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Hybrid membrane and thermal seawater desalination processes powered by fossil fuels: A comprehensive review, future challenges and prospects

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HIGHLIGHTS

- Challenges and opportunities membrane and thermal seawater desalination processes are highlighted.
- Fossil fuel based energy sources will continue to dominate in coming decades.
- Application of renewable energy based energy sources is getting the momentum.
- Several hybrid processes have potential for future commercial applications.
- Hybrid processes can mitigate fouling/scaling problems and can be more energy efficient.

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ABSTRACT

Various hybrid desalination systems have been proposed during the last two decades to improve the produced water quality, energy efficiency, water production rate and sustainability among others, receiving therefore a rapid industrial implementation. Desalination processes are energy intensive and this energy is mostly provided by fossil fuels, especially for large scale commercial plants. No doubt, the use of renewable energy (RE) sources is a way forward to decrease the environmental and related health impact to produce and supply freshwater in remote regions with severe water shortage and an unfavourable or unfeasible connection to the public electrical grid. However, most installed renewable energy desalination plants have small capacities, yet facing several issues for long term operation. Therefore, this study restricts to the use of fossil fuel based energy source for desalination and provides a thorough analysis summarising the design, operation, and performance, techno-economic and associated challenges of hybrid seawater desalination systems based on several experimental/real plant and simulation studies reported since 2000. It includes mature membrane-based and thermal-based desalination technologies, namely Reverse Osmosis (RO), multistage flash (MSF), and multi-effect distillation (MED), and a number of emerging hybrid membrane-thermal water desalination technologies. Future opportunities in hybrid systems, including RO/MSF and RO/MED are also highlighted.

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1. Introduction

Since the 1960s, the process of desalinating seawater has undergone a transformation, with a marked shift towards utilising the RO process (a pressure-driven membrane process) worldwide in many new plants surpassing and supplanting traditional thermal processes. For instance, over 60 % of desalination installations globally utilise RO technology as a result to its superior energy efficiency in comparison to traditional thermal processes [1]. Although RO in desalination has experienced incredible success and significant growth, it is also accompanied by several serious disadvantages, such as comparatively low water recovery, scaling and biofouling and high electrical energy costs, which normally account for half of the total cost of water production [2]. Since it is difficult to make RO desalination alone economical for developing nations due to the process restrictions, RO has ultimately become less favourable for energy-effective desalination. Additionally, high energy use is specifically correlated to high greenhouse gas emissions, which worsen the environment's quality. In addition, RO struggles significantly from a high rate of brine formation, for which the present brine disposal techniques are still insufficient to guarantee sustainable management [3]. Use of hybrid systems of seawater desalination including the RO process and other desalination technologies have increased globally as a result of their potential to elevate the performance indicators of the integrated processes while mitigating the operational cost and associated limitations.

Although desalination technologies appear to be mature enough to provide a stable source of freshwater from the sea, intensive research and development have been conducted in order to continuously improve these technologies by reducing their cost of desalination and making them more reliable, efficient and sustainable. This study delivers a comprehensive review of the current knowledge concerning the development of the hybrid systems of seawater desalination processes including RO with a critical evaluation of the main design, alternative processes layouts, operation, performance, and techno-economic perspectives. Furthermore, the main disadvantages and challenges of these hybrid systems are addressed.

Despite the whole world is against using fossil fuels and considering transition to renewable energies due to environmental considerations, this study focuses on evaluating the hybrid seawater desalination of membrane, thermal technologies and emerging technologies powered by fossil fuels due to the following practical and feasibility reasons:

- The intermittency in renewable energy generation is a vital challenge that retards the complete transition into the renewable energy systems.
- Maintaining the traditional seawater desalination technology is essential given the contrast between the performance of fossil fuels and renewable energies for very large-scale seawater desalination plants.
- It is essential to comprehend how fossil fuel-powered seawater desalination technologies are doing in order to progress these technologies and make them more effective and ecologically friendly, perhaps reducing CO_2 emissions.
- One major issue may be the economic effects of continuing to rely on fossil fuels, particularly in large-scale applications. Policy makers are constantly worrying about the comparatively high cost of renewable energy technology (as it stands) relative to fossil fuels when they refer to making the switch to renewable energy sources.
- Fossil fuel is highly efficient compared to renewable energies, considering the large capacity desalination plant requires its own power plant. Besides, not all renewable energy technologies are suitable in regions of water shortage, namely wind turbines are not popular or suitable in the Middle East. Finally, fossil fuel is abundant in the water scarcity regions that relies on desalination, making it a secure energy source.

Undoubtedly, the carbon footprint of hybrid seawater desalination systems that run on fossil fuels is the main concern. However, it should be noted that the advancement of Life Cycle Assessment (LCA) and progressive research have contributed to a more sustainable operation [4,5]. In this regard, the innovative carbon capture and storage systems aid to mitigate environmental impact [6]. Referring to the economic consideration, fossil fuel-powered seawater desalination systems will still have lower initial costs, and longer operation time compared to renewable alternatives (as currently stands). Yet, renewable energy technologies are considered as environmentally friendly solutions from the practical point of view, but there is lack of a complete life cycle analysis and costs studies that include the whole value chain processes of the circular carbon economy from materials used, fabrication process, transport, installation, footprint, operation and maintenance, and regeneration and disposal of these materials.

2. Overview of seawater desalination technologies

The seawater desalination market is primarily driven by the growing need for freshwater due to population growth leading to an intensified use of water for domestic, industrial, and agricultural purposes. However, according to World Health Organization (WHO) [7], almost two billion people lack access to properly managed drinking water. Membrane desalination such as RO and thermal desalination such as multi-stage flash distillation (MSF), multi-effect distillation (MED, with or without thermal vapour compression, TVC) are the two primary technologies used for desalination. While RO uses mechanical pressure to desalt seawater, MSF and MED techniques use heat to vapourise water under a reduced pressure. However, due to their high energy intensity, thermal techniques are less frequently considered for desalinating seawater, although they are still the preferred choice in some specific areas with low energy prices (or subsidised) or with a high need for water more than what RO can supply.

Fig. 1 shows the market shares of thermal and membrane seawater desalination techniques. Fig. 1 demonstrates unequivocally how effective the RO technology is when compared to MSF and MED technologies. As can be seen, RO technology accounted for around 65 % of the seawater desalination market in 2020, representing the highest market share. Due to its reduced energy usage when compared to thermal technologies, RO technology is predicted to dominate in the market. Nonetheless, thermal technologies are still anticipated to have a sizable market share in areas, like the Middle East and North Africa (MENA), where energy costs are low (due to government subsidy) with severe water shortages [8]. Furthermore, the MENA regions are predicted to hold the biggest regional market share in the global seawater desalination market. For example, the desalination plants installed in the MENA region in 2021 have accounted for 47.5 % of the world's desalination installed capacity, making Saudi Arabia, the United Arab Emirates, and

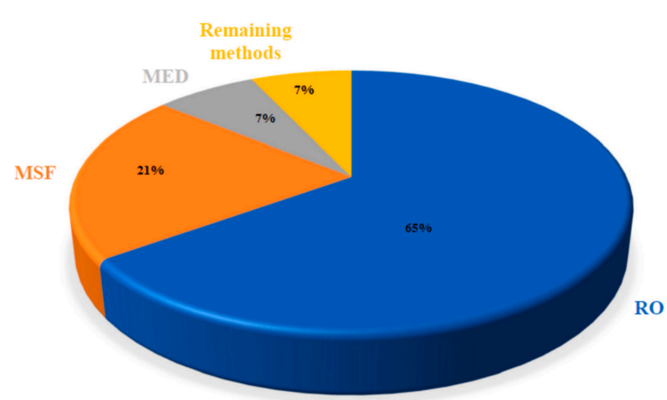

Fig. 1. Market shares of seawater desalination technologies (Adapted from [1]).

Kuwait as the main market players for medium and large-scale water desalination facilities [9,10]. The other remaining methods of seawater desalination such as humidification-dehumidification (HDH), nano-filtration, ionic filtration, electrodialysis, and capacitive deionization have only 7 % of the global market share as shown in Fig. 1. Specifically, Fig. 1 depicts the global desalination capacities of different seawater desalination techniques.

The discussion above introduces the fact that RO and thermal technologies including both MSF and MED are the most conventional seawater desalination methods. However, RO technology has more advantages over thermal technology and hence, it is quite fair to claim that the RO process serves as a baseline conventional technology [11]. Therefore, the main discussion in this paper would focus on innovative hybrid systems like RO/MSF and RO/MED with a thorough evaluation of several aspects including the design, operation and performance, specific energy consumption, freshwater production cost, and the faced limitations among others. However, it should be noted that there are a number of other promising and emerging hybrid membrane-thermal water desalination technologies which will be covered briefly in the current study such as Membrane Distillation/Reverse Osmosis (MD/RO) [12,13], Forward Osmosis/membrane Distillation (FO/MD) [14], Forward Osmosis/Multi-Stage Flash (FO/MSF) [15,16] that rely on fossil fuels for heat generation.

3. RO, MSF, and MED processes

3.1. RO process

A schematic illustration of a typical membrane element layout is presented in Fig. 2. RO systems use a variety of membrane materials, and their application is gaining a rapid popularity. The most often used RO modules is the spiral wound one, in which the membrane sheets are looped around an inner tube that collects the permeate [17]. Generally, RO provides considerable flexibility to handle diverse salinity levels, of a little area, and it is easy to operate and automate [18]. It should be highlighted that effective pre-treatment of the feed water can boost the reliability of RO plants. Pre-treatment, RO operation, and post-treatment of both the permeate and brine are the three processes that make up the RO desalination plant in general.

Only electric energy (produced mainly by using fossil fuel) is used in the RO process to supply the required pumping power. The energy consumption in membrane-based processes varies between 1.5 kWh/m^3 and 15 kWh/m^3, whereas the cost of freshwater can range from 0.26 US $/m^3 up to 1.87 US$/m^3 [19,20]. This energy consumption is dependent on the amount of dissolved salts in the feed water, feed water temperature, operating conditions, process scale, and energy source. According to the majority of recent studies, water recovery in RO plants may range from 35 % to 50 % [21]. Note, a wide range of RO process configurations can be seen in the public domain (some referring to real plant) [22].

3.2. MSF process

The MSF desalination system starts by flashing water under vacuum, followed by its evaporation and ends by its condensation. A series of stages (at different temperature and pressure) are considered, each stage consisting of a flashing pool, condensing tubes and distillate collectors. The vapour flashing from the pool is condensed around the tubes resulting in pre-heating of the incoming seawater. The condensed vapour is then collected and pumped into storage tanks to use as freshwater.

Generally, MSF plants are available in two forms: once-through MSF (MSF-OT) (the desalination process produces brine, which is released directly into the environment, typically into the sea. The brine is not recycled or used again in this process) and the most common brine recycling MSF (MSF-BR) process (here, freshwater is combined with concentrated brine to enhance overall water recovery and thus reduce environmental impact). MSF-BR process has 3 sections: the brine heating section, heat recovery section, and heat rejection section. A schematic representation of the MSF-BR process is shown in Fig. 3. The heat rejection section usually has two to three stages. Cold saltwater is fed through the heat exchanger tubes of the last heat rejection section.

The seawater becomes warmer as it moves from one stage to the next (from right to the left). Following its split into a make-up feed stream and a rejected stream, seawater exits the heat rejection section. In the MSF-BR process, part of the brine from the last stage is incorporated into the feed water. Finally, externally provided steam is utilised to heat the feed water in the brine heater. This elevates the feed water temperature to what is known as “top brine temperature” (TBT) ranging between 90 and 110 °C. As water is flashed (vapourized) in each stage, the concentration of brine rises. After part recycling, the concentrated brine is discarded as a blow-down (Fig. 3).

A typical MSF system might have 4 to 40 stages [23] and produces 450 to 57,000 m^3 of freshwater per day. Use of fossil fuel is dominant in most of the commercial MSF plants and the cost of producing freshwater of MSF using fossil fuel is US$ 0.28 per m^3 [24]. Furthermore, Ali et al. [25] studied an MSF-OT process with 25 stages operating with 42,000 ppm seawater salinity producing 378.8 kg/s of freshwater with performance ratio (PR) of 10.6 % PR is identical to GOR which is defined as the fraction of the total energy input that is converted to freshwater or the mass of freshwater produced to the mass of steam consumed. El-Ghonemy [26] mentioned that GOR of a typical MSF is 8 and specific electricity consumption is between 3 and 5 kWh/m^3. The benefit of MSF systems is their high output rates. Note that the amount of time that the heat-exchanging surfaces are in contact with the brine is minimal, which prevents corrosion and erosion issues. Compared to MED, the MSF procedure is more reliable, simpler to use, and has a longer service lifetime [27]. Unfortunately, MSF has a high installation cost [28].

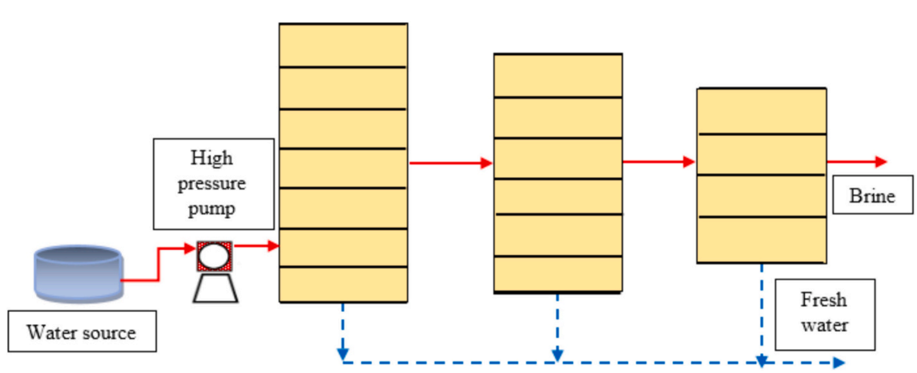

Fig. 2. A simple schematic diagram of a multistage RO process.

