rankine cycles [ORC]. Energy Convers Manage 2010;51:2913–20.

[68] Nafey AS, Sharaf MA, García-Rodríguez L. Thermo-economic analysis of a combined solar organic Rankine cycle-reverse osmosis desalination process with different energy recovery configurations. Desalination 2010;261:138–47.

[69] Tchanche BF, Lambrinos G, Frangoudakis A, Papadakis G. Exergy analysis of micro-organic Rankine power cycles for a small scale solar driven reverse osmosis desalination system. Appl Energy 2010;87:1295–306.

[70] Geng D, Du Y, Yang R. Performance analysis of an organic Rankine cycle for a reverse osmosis desalination system using zeotropic mixtures. Desalination 2016;381:38–46.

[71] Lourenço AB, Carvalho M. Exergoeconomic and exergoenvironmental analyses of an off-grid reverse osmosis system with internal combustion engine and waste heat recovery. Chem Eng J Adv 2020;4:100056.

[72] Jamil MA, Elmutasim SM, Zubair SM. Exergo-economic analysis of a hybrid humidification dehumidification reverse osmosis (HDH-RO) system operating under different retrofits. Energy Convers Manage 2018;158:286–97.

[73] Abdelgaied M, Kabeel AE, Kandeal AW, Abosheiasha HF, Shalaby SM, Hamed MH, et al. Performance assessment of solar PV-driven hybrid HDH-RO desalination system integrated with energy recovery units and solar collectors: Theoretical approach. Energy Convers Manage 2021;239:114215. https://doi.org/10.1016/j.enconman.2021.114215.

[74] Narayan GP, McGovern RK, Zubair SM, Lienhard JH. High-temperature-steam-driven, varied-pressure, humidification-dehumidification system coupled with reverse osmosis for energy-efficient seawater desalination. Energy 2012;37:482–93.

[75] G.P. Narayan, R.K. McGovern, J.H. Lienhard, S.M. Zubair, Variable pressure humidification dehumidification desalination system, in: ASME/JSME 2011 8th Thermal Engineering Joint Conference, American Society of Mechanical Engineers Digital Collection; 2011.

[76] Al-Sulaiman FA, Prakash Narayan G, Lienhard JH. Exergy analysis of a high-temperature-steam-driven, varied-pressure, humidification–dehumidification system coupled with reverse osmosis. Appl Energy 2013;103:552–61.

[77] Kumar R, Shukla AK, Sharma M, Nandan G. Thermodynamic investigation of water generating system through HDH desalination and RO powered by organic Rankine cycle. Mater Today: Proc 2021;46:5256–61.

[78] Soliman MN, Guen FZ, Ahmed SA, Saleem H, Khalil MJ, Zaidi SJ. Energy consumption and environmental impact assessment of desalination plants and brine disposal strategies. Process Saf Environ Prot 2021;147:589–608.

[79] Panagopoulos A, Haralambous K-J, Loizidou M. Desalination brine disposal methods and treatment technologies - A review. Sci Total Environ 2019;693:133545.

[80] Ersever I, Ravindran V, Pirbazari M. Biological denitrification of reverse osmosis brine concentrates: I. Batch reactor and chemostat studies. J Environ Eng Sci 2007;6:503–18.

[81] Ahmed M, Williams P. Assessment of desalination technologies for high saline brine applications — Discussion Paper, Desalination and Water Treatment. Desalin Water Treat 2011;30:22–36.

[82] Park K, Burlace L, Dhakal N, Mudgal A, Stewart NA, Davies PA. Design, modelling and optimisation of a batch reverse osmosis (RO) desalination system using a free piston for brackish water treatment. Desalination 2020;494:114625.

[83] Ning RY, Tarquin A, Trzcinski M, Patwardhan G. Recovery optimization of RO concentrate from desert wells. Desalination 2006;201:315–22.

[84] Subramani A, Cryer E, Liu L, Lehman S, Ning RY, Jacangelo JG. Impact of intermediate concentrate softening on feed water recovery of reverse osmosis process during treatment of mining contaminated groundwater. Sep Purif Technol 2012;88:138–45.

[85] Katal, R. Teo, Y.S. Jafari, I. Masudy-Panah, S. An Overview on the Treatment and Management of the Desalination Brine Solution, in; 2020.

[86] Kotb KM, Elkadeem MR, Khalil A, Imam SM, Hamada MA, Sharshir SW, et al. A fuzzy decision-making model for optimal design of solar, wind, diesel-based RO desalination integrating flow-battery and pumped-hydro storage: Case study in Baltim, Egypt. Energy Convers Manage 2021;235:113962. https://doi.org/10.1016/j.enconman.2021.113962.

[87] Elmaadawy K, Kotb KM, Elkadeem MR, Sharshir SW, Dán A, Moawad A, et al. Optimal sizing and techno-enviro-economic feasibility assessment of large-scale reverse osmosis desalination powered with hybrid renewable energy sources. Energy Convers Manage 2020;224:113377.