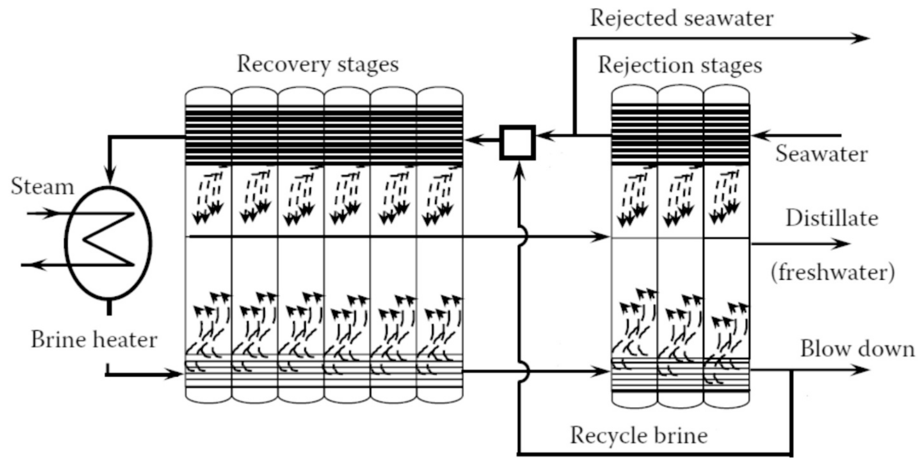

Fig. 3. A representation of the brine recycling MSF process (Adapted from [29]).

3.3. MED process

A schematic of the MED procedure is shown in Fig. 4. MED is the oldest and most well-known thermal desalination method. In particular, MED features a series of effects where the vapour from one effect is utilised to evaporate water in the following effect. A horizontal tube bundle is present in each effect. In order to facilitate a quick boiling and evaporation, seawater is sprayed onto the surface of the tube bundles. Steam from power plant turbines or a boiler is used to heat the first effect. In other words, only the first effect, which is produced independently of the distillation process—uses the produced primary steam. The steam created in each preceding effect heats the surfaces of all other effects. The feed water is heated as the steam from the last effect condenses in a different heat exchanger known as the final condenser, which is cooled by the entering seawater.

Most commercial MED processes use fossil fuel. There are typically 4 to 16 effects in MED. The thermal vapour compression (TVC) (Fig. 5) and MED are typically coupled [30]. The maximum temperature at which MED runs, which is around 70 °C, reduces the likelihood of scalability problems. Compared to MSF, MED exhibits greater GOR, which is between 10 and 18 (i.e., production of more water per amount of steam consumed while using less electricity) [31]. The main issues with MED are corrosion and erosion of components that come into contact with brine, namely heat exchangers. Moreover, the internal corrosion and $CaCO_3$ scaling of the vertical tube evaporator reduce its efficient service lifetime [27].

For the specific conditions of seawater salinity, steam temperature, and mass flow rate of MED, of 39,000 ppm, 70 °C, and 8 kg/s, respectively, the freshwater production cost of with and without TVC were estimated to be 1.02 $/m^3$ and 0.78 $/m^3$, respectively [32].

4. Seawater desalination based on hybrid RO, MSF and MED systems

As pointed out previously, the most effective method for desalting seawater is RO, to meet the demand of freshwater, although the capacity for worldwide desalination is still mostly based on thermal processes like MED and MSF, especially in the Gulf countries. However, thermal technologies are energy intensive and mostly depends on fossil fuels but produces higher quality water compared to RO technology. When different grades of water are required, hybrid methods combining both techniques can be more appropriate [35].

This section intends to review the experimental and model-based studies of the membrane and thermal based hybrid systems for seawater desalination focusing on the design, operation and performance of these processes and their main shortcomings. The performance

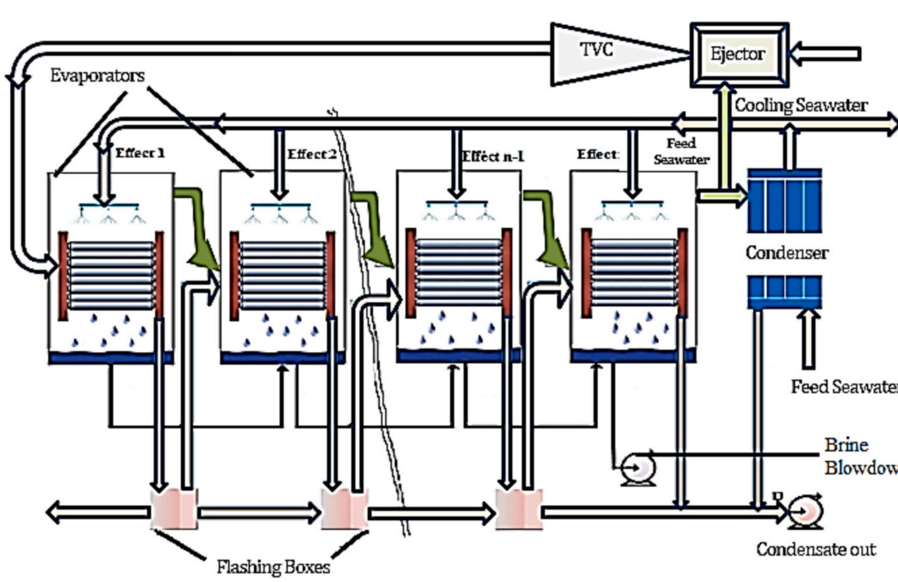

Fig. 4. A representation of MED coupled to TVC process (Adapted from [33]).

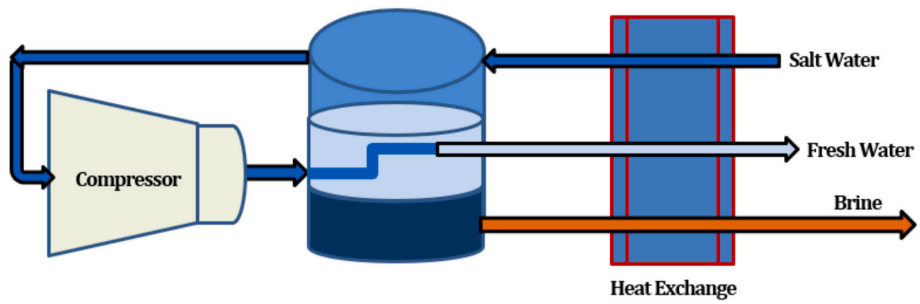

Fig. 5. A representation of thermal vapour compression (Adapted from [34]).

indicators of the hybrid systems will include the overall productivity, product salinity, specific energy consumption, and water production cost (if available).

4.1. RO-MSF hybrid systems for seawater desalination

Various RO-MSF hybrid pilot plants have been proposed for efficient seawater desalination. El-Sayed et al. [36] evaluated the performance of two RO membrane plants of different configurations combined with MSF system. The hybrid system consists of MSF unit, a pre-treatment stage, and two RO lines with two different types of RO membrane modules spiral wound and hollow fibre. The complete experimental configuration is shown schematically in Fig. 6. The feed water temperature for the RO process, which is the seawater rejected stream of the MSF heat rejection section, ranged from 30 °C to 36 °C. With this hybrid RO-MSF, a higher water productivity than that of MSF or RO stand-alone systems was achieved (e.g., more than 38 % improved noticed compared to that achieved by individual process for each of the two tested RO units based on spiral wound and hollow fibre modules with 0.2 % decrease in the produced water quality). In this regard, the spiral wound RO membrane module-based unit exhibited higher stability compared to the hollow fibre module-based RO unit. More importantly, the utilisation of the hybrid system enabled to lessen the overall specific energy consumption (amount of energy required to produce one cubic meter of fresh water, which is measured by kWh/m^3) between 15 % and 25 % if compared to the required energy of each isolated RO and MSF processes. The hybrid system formed by the hollow fibre module-based RO unit and MSF resulted in 5.8 and 6.2 kWh/m^3 specific energy consumption, respectively, compared to 6.8 and 7.8 kWh/m^3 of the RO process alone using hollow fibre and spiral wound modules, respectively. The study also identified several operational challenges, including RO membrane fouling and scaling, the need for periodic chemical cleaning, and the requirement for precise control of the feed water flow rate.

Al-Bahri et al. [37] investigated the influence of the feed water temperature on the performance of multi-stage RO units in RO-MSF hybrid systems. The study aimed to identify the optimum feed water temperature for the RO unit to achieve a maximum productivity. Fig. 7 depicts the schematic diagram of the integrated system used to desalinate seawater with a TDS of 39,500 ppm and 80 bar inlet pressure of the RO unit. To maintain a fixed seawater temperature of the RO process, the blend of seawater and the cooling rejected brine of MSF were mixed and fed to the multi-stage RO process (parallel configuration). The

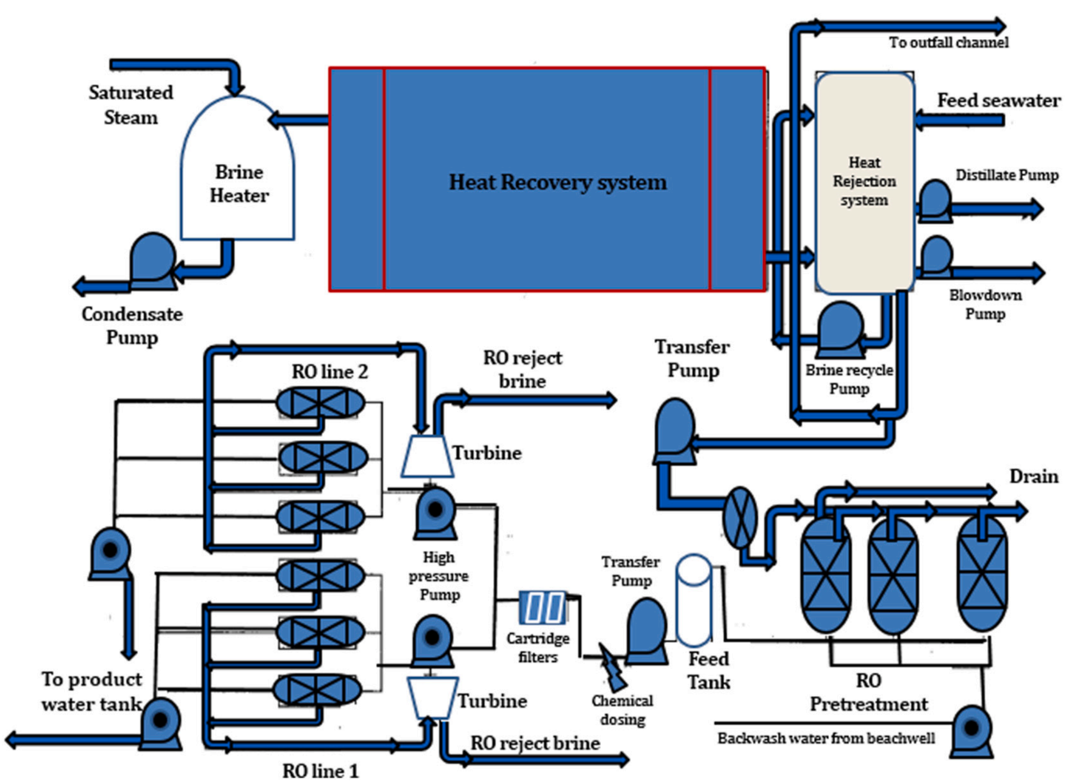

Fig. 6. A representation of an integrated RO-MSF system (Adapted from [36]).

optimum seawater temperature by the simulation-based model was found to be between 27 °C and 28 °C, which entails the maximum productivity for different operational years (23–25 m^3/day between 1 and 3 years). Accordingly, the nominal productivity of the RO modules was 25.6 m^3/day at standard conditions, which quantify the maximum lifetime output of the membranes.

To present the competitiveness of an integrated system of UF-NF-RO-MSF compared to the RO system, Turek [38] performed a critical analysis of a seawater desalination and crystallisation (i.e., salt production system). The study highlighted the incorporation of various desalination technologies to improve energy efficiency and lower the cost of the produced freshwater. UF and NF units were used along the pre-treatment step. The UF unit removed larger particles, suspended solids, and some microorganisms, while the NF unit removed dissolved solids and contaminants. The RO and MSF were linked in a series (i.e., the brine of the RO process is fed to MSF for further polishing). In this regard, the permeate of RO is linked to the distillate of MSF to form the production line. The findings demonstrated that the freshwater production cost of RO (with 65 % recovery factor) is USD$ 0.63 per cubic meter of freshwater, while the overall freshwater production cost of the integrated system is USD$ 0.37/m^3 with an overall water recovery of 77.2 %.

Cardona et al. [39] conducted a detailed economic analysis of a hybrid RO-MSF system in which the brine of the RO unit is fed to MSF one. Using the RO process at the beginning would ascertain the removal of majority salt from the feed water and therefore reduces the load on the subsequence process of MSF. Also, this configuration would ascertain the reduction of water quantity to be treated in the pre-treatment stage, which includes chlorination, coagulation and filter for the separation of suspended particles, and therefore would decrease the overall freshwater production cost. The product stream of the series configuration is the mix of RO permeate and MSF distillate. However, one of the most disadvantages of this configuration would increase the risk of scaling and fouling in the RO system. Compared to the parallel configuration of RO and MSF (i.e., applying feed water to both RO and MSF simultaneously), the series configuration of RO and MSF showed a bit higher specific energy consumption. This is due to having a lower feed flow rate in the parallel configuration of RO and MSF, which in turn increases the water residence time inside the RO modules and improves the productivity of RO process which reduces the specific energy consumption.

Helal et al. [40,41] presented comprehensive studies on the integration of RO and MSF processes considering different levels of integration providing a detailed evaluation of the overall performance of each integrated system and associated water production cost. Besides the brine recycle MSF plant (3 rejection stages) and a two-stage RO process, Helal et al. [40] investigated seven RO-MSF configurations, specifically between RO and brine recycle and once-through MSF units. Figs. 8 and 9 depict two examples of the tested configurations: (1) an independent two stages RO and brine recycle MSF and common intake (Fig. 8), and (2) a once-through MSF and single-stage RO hybrid seawater desalination plant (Fig. 9). The optimal configuration was identified via sensitivity analysis and model optimisation resulting in the lowest freshwater production cost. The study considered seawater salinity of 42,000 ppm at 25 °C, 110 °C as the top brine temperature of MSF, 114 °C as the steam temperature. The optimisation problem considered 60 bar and 80 bar as the upper and lower bounds of inlet pressure of RO, respectively, and permeate salinity and brine salinity of less than 750 ppm, and 67,000 ppm, respectively, for all the tested configurations. The claimed optimisation results by Helal et al. [41] indicated that the two-stage RO plant exhibited the most promising economic and performance features with a freshwater production cost of 0.75 \$/m^3, a specific capital cost of 1384 \$/m^3 and a maximum water recovery of 37.6 % (The water production cost of MSF was 1.1 USD \$/m^3, its specific capital cost was 1476 USD\$/m^3, and its water recovery was 10.7 %). However, the integration of RO to MSF resulted in a reduction between 17 and 24 % of the freshwater production cost of a single MSF while doubling the water recovery. It must be pointed out that, the performance indicators of the RO system can be further improved if the optimised RO-MSF is applied for the desalination of

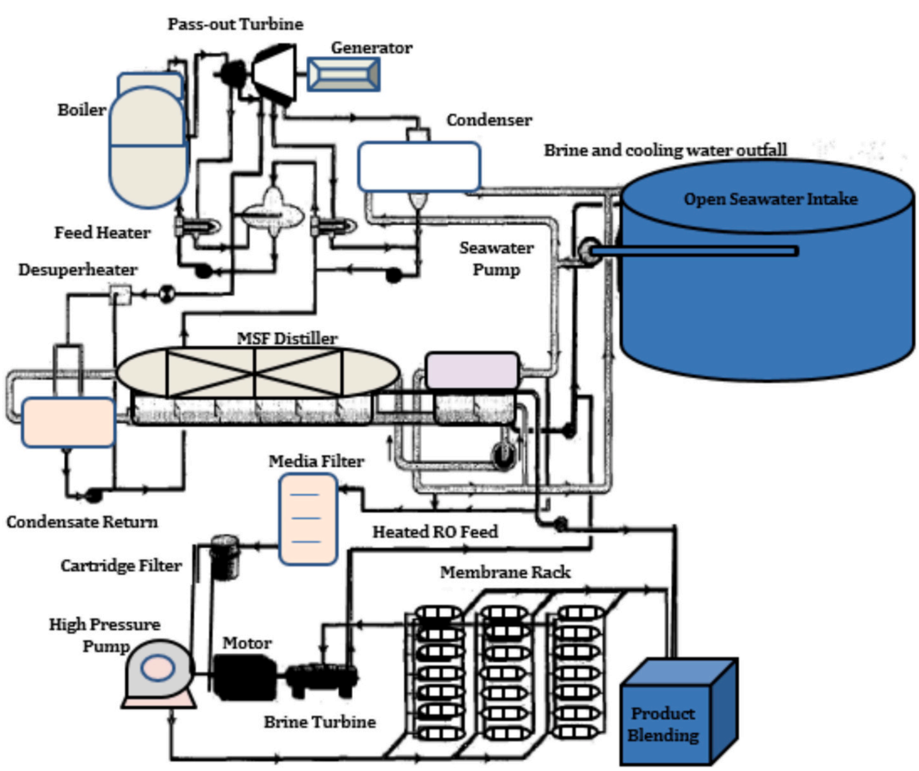

Fig. 7. A representation of the integrated RO-MSF system (Adapted from [37]).

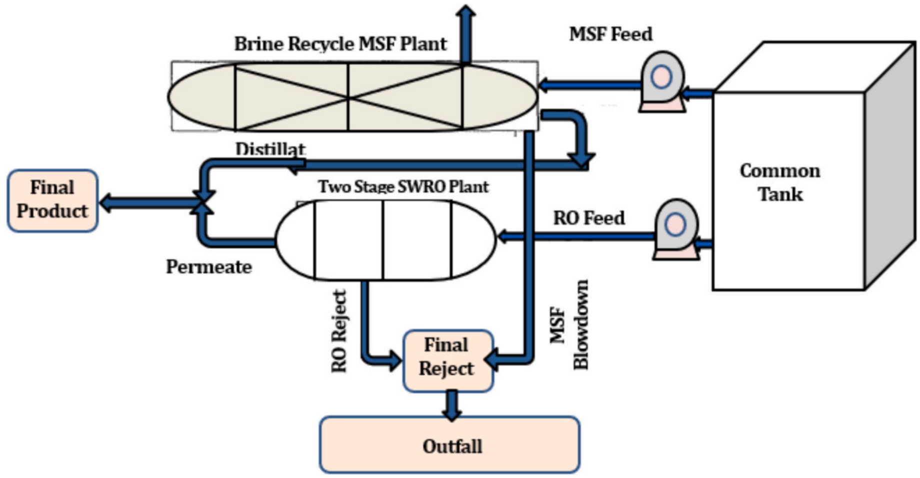

Fig. 8. A representation of an independent two stages RO and brine recycle MSF and common intake (Adapted from [40]).

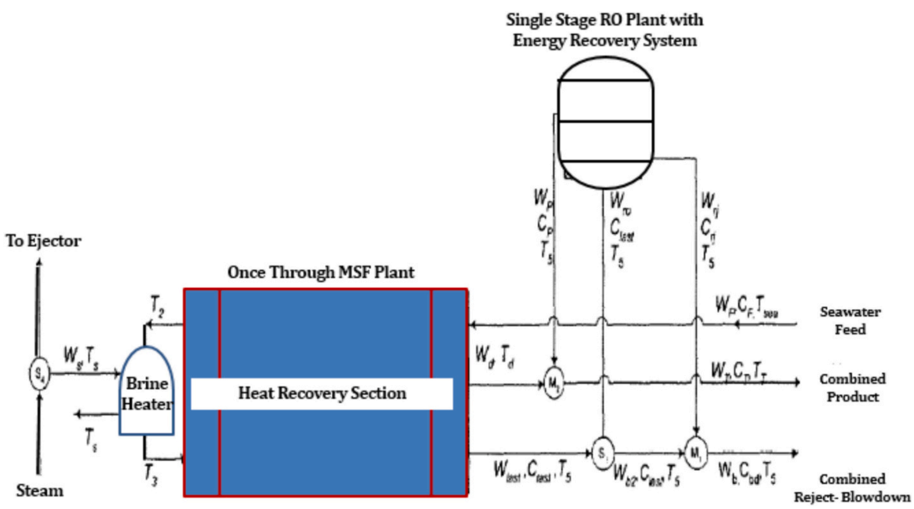

Fig. 9. A representation of a fully integrated seawater desalination plant of once-through and RO processes (Adapted from [40]).

brackish water having less than 20,000 ppm TDS.

Marcovecchio et al. [42] developed a model for the hybrid RO-MSF systems to find out the optimum process design and inlet conditions for a given water production. Fig. 10 presents the hybrid system of 29 stages of MSF unit and 2-stages RO process. A part of the blow-down stream of MSF is fed into RO that contains an energy recovery device (ERD). The model developed was tested to desalinate seawater salinity of 45,000 ppm at 25 °C using DuPont's B10 hollow fibre modules working between 55.2 and 68.8 bar. The optimisation results introduced detailed design characteristics and inlet conditions of MSF and RO units that would satisfy the lowermost freshwater production cost of 1.259 $/m^3$ at 60000 m^3/day of water production rate. Some of the obtained most important optimal characteristics are: For MSF: stage length (0.75 m), stage width (21.52 m), number of tubes per stage (1000), and for RO: seawater concentration (52,190.5 ppm), pump pressure (69,7 bar).

Lisbona et al. [43] experimentally examined different configurations of the hybrid RO-MSF system while alternative fuel cells were used to power the RO unit and a heat exchanger was used to preheat the feed water (Fig. 11). The two systems of solid oxide fuel cell and molten carbonate fuel cell, operated at high temperatures, 650 °C and 900 °C, respectively. The preheating option of RO unit was identified as a good option to improve its water productivity. The fuel cells operated with nitrogen or natural gas to generate electricity, which was directly supplied to the RO unit while the waste heat was utilised to produce low-pressure steam for the MSF unit via a heat recovery steam generator. Both RO and MSF units were fed with a seawater of 36,000 ppm salinity at 20 °C. The RO unit was supplied with an energy recovery system to absorb the surplus energy from the high-pressure brine. The overall water productivity of the hybrid system was 3074 m^3/day considering a specific energy consumption of 4 kWh/m^3 for RO and a GOR of 10 for the MSF unit. The salinity of the product water of RO and MSF were 360 ppm and 50 ppm, respectively. The efficiency of molten carbonate and solid oxide fuel cells were found to be 78 %, and 95 %, respectively. However, it is not beneficial to utilise solid oxide or molten carbonate fuel cells due to their high-investment cost.

Marcovecchio et al. [44] derived a comprehensive model for the hybrid RO-MSF systems to investigate the optimal design (i.e., equipment sizes and inlet conditions) that should result in the lowest freshwater production cost. A schematic diagram of the proposed RO-MSF hybrid system, consisting of two RO units (DuPont's B10 hollow fibre modules) and two options of MSF units with and without brine-recycling, is shown in Fig. 12. Seawater was fed to both MSF and RO. However, part of the MSF brine was also fed to the two RO units. The products of the MSF and RO were mixed to form the final product stream. Optimisation was built as MINLP and solved using the Improve-Branch algorithm developed by the same authors. For a fixed product rate of 48,000 m^3/day and salinity of 570 ppm, an optimisation procedure was carried out for seawater with salinity and temperature of

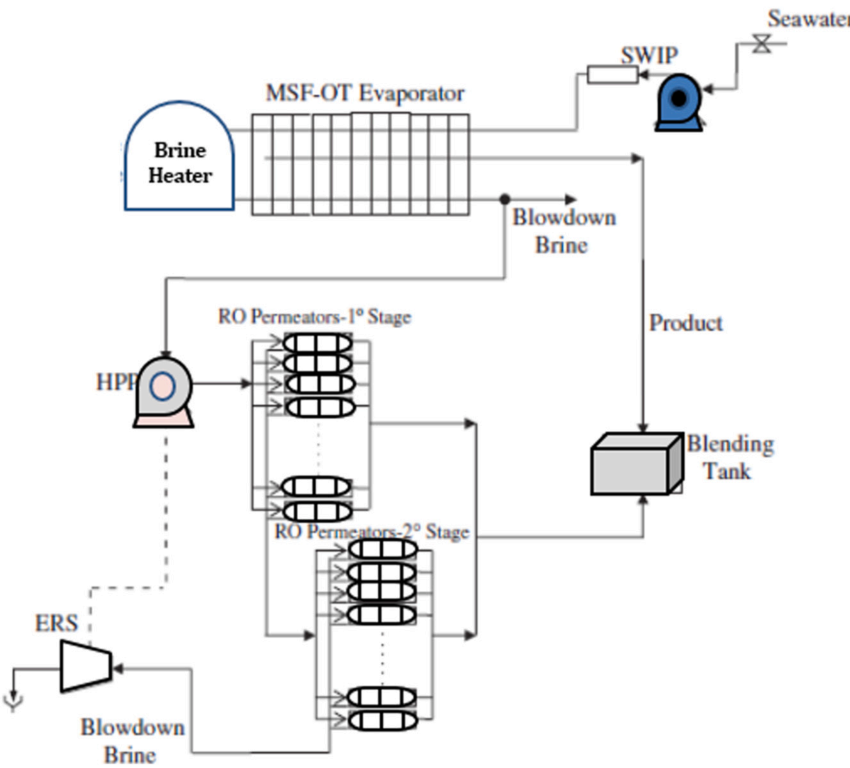

Fig. 10. A representation of integrated RO-MSF systems (Adapted from [42]).

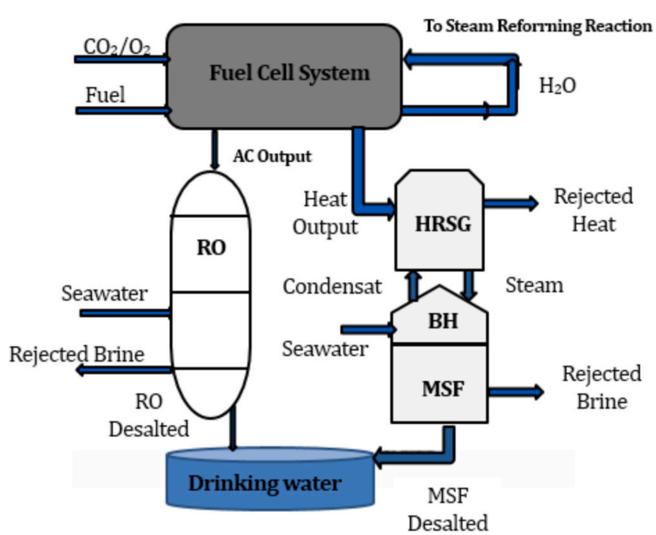

Fig. 11. Integrated fuel cell and RO-MSF systems (Adapted from [43]).

41,000 ppm and 25 °C. Fig. 13 shows the optimal design of the hybrid RO-MSF system with the detailed characteristics of inlet and outlet streams. The optimal superstructure shows the utilisation of brine-recycling MSF and an independent first RO unit where its brine is fed to the second RO unit. However, the brine of the second RO unit is exploited to increase the feed water of MSF. The optimal design resulted in the lowermost freshwater production cost of 0.824 $/m^3 with 6861.6 m^3/day and 41,143.2 m^3/day water production rate of MSF and RO units, respectively, maintaining the constraint of product salinity of 570 ppm.