[88] Hoepner T. A procedure for environmental impact assessments (EIA) for seawater desalination plants. Desalination 1999;124:1–12.

[89] Einav R, Harussi K, Perry D. The footprint of the desalination processes on the environment. Desalination 2003;152:141–54.

[90] Eastwood RA, Macdonald RW, Ehn JK, Heath J, Arragutainaq L, Myers PG, et al. Role of River Runoff and Sea Ice Brine Rejection in Controlling Stratification Throughout Winter in Southeast Hudson Bay. Estuaries Coasts 2020;43:756–86.

[91] Torquemada YF, Lizaso JLS. Monitoring of brine discharges from seawater desalination plants in the Mediterranean. Int J Environ Health 2007;1(3):449. https://doi.org/10.1504/IJENVH.2007.017870.

[92] Missimer TM, Maliva RG. Environmental issues in seawater reverse osmosis desalination: Intakes and outfalls. Desalination 2018;434:198–215.

[93] Ali M.E.A. Nanofiltration Process for Enhanced Treatment of RO Brine Discharge 11; 2021, 212.

[94] Esmaeilion F. Hybrid renewable energy systems for desalination. Appl Water Sci 2020;10:84.

[95] Mohammadesmaeili F, Badr MK, Abbaszadegan M, Fox P. Mineral recovery from inland reverse osmosis concentrate using isothermal evaporation. Water Res 2010;44:6021–30.

[96] Mohammadesmaeili, F. Badr M.K., Abbaszadegan M., Fox P., Byproduct Recovery from Reclaimed Water Reverse Osmosis Concentrate Using Lime and Soda-Ash Treatment Water environment research : a research publication of the Water Environment Federation, 82, 4; 2010, 342-350.

[97] Seigworth A, Ludlum R, Reahl E. Case study: Integrating membrane processes with evaporation to achieve economical zero liquid discharge at the Doswell Combined Cycle Facility. Desalination 1995;102:81–6.

[98] Ahmed M, Arakel A, Hoey D, Thumarukudy MR, Goosen MFA, Al-Haddabi M, et al. Feasibility of salt production from inland RO desalination plant reject brine: A case study. Desalination 2003;158(1-3):109–17.

[99] Ng HY, Tang W, Wong WS. Performance of Forward (Direct) Osmosis Process: Membrane Structure and Transport Phenomenon. Environ Sci Technol 2006;40: 2408–13.

[100] Achilli A, Cath TY, Marchand EA, Childress AE. The forward osmosis membrane bioreactor: A low fouling alternative to MBR processes. Desalination 2009;239: 10–21.

[101] Mi B, Elimelech M. Organic fouling of forward osmosis membranes: Fouling reversibility and cleaning without chemical reagents. J Membr Sci 2010;348: 337–45.

[102] Lee S, Boo C, Elimelech M, Hong S. Comparison of fouling behavior in forward osmosis (FO) and reverse osmosis (RO). J Membr Sci 2010;365:34–9.

[103] Wang R, He C, Chen W, Zhao C, Huo J. Rich B active centers in Penta-B2C as high-performance photocatalyst for nitrogen reduction. Chin Chem Lett 2021. https://doi.org/10.1016/j.cclet.2021.05.024.

[104] Tang W, Ng HY. Concentration of brine by forward osmosis: Performance and influence of membrane structure. Desalination 2008;224:143–53.

[105] Adham S, Oppenheimer J, Liu L, Kumar M. Dewatering reverse osmosis concentrate from water reuse using forward osmosis. WateReuse Foundation Res Rep 2007:1–52.

[106] Kazner C, Jamil S, Phuntsho S, Shon HK, Wintgens T. Forward osmosis for the treatment of reverse osmosis concentrate from water reclamation: Process performance and fouling control. Water Sci Technol 2014;69:2431–7.

[107] Martinetti CR, Childress AE, Cath TY. High recovery of concentrated RO brines using forward osmosis and membrane distillation. J Membr Sci 2009;331:31–9.

[108] Hancock NT, Nowosielski-Slepowron MS, McGinnis RL. High recovery brine treatment using forward osmosis. AMTA/AWWA Membr Technol Confer Expos 2013;2013:1190–203.

[109] McGinnis RL, Hancock NT, Nowosielski-Slepowron MS, McGurgan GD. Pilot demonstration of the NH3/CO2 forward osmosis desalination process on high salinity brines. Desalination 2013;312:67–74.

[110] Holloway RW, Childress AE, Dennett KE, Cath TY. Forward osmosis for concentration of anaerobic digester centrate. Water Res 2007;41:4005–14.

[111] Zhang Y, Chong JY, Xu R, Wang R. Effective separation of water-DMSO through solvent resistant membrane distillation (SR-MD). Water Res 2021;197:117103. https://doi.org/10.1016/j.watres.2021.117103.