Wu et al. [45] evaluated the economic aspects of the cogeneration of power plants with an RO-MSF hybrid system consisting of a multi-stage RO and 21 stage MSF units (Fig. 14). The power generation cycle contains a boiler and steam turbine that produces the electrical and thermal energy simultaneously. The boiler is responsible to generate superheated steam, which is fed to the turbine to generate electricity to power RO and MSF units and the grid. Seawater (42,000 ppm) is fed into the MSF unit and heated throughout the heat rejection section of MSF while part of the rejected water is fed to RO unit and the second part is fed to the heat recovery section of MSF. The cooling water exit recovery section is fed to the brine heater to heat it up to the desired temperature using the steam leaving the turbine. The blow-down brine concentration of MSF unit is around 70,000 ppm. The product streams of MSF and RO units are mixed to form the product water of less than 500 ppm. MINLP optimisation was considered to find the lowest total annualised cost of the cogeneration system while satisfying the water demand and power supply demand constraints of 288,000 m^3/day and 250 MW, respectively. The optimisation introduced two different optimal configurations: i)- for water productivity lower than 8000 m^3/day, the RO process can be relaxed, and ii)- for a water productivity higher than 8000 m^3/day, both RO and MSF operate simultaneously with steam turbines.

Bandi et al. [46] used a differential evolution algorithm via a global optimisation approach to figure out the optimal design of the hybrid brine-recycling MSF and a single-stage RO unit (DuPont's B10 hollow fibre membrane module, total membrane area 152 m^2) and an energy recovery system. Five scenarios of different stream connections were studied. Fig. 15 shows as an example the fifth scenario of the hybrid RO-MSF system. In this scenario, the cooling water reject stream of MSF is fed to the RO unit using a high-pressure pump besides using the brine of RO to serve the make-up stream of MSF. The salinity of the used seawater was 42,000 ppm and its temperature was 25 °C. 3 heat rejection stages in MSF were considered. The total annualised cost was minimised while adjusting a set of independent variables and inequality constraints. For instance, the decision variables of heat recovery stages and the number of modules of RO were optimised between 18 and 30, and 2000 and 10,000, respectively. The optimal configuration was found to be scenario 4 (Fig. 16), which resulted in the lowest freshwater production cost (0.97 $/m^3) with 28.3 % water recovery. This

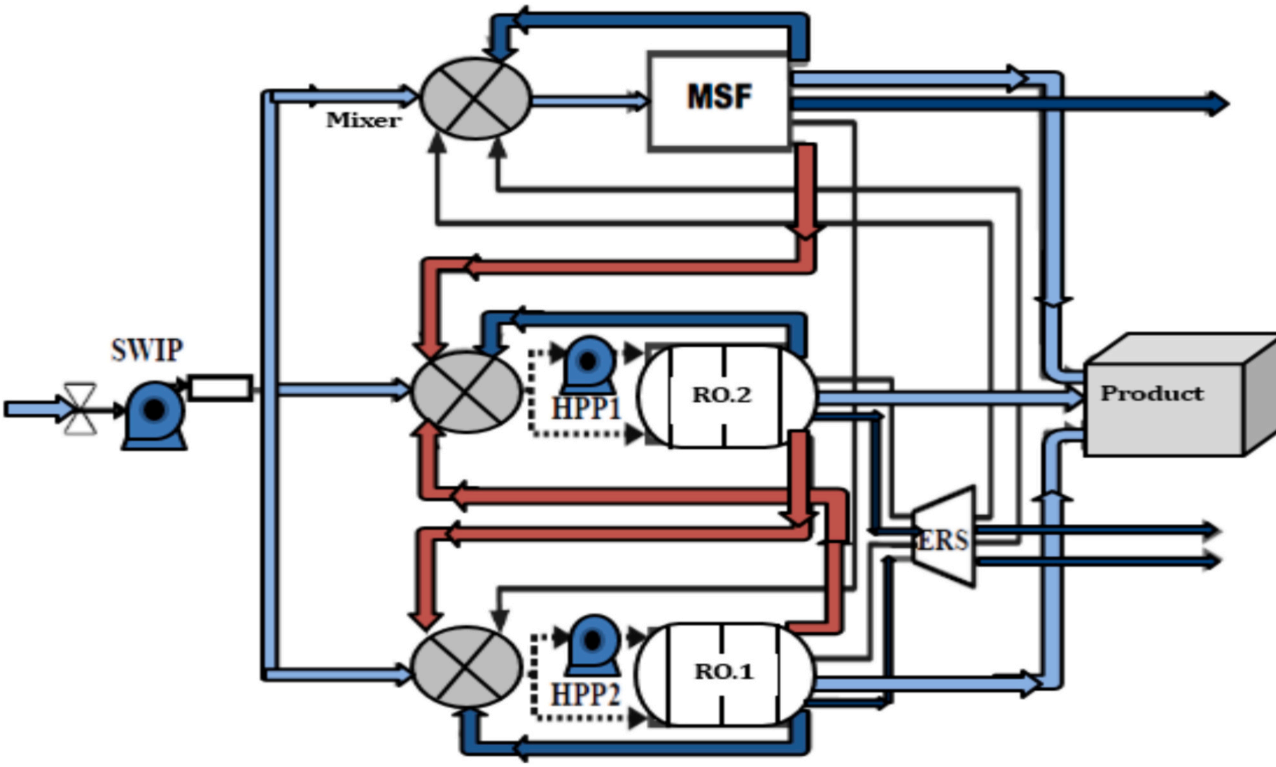

Fig. 12. A representation of the proposed integration of two RO units and brine recycling MSF (Adapted from [44]).

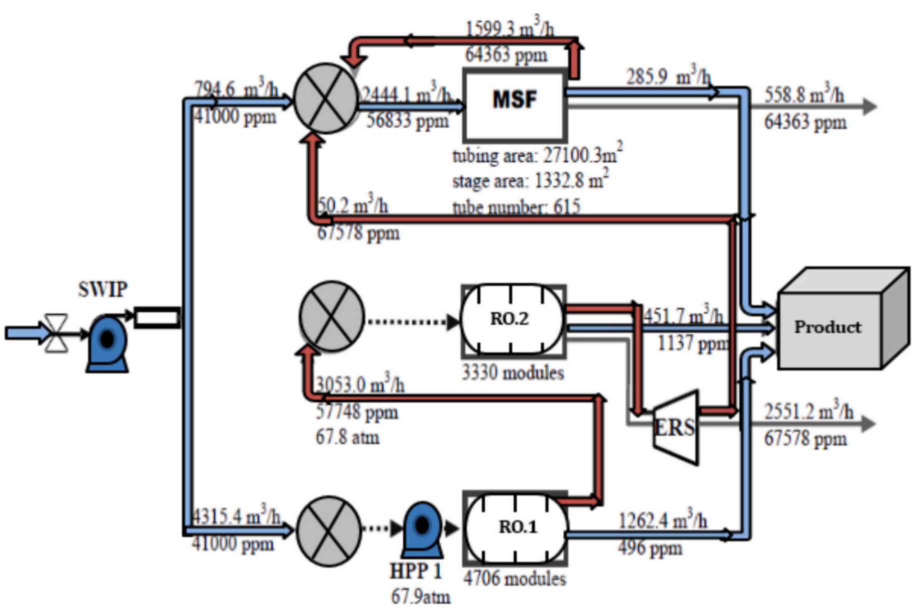

Fig. 13. A representation of the optimal design of two RO units and one MSF unit (Adapted from [44]).

configuration is quite similar to scenario 5 except the brine of RO is split into two streams; one portion as the disposed stream while the other portion serves the make-up feed of the MSF.

We would draw attention to the fact that the integrated desalination systems powered by fossil fuels were the main focus of this evaluation. On the other hand, the solar energy (an example of renewable energy) has been used to power the hybrid systems of water desalination techniques. For instance, the possibility of merging a photovoltaic solar farm with an integrated system of MED and RO processes in a desalination plant was investigated by Filippini et al. [47] in order to produce power sustainably and at a reasonable cost. Table 1 summaries the previous conducted studies on hybrid RO-MSF systems proposed for seawater desalination and powered by fossil fuels, including the design, inlet operating conditions, water productivity, water product salinity, economic aspects, and associated challenges and future perspectives.

4.2. RO-MED hybrid systems for seawater desalination

Within the field of water desalination, the current review highlights the use of fossil fuels to drive several types of hybrid systems.

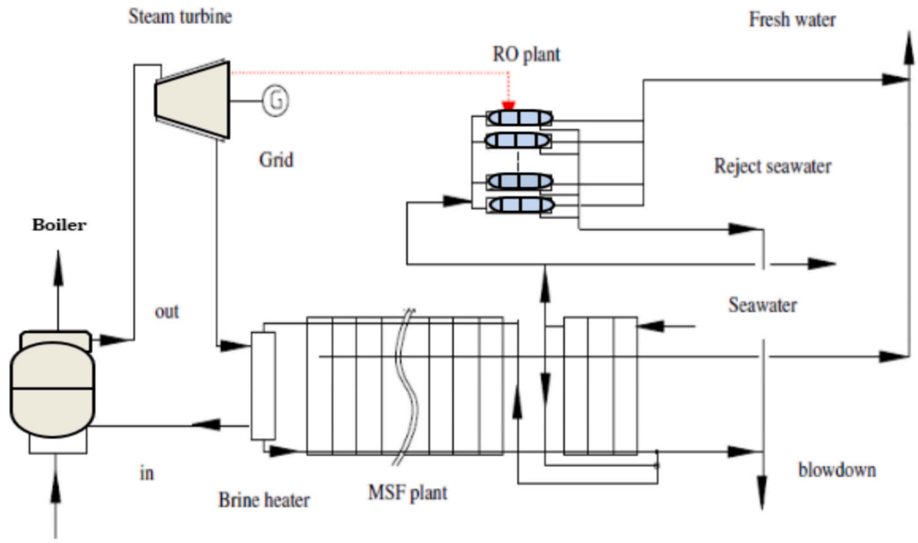

Fig. 14. A representation of the cogeneration system of the power plant/RO-MSF hybrid system (Adapted from [45]).

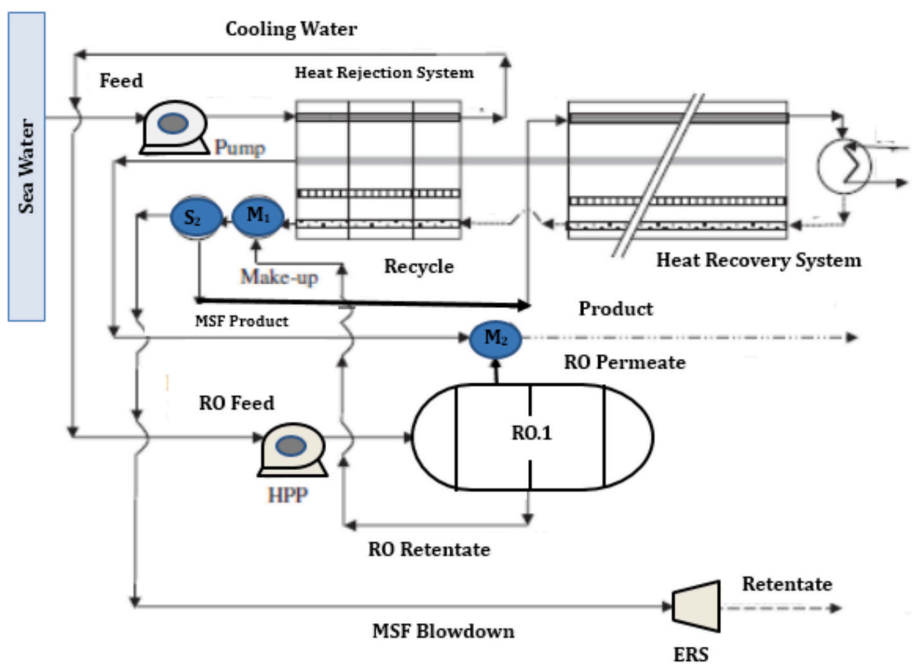

Fig. 15. A representation of one of the studied scenarios of the hybrid brine recycling MSF and a single-stage RO unit (scenario 5) (Adapted from [46]).

Nonetheless, it is critical to recognise how cutting-edge renewable energy sources are increasingly being incorporated into desalination technology. For example, Jamshidian et al. [48] introduced different scenarios of an integrated RO-MED processes and the solar CHP system to evaluate technical and economical indices. However, two notable disadvantages of solar energy are its high cost and intermittent nature. Several studies have been carried out on the feasibility of integrating RO and MED technologies powered by fossil fuels for seawater desalination.

Cardona et al. [49] appraised the economic viability of a hybrid MED unit of 2000 m^3/day and a single-stage seawater RO unit with a natural gas reciprocating engine (NGRE). NGRE provided the electricity required to power the RO process while heating the feed water of the RO unit by utilising the cooling water of the MED last stage. Furthermore, the high-temperature exhaust gases produced the steam required for the MED. Fig. 17 shows the schematic diagram of the RO-MED hybrid system and the NGRE. Specifically, seawater with salinity of 38,000 ppm was fed to the MED unit and the brine of the MED unit was fed to the single-stage RO unit. Two heat exchangers were used to recover heat from the cooling jacket water and high-temperature exhaust gases. The permeate of both MED and RO units are combined to form the product line. In this regard, the model-based simulation showed that the 12 effects of MED resulted in the lowest specific energy consumption. In addition, the optimum feed temperature of the MED unit was found to be 112 °C with an exit brine temperature of 40 °C. The optimal configuration of the hybrid system shown in Fig. 17 was further investigated via simulation by varying the inlet feed flow rate of the RO unit. The results showed that 5334 m^3/day and 3334 m^3/day of the feed flow rate of MED and RO, respectively, would give the lowest freshwater production cost of the hybrid RO-MED system of USD$ 1.25/m^3 and a specific energy consumption of 4.5 kWh/m^3.

Manesh et al. [50] coupled a steam network of site utility and RO-MED hybrid system for seawater desalination. Based on a developed

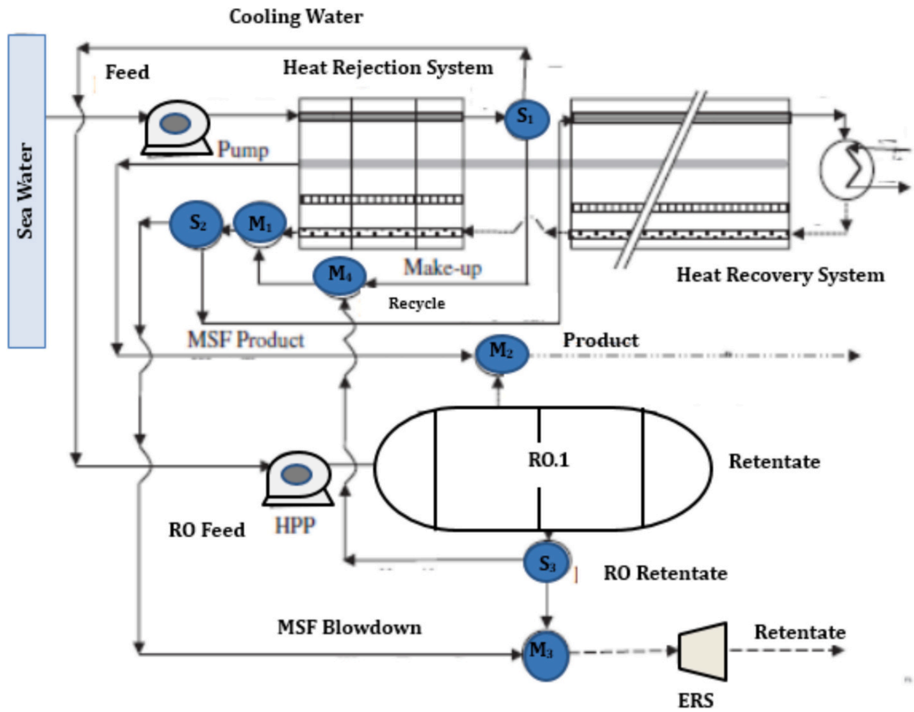

Fig. 16. A representation of the proposed optimal RO-MSF configuration (Adapted from [46]).

model, the authors provided a complete exergetic and economic analysis, and determined the best configuration of the hybrid system. Fig. 18 shows the integrated processes proposed by Manesh et al. [50] to desalinate 36,000 ppm of seawater. Six effects were selected for the MED unit with a top brine temperature of 67 °C. The multi-objective genetic algorithm was used to maximise the GOR and minimise the freshwater production cost simultaneously while finding the optimum values of operating variables of MED and RO in the hybrid system. As an example, the MED operating parameters are (60–80 °C) steam temperature, (60–80 °C) top brine temperature, (5–45 bar) motive steam pressure, (3−10) number of effects, while the operating parameters of the RO process are (40–82 bar) pump pressure, (71.97–388.8 m^3/day) feed flow rate and (5–8) number of RO membrane modules. A number of constraints such as a salinity of 250 ppm of the product water, and 70,000 ppm and 45 °C of the brine of the RO unit were imposed. The overall optimum productivity was found to be 12,6300 m^3/day, with a share of 42.2 % for the MED unit and 57.8 % for the RO unit. The highest GOR was found to be 9.1 giving the lowest freshwater production cost of USD $ 0.81/m^3 and 2.57 kWh/m^3 specific energy consumption of the RO unit.

Shahzad et al. [51] suggested a hybrid system of RO and MED with an adsorption cycle. The seawater was fed into a single-pass RO spiral wound modules with an ERD to absorb the surplus energy of the brine and operate a vacuum pump of the MED. The brine is fed into four effects evaporation adsorption system, arranged in a vertical stack, while the adsorption bed is used to adsorb produced vapour of the effects. Thus, the water recovery increases from the first effect to the last effect as a result of an integrated adsorption bed that aids to increase the evaporation rate. A schematic diagram of the integrated system is depicted in Fig. 19. A simulation model of the whole integrated processes was carried out for an inlet seawater salinity of 35,000 ppm at 25 °C, which resulted in a brine of 50,000 ppm from the RO unit that fed the evaporator-1 of the MED unit. The brine disposed of the last MED effect was around 185,000 ppm. More importantly, the proposed system obtained the highest water recovery, 81 %, with 3.5 kWh_{elec}/m^3, 1.38 kWh_{elec}/m^3 and 1.76 kWh_{elec}/m^3 specific energy consumption of RO, adsorption cycle, and hybrid system, respectively.

Sadri et al. [52] developed a comprehensive model to carry out the exergy analysis, determine the thermodynamic characteristics and evaluate the GOR of the hybrid RO-MED/TVC system. The exergy destruction including the physical and chemical exergy and the exergetic efficiency were estimated. The multi-objective optimisation based on genetic algorithm was utilised to determine the optimal coupling configuration of the RO and MED/TVC units in the hybrid system while identifying the greatest exergetic efficiency (objective function). The researchers presented the hybrid system in a series mode of parallel-cross five effect MED linked to RO unit (Fig. 20). Specifically, a portion of seawater (42,000 ppm at 25 °C) is fed into a single pressure vessel of RO unit that holds seven spiral wound membrane modules (37.2 m^2). The second portion is blended with the brine of RO and fed the MED-TVC unit for further recovery. The authors attempted to investigate the feasible ratio of input seawater into RO and MED units that lead to the highest water recovery. As a case study, the Qeshm MED distillation plant in the southern part of Iran was analysed. The simulation results showed that the maximum exergy destruction occurred in the TVC section of MED unit compared to that of the entrained and condensing vapour streams. Furthermore, the first effect of MED unit exhibited the maximum exergy destruction compared to other effects due to the high heat loss. Furthermore, the RO process was found to have a lower exergy destruction when compared to MED. The inlet parameters of the MED unit such as inlet seawater salinity and temperature, the design parameter (the number of effects) were optimised while minimising the exergy destruction of MED and RO (multi-objective function). The final optimisation results indicated 12.8 % and 8.63 % as the exergetic efficiency of RO and MED, respectively, while identifying the optimal operating variables, such as 9 effects of MED, 32 °C seawater temperature and 75 °C steam temperature. Consequently, this resulted in an increase in GOR of the integrated RO-MED/TVC system from 7.83 % to 7.85 %.

Filippini et al. [47] developed different configurations of coupling RO and MED/TVC for seawater desalination and evaluated their feasibility via comparing the performance metrics of freshwater productivity, freshwater purity, energy consumption, and recovery ratio via model-based simulation study that investigated the influence of variable

Table 1
A summary of the proposed RO-MSF hybrid systems studies for seawater desalination.

Authors and year	Type of study	Design	Inlet seawater conditions	Highlighted results: Productivity (m^3/day), product salinity (ppm), water recovery (%), specific energy consumption (kWh/m^3), and freshwater production cost (\$/m^3)	Challenges and future perspectives
El-Sayed et al. [36]	Model based simulation	A pre-treatment stage, MSF unit, and two stages of RO unit. Seawater rejected stream of the MSF is fed to RO	28 °C	Improvement of water recovery of RO by 38 % compared to a single process; 5.8–6.2 kWh/m^3	A number of operational difficulties were identified, such as membrane fouling and scaling, the requirement for routine chemical cleaning, and the necessity of exact control over the feed water flow rate.
Al-Bahri et al. [37]	Experimental	MSF and multi-stage RO. Blended seawater and water rejected steam of MSF heat rejection section are joined and fed to RO	39,500 ppm	Optimum seawater temperature between 27 and 28 °C to achieve maximum productivity between 23 and 25 m^3/day.	Despite the proposed configuration leads to higher RO water flux, fouling has not been implicitly covered. The results showed a significant decrease of water productivity as a result of increasing the operational time. Feed heating may not be viable in colder seawater conditions. Tendency of bio-fouling at higher temperature may not be avoided.
Turek [38]	Model based simulation	Pre-treatment step of UF and NF units and the hybrid RO-MSF system		61.3 %; RO: 0.63 \$/m^3; Hybrid system: 0.43 \$/m^3	To guarantee the best performance and lifespan, all units require regular maintenance and cleaning. The UF, NF, and RO membranes are susceptible to fouling, scaling, and biofilm formation, which lowers their effectiveness. The freshwater production cost.
Helal et al. [40,41]	Model based simulation and optimisation	Brine recycle MSF plant (3 rejection stages) and a two-stage RO plant. Comparison of the nine different scenarios based on minimum water cost, specific capital cost, and water recovery.	42,000 ppm; 25 °C	RO: 0.75 \$/m^3, 37.6 %; MSF: 1.1 \$/m^3, 10.7 %; Hybrid: reduced the freshwater production cost of MSF by 17 to 24 % while doubling water recovery; 750 ppm	It is critical to evaluate the optimum system's overall cost-effectiveness and viability from an economic standpoint for the desalination of brackish water less than 10,000 ppm. Capital costs, operating costs, energy usage, maintenance needs, and the price of produced water are all factors to be taken into account
Marcovecchio et al. [42]	Model based simulation and optimisation	29 stages of MSF unit and 2-stages RO process with an ERD. Part of the blow-down stream of MSF is fed into RO. A superstructure of different alternative arrangements of the hybrid MSF and RO desalination process to achieve economic improvements.	45,000 ppm; 25 °C	1.259 \$/m^3	It would be interesting to evaluate the performance of an adapted design of this study. The brine of RO can be recycled back to the brine heater of MSF for further treatment. The network configuration of the RO process including feed/retentate bypass could be considered.
Lisbona et al. [43]	Experimental	Alternative fuel cells to power RO and preheat the feed water of MSF and RO processes	36,000 ppm; 20 °C	3074 m^3/day; RO: 4 kWh/m^3, 360 ppm. MSF: GOR = 10, and less than 50 ppm	Change of the efficiency of the fuel cells depending on the operating environment. Need to size properly and optimise the fuel cell system. Need to use the waste heat produced by the fuel cell system for preheating the feed water t. Thermal management systems and heat exchangers require careful planning and optimisation. Use of solid oxide or molten carbonate fuel cells over extended periods is not financially viable.
Marcovecchio et al. [44]	Model based simulation and optimisation	Two RO units and two options of MSF unit, brine-recycling and without recycling MSF	41,000 ppm; 25 °C	Optimum configuration: Brine-recycling MSF and independent first RO unit where its brine is fed into the second RO unit. 570 ppm RO: 41143.2 m^3/day; MSF: 6861.6 m^3/day; 0.824 \$/m^3	Investigation of the optimal operating conditions that would satisfy the maximum water productivity
Wu et al. [45]	Model based simulation and optimisation	Cogeneration of power plant to provide electrical and thermal energy for the hybrid system of multistage RO and MSF (21 stages) processes, respectively	42,000 ppm; 25 °C	8000 m^3/day; 500 ppm	Challenges related with cogeneration: efficiency optimisation, integration complexity, system sizing, and water treatment considerations. Variable demand of fresh water and variable demand of power over 24 h.
Bandi et al. [46]	Model based simulation and optimisation	Five scenarios of brine-recycling MSF and a single-stage RO unit with an ERD. The cooling water reject stream of MSF is fed to the RO unit.	42,000 ppm; 25 °C	28.3 % (greatest recovery) 0.97 \$/m^3 (lowest fresh water production cost) Optimal configuration: the brine of RO was split into two streams, one as	Hybrid multi stage RO and MSF processes should be explored.

(continued on next page)

Table 1 (*continued*)

Authors and year	Type of study	Design	Inlet seawater conditions	Highlighted results: Productivity (m^3/day), product salinity (ppm), water recovery (%), specific energy consumption (kWh/m^3), and freshwater production cost ($\$/m^3$)	Challenges and future perspectives
		Challenges of different optimisation algorithm to obtain optimal result have been highlighted.		disposed stream while the other serves the make-up feed for the MSF.	