[112] Macedonio F, Drioli E, Gusev AA, Bardow A, Semiat R, Kurihara M. Efficient technologies for worldwide clean water supply. Chem Eng Process Process Intensif 2012;51:2–17.

[113] Camacho L, Dumée L, Zhang J, Li J-d, Duke M, Gomez J, et al. Advances in Membrane Distillation for Water Desalination and Purification Applications. Water 2013;5(1):94–196.

[114] Li B, Sirkar KK. Novel Membrane and Device for Direct Contact Membrane Distillation-Based Desalination Process. Ind Eng Chem Res 2004;43(17):5300–9.

[115] Wang J, He C, Huo J, Fu L, Zhao C. A Theoretical Evaluation of Possible N2 Reduction Mechanism on Mo2B2. Adv Theory Simul 2021;4(5):2100003. https://doi.org/10.1002/adts.v4.510.1002/adts.202100003.

[116] Liu K, Roddick FA, Fan L. Impact of salinity and pH on the UVC/H2O2 treatment of reverse osmosis concentrate produced from municipal wastewater reclamation. Water Res 2012;46:3229–39.

[117] Mericq J-P, Laborie S, Cabassud C. Vacuum membrane distillation of seawater reverse osmosis brines. Water Res 2010;44:5260–73.

[118] Creusen, R.J.M. van Medevoort, J. Roelands, C.P.M. Duivenbode, J.A.D.v.R.v. Brine Treatment by a Membrane Distillation-crystallization (MDC) Process, Procedia Eng, 44; 2012. 1756-1759.

[119] Susanto Heru. Towards practical implementations of membrane distillation. Chem Eng Process Process Intensif 2011;50(2):139–50.

[120] Criscuoli A, Drioli E. Energetic and exergetic analysis of an integrated membrane desalination system. Desalination 1999;124:243–9.

[121] Edwie F, Chung T-S. Development of hollow fiber membranes for water and salt recovery from highly concentrated brine via direct contact membrane distillation and crystallization. J Membr Sci 2012;421–422:111–23.

[122] Dumée LF, Sears K, Schütz J, Finn N, Huynh C, Hawkins S, et al. Characterization and evaluation of carbon nanotube Bucky-Paper membranes for direct contact membrane distillation. J Membr Sci 2010;351:36–43.

[123] Tun CM, Groth AM. Sustainable integrated membrane contactor process for water reclamation, sodium sulfate salt and energy recovery from industrial effluent. Desalination 2011;283:187–92.

[124] Xu E, Wang Y, Wu L, Xu S, Wang Y, Wang S. Computational Fluid Dynamics Simulation of Brine-Seawater Mixing in a Rotary Energy Recovery Device. Ind Eng Chem Res 2014;53:18304–10.

[125] Janghorban Esfahani I, Ifaei P, Rshidi J, Yoo C. Control performance evaluation of reverse osmosis desalination system based on model predictive control and PID controllers. Desalin Water Treat 2016;57:26692–9.

[126] Janson, S.A. A. Benyahia, F. Dores, R. Husain, A. Minier-Matar, J. Membrane distillation of high salinity brines using low grade waste heat, in: Proceedings of the Membrane Technology Conference, American Membrane Technology Association (AMTA)/American Water Works Association (AWWA), Phoenix, Arizona;2013.

[127] Gabelich CJ, Williams MD, Rahardianto A, Franklin JC, Cohen Y. High-recovery reverse osmosis desalination using intermediate chemical demineralization. J Membr Sci 2007;301:131–41.

[128] Gabelich CJ, Xu P, Cohen Y. Chapter 10 Concentrate Treatment for Inland Desalting. In: Escobar IC, Schäfer AI, editors. Sustainability Science and Engineering. Elsevier; 2010. p. 295–326.

[129] Zhu A, Christofides PD, Cohen Y. Effect of Thermodynamic Restriction on Energy Cost Optimization of RO Membrane Water Desalination. Ind Eng Chem Res 2009; 48:6010–21.

[130] Zhu A, Rahardianto A, Christofides PD, Cohen Y. Reverse osmosis desalination with high permeability membranes — Cost optimization and research needs. Desalin Water Treat 2010;15:256–66.

[131] Cob SS, Beaupin C, Hofs B, Nederlof MM, Harmsen DJH, Cornelissen ER, et al. Silica and silicate precipitation as limiting factors in high-recovery reverse osmosis operations. J Membr Sci 2012;423:1–10.

[132] Thiel GP, Tow EW, Banchik LD, Chung HW, Lienhard JH. Energy consumption in desalinating produced water from shale oil and gas extraction. Desalination 2015; 366:94–112.

[133] DOW FILMTEC Membranes, SW30HR-380 High Rejection Seawater RO Element Product Manual, in; 2013.

[134] DOW FILMTEC Membranes, SW30XHR-440i Seawater Reverse Osmosis Element Product Manual, in; 2013.

[135] TORAY Membranes, TM800M Standard SWRO Product Manual, in, July; 2013.