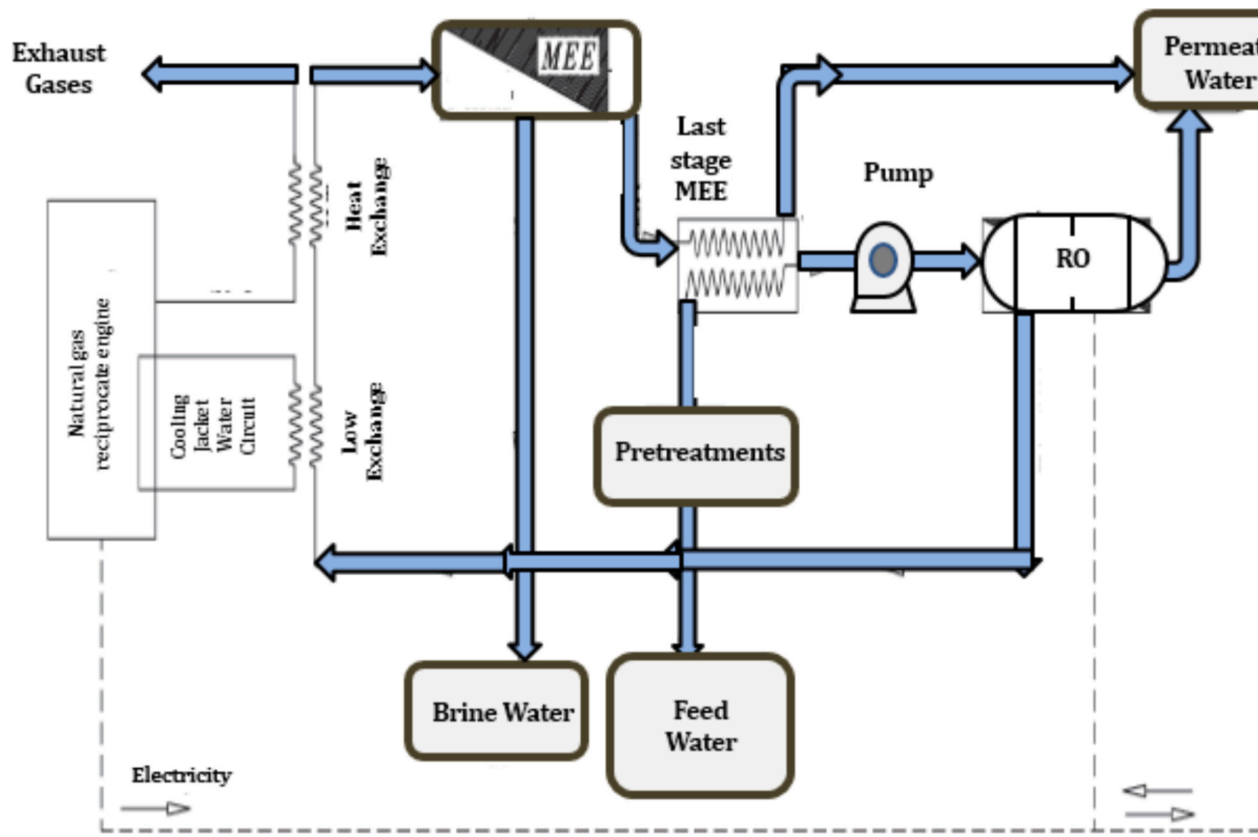

Fig. 17. A representation of the RO-MED hybrid system and NGRE to supply electricity and water (Adapted from [49]).

amount of steam and seawater conditions. The RO system contained 43 pressure vessels of three stages (a series of 20-15-8) where each pressure vessel held eight RO spiral wound modules of TM820M-400/SWRO. The MED/TVC unit is composed with ten effects where each effect comprises an evaporator, a pre-heater for the feed and a flashing box. The system was designed to take advantage of the strengths of both RO and MED/TVC units to achieve high water productivity and low energy consumption. The four configurations considered were as follows:

i)- The simple hybridization where the seawater split into two parts to feed the coupled processes of RO and MED/TVC, and therefore each process operates independently.
ii)- The RO was placed upstream in the integrated RO and MED/TVC where the RO brine was the feed water of the MED/TVC unit (Fig. 21).
iii)- The MED/TVC was placed upstream in the integrated system where the brine of the MED/TVC was the feed water of RO.
iv)- A single stage of 43 parallel pressure vessels of RO process is placed upstream in the integrated RO and MED/TVC. The brine of RO is the feed water for the MED/TVC.

Based on the quality and quantity of disposed brine, the hybrid RO-MED/TVC system was established to be the best configuration (Fig. 21) in terms of the quantity and quality of the produced freshwater when the RO unit was placed upstream. Given that the MED/TVC? process accounts for 75 % of the system's production in this configuration (RO upstream), the sensitivity analysis with the most pertinent operational parameters revealed that the quantity and quality of the produced water were significantly influenced by the amount of vapour employed in the MED/TVC? system. The simulation results with 37,000 ppm seawater salinity at 25 °C led to freshwater productivity of 7931.52 m^3/day, with an average specific energy consumption of 14.51 kWh/m^3, freshwater salinity of 138 ppm, and the recovery ratio of 36 %.

Cao et al. [53] investigated the design and performance of a hybrid RO-TVC combined with a pressure exchanger system. Fig. 22 depicts the corresponding diagram of this hybrid system with a pressure exchanger. The TVC unit contains an evaporator, a condenser, and a steam generator, while RO unit contains a high-pressure, a single membrane module and a pressure exchanger to absorb energy from the high-pressure disposed brine. The product line constitutes the freshwater obtained from both the TVC and RO units. The impact of key design parameters on the performance indicators was investigated on a series of TVC and RO configurations using a model-based technique. The TVC stage utilised a vapour compressor to elevate the temperature and pressure of seawater.

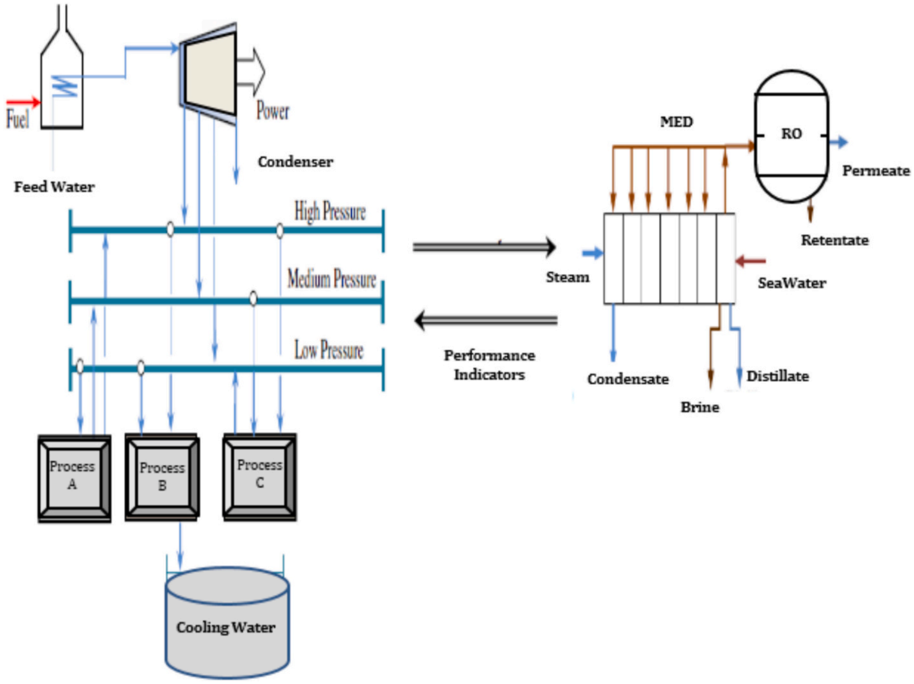

Fig. 18. A representation of the RO-MED hybrid system coupled to a steam network of site utility (Adapted from [50]).

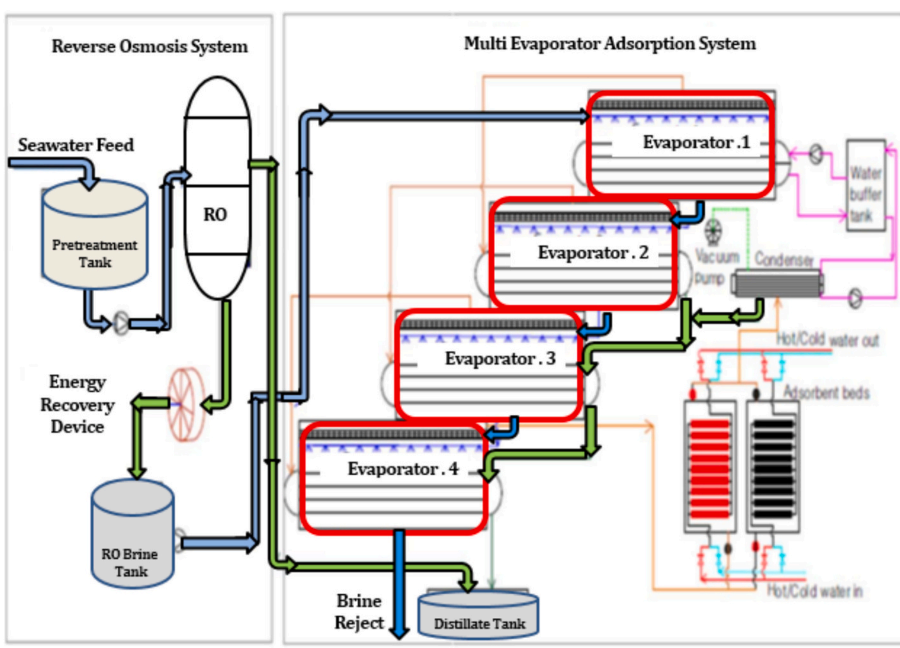

Fig. 19. A representation of RO unit and the multi-evaporator adsorption system (Adapted from [51]).

Thus, the hybrid system was designed to combine the advantages of both TVC and RO technologies to enhance the efficiency of seawater desalination. The hybrid system was designed in three configurations of TVC unit followed by an RO unit, a parallel and a stand-alone system. To assess the effectiveness of the TVC unit, the performance ratio, defined as the quantity of the produced water per unit mass of motive steam, which is identical to GOR, and the specific energy consumption were used in this investigation as performance indicators, while the considered operating variables were seawater temperature, motive steam pressure, boiling temperature, compression ratio, leakage ratio and mixing rate of the pressure exchanger of the RO process. The results demonstrated that the series RO-TVC configuration (i.e., the brine of the TVC unit is used as feed for RO unit) outperform the other configurations, namely the parallel and stand-alone systems. It was found that the RO-TVC series led to the highest performance ratio.

The improvement of performance indicators (i.e., the highest water productivity and the lowermost specific energy consumption) could be obtained at low seawater temperature, increased motive steam pressure, high boiling temperature, low compression ratio, low leakage ratio, and low mixing rate of the pressure exchanger. The lowest value of the specific energy consumption achieved was 0.659 kWh/m^3 at the boiling temperature and seawater temperature of 40.65 °C and 5.6 °C, respectively. Furthermore, the maximum performance ratio was obtained at 69.25 °C and 5.6 °C of the boiling temperature and seawater

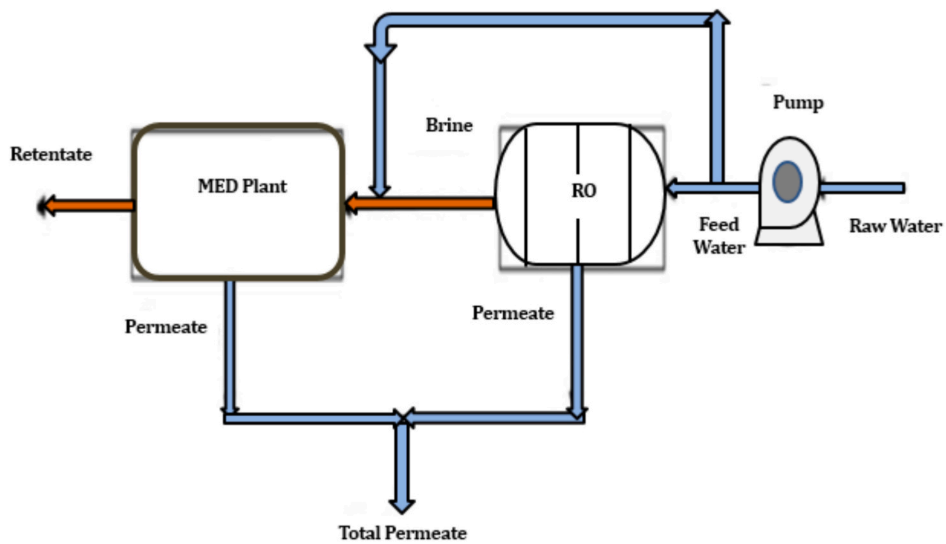

Fig. 20. A representation of the series mode of the integrated RO- MED/TVC units (Adapted from [52]).

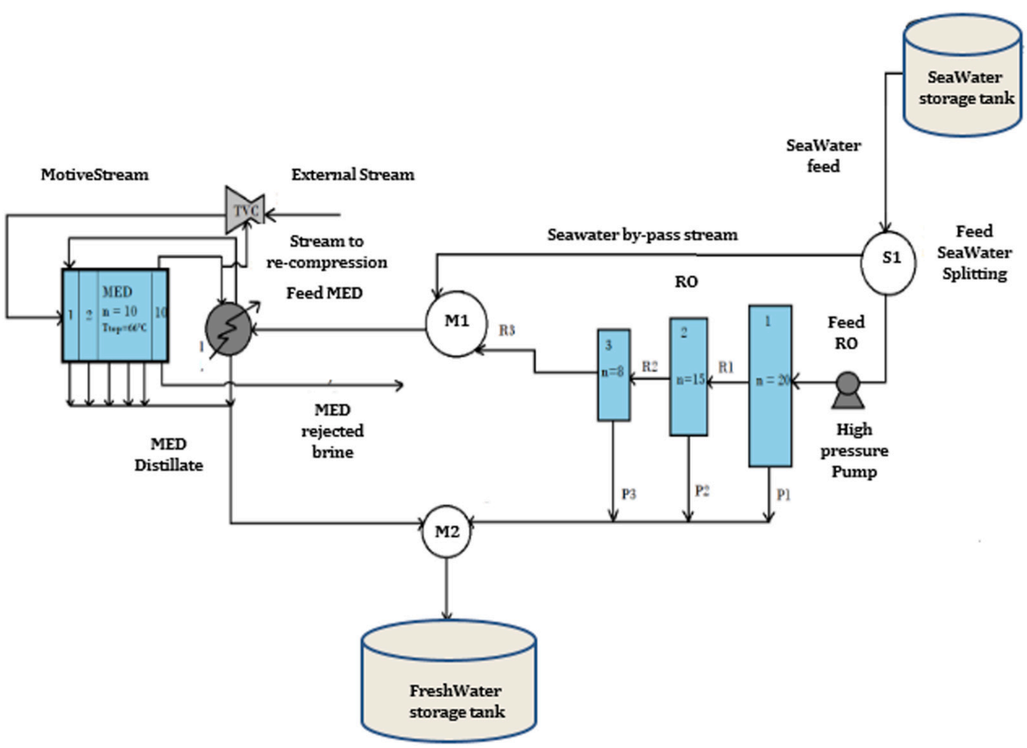

Fig. 21. RO upstream in the integrated RO-MED/TVC system (Adapted from [47]).

temperature, respectively. This outcome revealed the importance of a high boiling temperature. On the other hand, the specific energy consumption value of 1.38 kWh/m^3 was obtained at a steam pressure and compression ratio of 2.5 MPa and 3.76, respectively, indicating the importance of utilising a low compression ratio. Furthermore, the maximum performance ratio of 0.18 was obtained at a steam pressure and a compression ratio of 1 MPa and 2, respectively, showing the importance of a reduced steam pressure to get the maximum performance ratio. The minimum values of the leakage ratio and compression ratio of pressure exchangers, 0.02 and 0.06, respectively, led to a specific energy consumption of 1.064 kWh/m^3.

Sadri et al. [54] considered model based optimisation using genetic algorithm for a hybrid RO-MED/TVC with adsorption technology for seawater desalination (Fig. 23). The combination of the RO brine and part of feed seawater was used as feed for the MED unit while the last effect of the MED/TVC was linked to the adsorption process (silica gel) that used the vapour of the last effect. Sadri et al. [54] considered the RO unit to treat the MED/TVC cooling water, the water generated by the MED/TVC passes through a heat exchanger to preheat the RO feed water, the inlet RO feed water and the brine from the MED/TVC to exchange heat, and parallel RO and MED/TVC combination. Both thermodynamic and exergetic analysis of the proposed system were carried out. The simulation outcomes showed that the freshwater production cost and water productivity were US \$1.3/m^3 and 9542.88 m^3/day, respectively. Furthermore, the exergy efficiency of the proposed hybrid system was increased to 19.92 % compared to 5.97 % of the RO-MED/

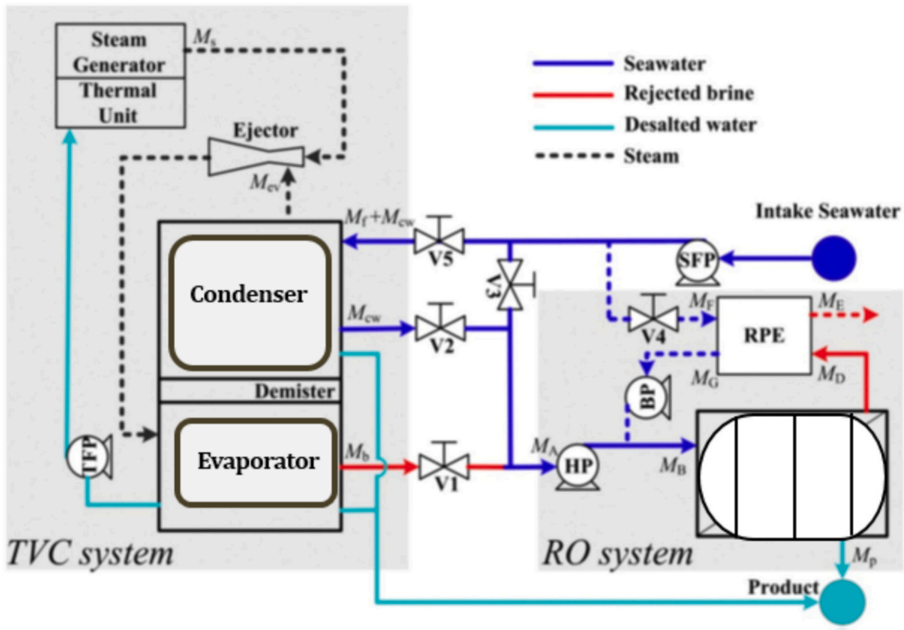

Fig. 22. A representation of an RO-TVC hybrid system with a pressure exchanger (Adapted from [53]).

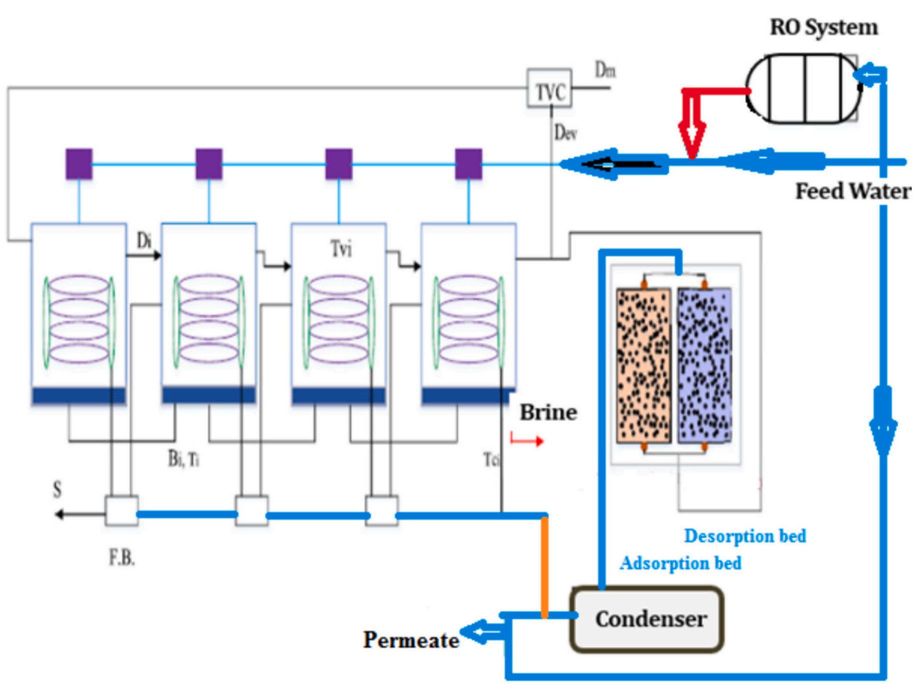

Fig. 23. A representation of the RO-MED/TVC hybrid system with adsorption unit for seawater desalination (Adapted from [54]).

TVC system. The highest exergy destruction was shown in the heat transfer process of the MED/TVC, which was up to 82 % compared to 15 % and 3 % of adsorption and RO processes, respectively. The overall productivity was increased up to 15,240.96 m^3/day (i.e., an increase of 59.7 % compared to the original plant), while the fresh water production cost was reduced 32.3 % achieving US $0.8/$m^3$. However, it should be noted that the adsorption bed system requires periodic replacement of the activated carbon to maintain its adsorption capacity besides the associated challenge of disposing of the spent activated carbon.

Al-Obaidi et al. [32] evaluated the freshwater production cost of an optimum hybrid of RO-MED/TVC system with RO as an upstream process. A developed repetitive simulation technique based model was used to investigate the influences of the variable steam flow rate and temperature of the MED/TVC unit and pump pressure, and seawater flow rate of the RO unit (being the seawater concentration 39,000 ppm and its temperature 25 °C) on the freshwater production cost of the hybrid system. It was observed that the RO-MED hybrid system outperformed the RO-MED/TVC hybrid system. An optimisation study without TVC was performed looking to achieve the best freshwater production cost. The optimised parameter values were 77.9 bar pump pressure, 9244.8 m^3/day seawater flow rate, 68.1 °C steam temperature, and 9.71 kg/s steam flow rate. Moreover, it was observed that the hybrid system was sensitive to the cost of steam and electricity. For instance, 50 % rise in energy cost resulted in a 22 % increase in the freshwater production cost. On the other hand, a 50 % increase in steam costs resulted in 7 % enhancement of the freshwater production cost.

To make the integrated RO-MED system more economically viable, the optimisation was directed to find the optimum values of the involved operational parameters to fulfil the lowest freshwater production cost. Accordingly, US $0.66/m^3 was obtained as the lowermost freshwater production cost at a specific energy consumption of 16.37 kWh/m^3, water productivity of 12,398.4 m^3/day, freshwater salinity of 122 ppm, and recovery ratio of 32.5 %. In general, the study provided valuable insights into the design, performance, and economic aspects of the integrated system and its potential to be used for seawater desalination.

Al-hotmani et al. [55] introduced five novel configurations of hybrid RO-MED/TVC desalination process based on the use of permeate reprocessing mode of the RO process (feed seawater salinity was 39,000 ppm and the temperature was 25 °C). As illustrated in Fig. 24, the permeate reprocessing mode characterises by feeding the collected permeate of proceeding RO stages (stages 1 and 2) into the third stage for further processing. The ERD is used to increase the permeate's pressure and assure the filtration in the third stage.

The developed simulation showed the superiority of a simple integrated system of permeate reprocessing mode of RO with an ERD and MED/TVC (Fig. 24) while both permeates of RO and MED/TVC were combined to form the product line. This configuration elucidated the lowest values of the product water salinity and the specific energy consumption besides the highest productivity at reduced brine flow rate and salinity. Statistically, this design required 14.259 kWh/m^3 of energy while producing 7770.816 m^3/day of freshwater at 10.88 ppm salinity leading to 30.6 % water recovery.

Saifaoui et al. [56] studied the feasibility of utilising the heat-recovery from the exothermic sulfuric acid production process to desalinate seawater using the hybrid RO-MED system. The power block was used to provide the necessary electrical energy to power RO and MED, and thermal energy for the MED unit. Fig. 25 shows the proposed configuration of RO and MED for seawater desalination using waste heat from sulfuric acid plants. The RO system includes a pre-treatment unit, a high-pressure pump, a membrane module, and a permeate collection unit. The MED system consists of multiple evaporators and a condenser. The amount of heat recovered from the sulfuric acid plant is then utilised to desalinate seawater. Precisely, the efficacy of the Rankine cycle versus the thermal heat of the RO process at various pressures and flow rates of steam was considered. The efficacy of the Rankine cycle was upgraded up to 89.58 % at 3300 kJ/kg thermal heat for a steam pressure of 20,000 kPa and steam flow rate in the evaporator of 1.5 kg/s. The outcomes of this analysis disclosed that heat coupling had a noteworthy impact on the energy and exergetic performance of electrical and water cogeneration. The volume of drinking water produced enlarged with increasing the working temperature of the RO unit, but its quality was reached up to 1545 ppm. Thus, a careful choice of the operating temperature of the RO process should be well thought-out in the proposed hybrid system.

Emamdoost et al. [57] examined the application of a thermal coupling of RO and MED technologies to advance the desalination performance in combined water and power plants. Two alternative thermal coupling configurations were considered. The first thermal internal coupling method utilised the RO brine as the condenser coolant water of the MED unit. This in turn has reduced the quantity of seawater that should be used in the condenser, positively reducing the required steam and thus reducing the energy consumption. The second method used the MED brine to preheat the feed water of the RO unit. Figs. 26 and 27 present the schematic diagrams of the integrated MED and RO units using the two methods of internal coupling. The MED unit consisted of two effects to desalinate seawater (45,500 ppm at 35 °C) while the RO unit contained 8 parallel stages of seawater membrane modules (i.e., 47 pressure vessels in each stage where each pressure vessel holds 7 membrane modules in series). The model-based simulation for the first coupling configuration indicated the possibility of having 12,000 m^3/

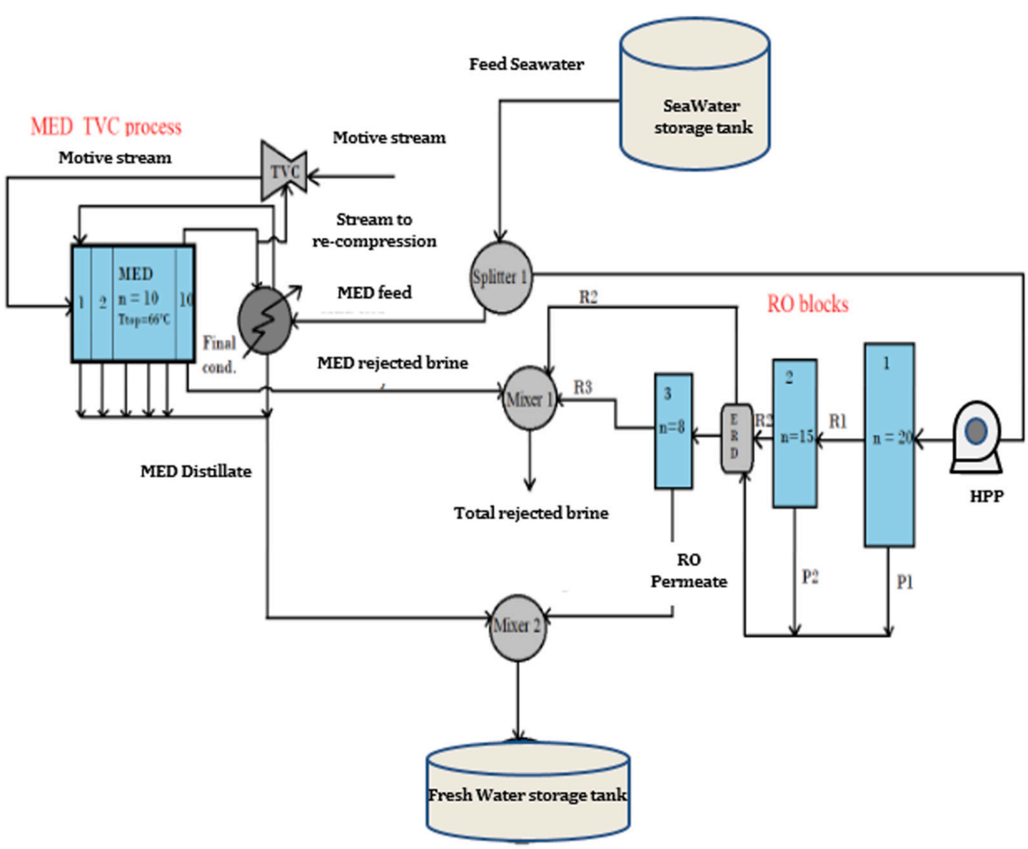

Fig. 24. A representation of integrated permeate reprocessing RO and MED/TVC units (Adapted from [55]).

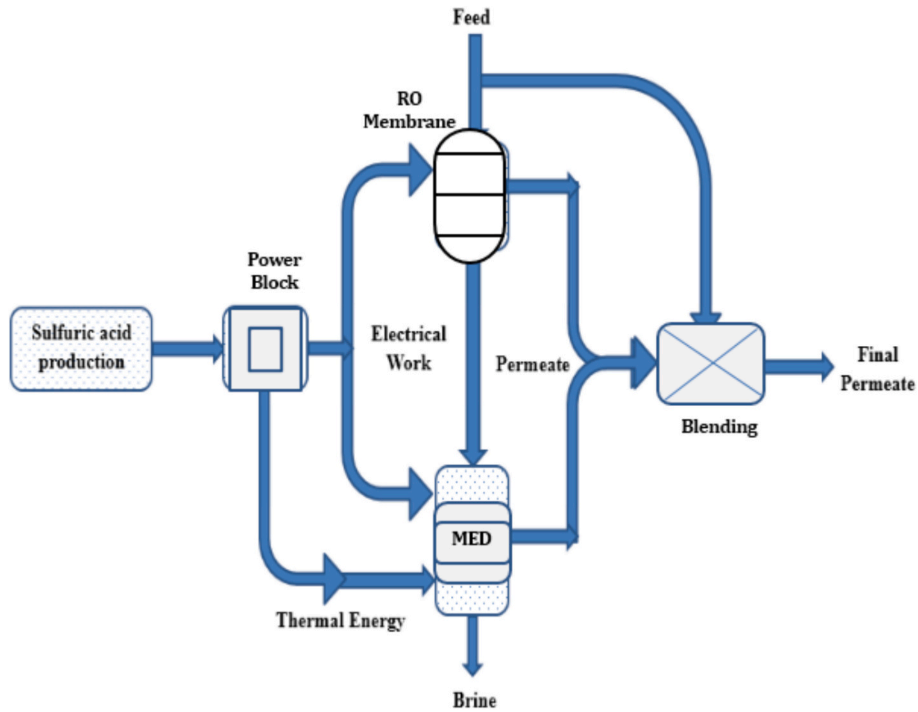

Fig. 25. An integrated system of RO and MED with heat recovery from sulfuric acid production unit (Adapted from [56]).

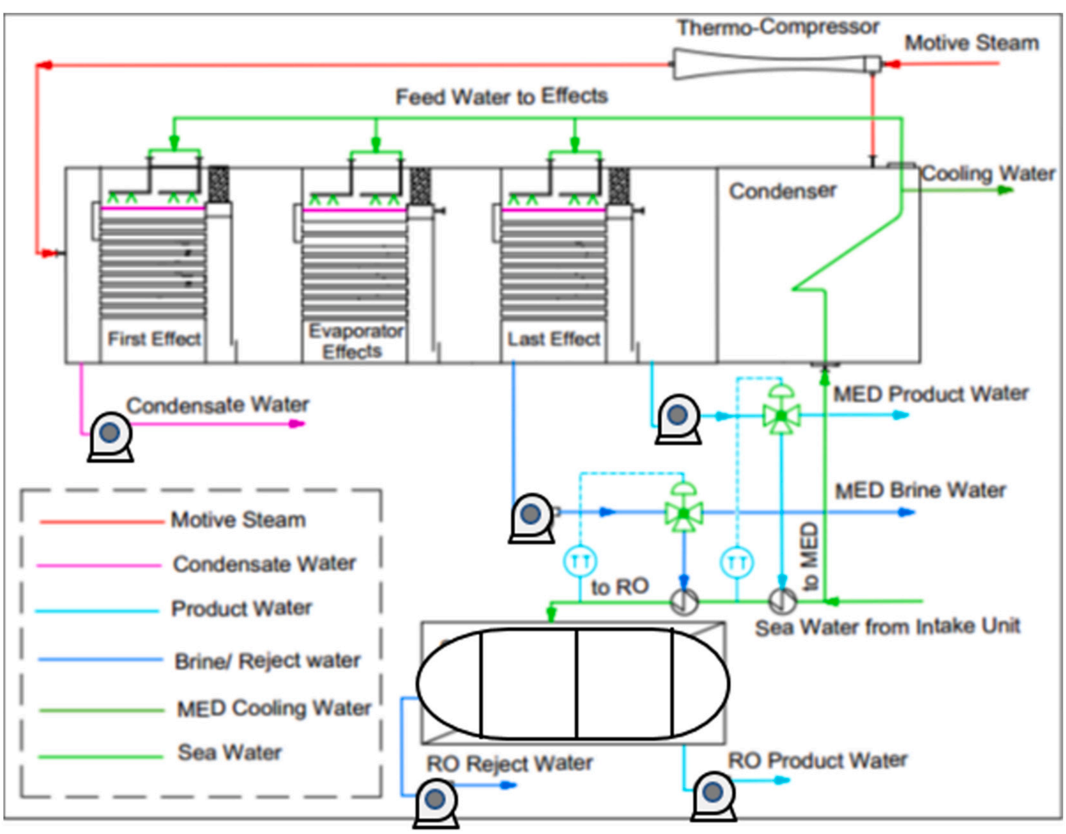

Fig. 26. An integrated system of RO-and MED using the first internal coupling technique (Adapted from [57]).

day of freshwater from the MED unit and 32,160 m^3/day of freshwater from the RO unit. In addition, the specific energy consumption of MED and RO units were 2.11 kWh/m^3 and 3.89 kWh/m^3, respectively. In this regard, the freshwater production cost of MED and RO units were 0.9 US $/$m^3$ and 0.58 US$/$m^3$, respectively. The results showed that the proposed configuration exhibited a lower energy consumption of MED, and a lower production cost of MED compared to the conventional MED and RO systems without thermal coupling.

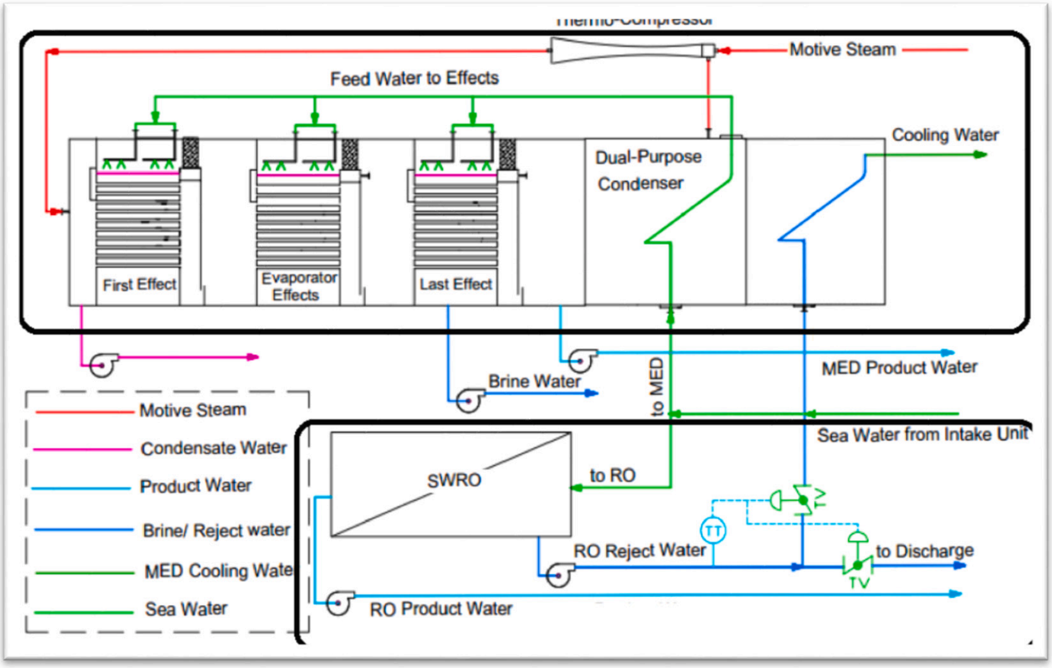

Fig. 27. An integrated system of RO and MED using the second internal coupling technique (Adapted from [57]).

The simulation of the second coupling technique presented an upsurge in specific energy consumption of RO unit to 4.6 kWh/m^3 while the MED unit consumed 3.82 kWh/m^3 compared to those achieved for the first coupling method. The water productivity of MED in this technique was the same as in the first technique while the water productivity of RO process was condensed to 15,999.36 m^3/day. Additionally, the freshwater product cost of RO and MED were 0.82 and 1.1 US$/m^3, respectively for the second coupling technique.

Al-hotmani et al. [58] demonstrated two innovative designs of double RO units including retentate and permeate reprocessing modes combined to an MED/TVC unit (Figs. 28 and 29). The permeate of the three connected units form the product line of freshwater while the retentate of the second RO unit forms the brine disposed stream.

The model-based simulation of the three connected units displayed the merits of applying the two permeate reprocessing RO units and the MED/TVC unit compared to all other configurations. Statistically, this layout displayed the lowermost specific energy consumption of 14.253 kWh/m^3, a high productivity of 8467.5456 m^3/day, and a low brine flowrate of 13,029.8976 m^3/day. The simulation outcomes obviously verified the high performance of double RO units and MED/TVC unit compared to single RO unit combined to MED/TVC unit due to the detected high water productivity and total water recovery rate, and to

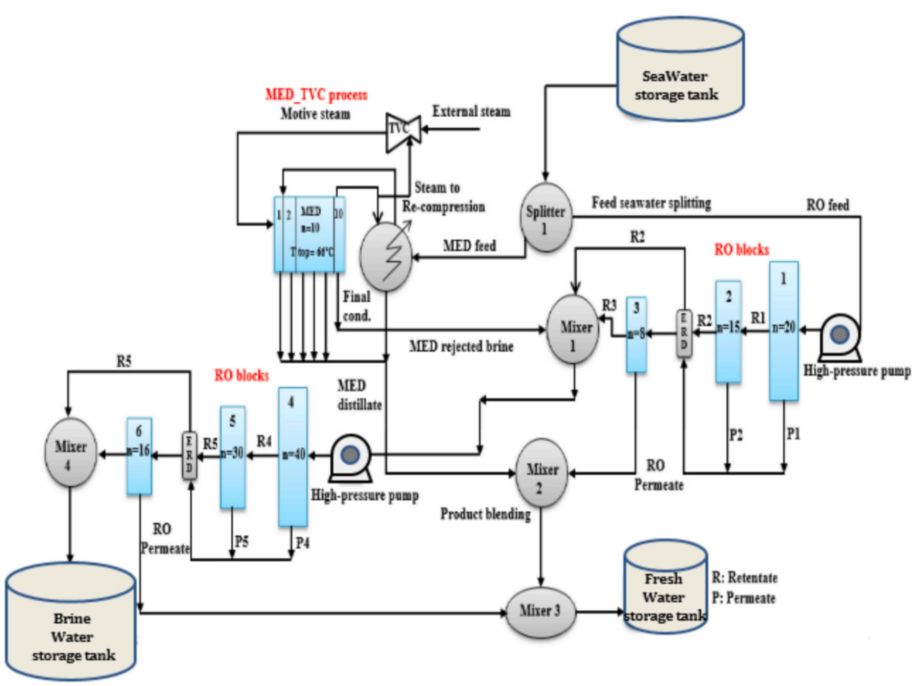

Fig. 28. A representation of double permeate reprocessing RO unit and MED unit for seawater desalination (Adapted from [58]).

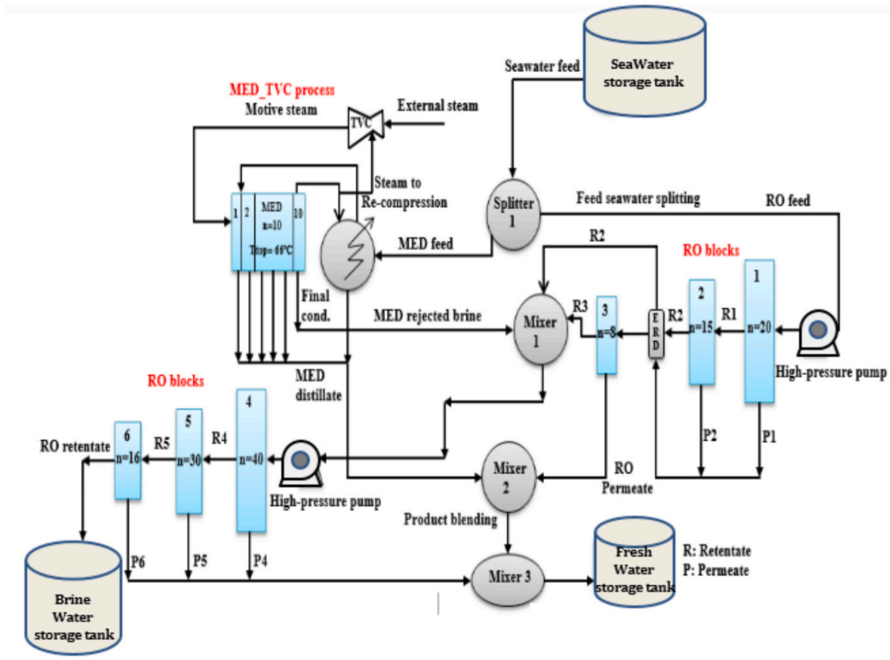

Fig. 29. A representation of integrated system of double permeate and retentate reprocessing RO modes and MED unit for seawater desalination (Adapted from [58]).

the practical lessening in disposed water at low specific energy consumption (Al-hotmani et al. [55]).

Al-hotmani et al. [59] considered a single-objective optimisation to minimise the specific energy consumption of the seawater desalination through a hybrid system established by Al-hotmani et al. [55], which integrates the permeate reprocessing RO mode and the MED/TVC while optimising a variety of operating variables. Fig. 24 presents the simple hybrid RO/MED system of Al-hotmani et al. [55] used for the treatment of seawater having 39,000 ppm and 25 °C. The continuous variables under consideration were the pump pressure, seawater feed flow rate and water temperature of RO process in addition to steam flow rate and temperature of MED process. The salinity of the product water and the overall recovery ratio were constrained at 100 ppm and 30 %, respectively.

The obtained optimisation results showed a reduction of 18.25 % of the specific energy consumption, being the optimal value 11.685 kWh/m^3 compared to that, of 14.296 kWh/m^3, claimed by Al-hotmani et al. [55]. This is associated with the optimal productivity of 9464.77 m^3/day (at 7 ppm of product salinity) compared to the one presented by Al-hotmani et al. [55] of 7770.81 m^3/day. Besides, the recovery ratio also increased from 30.66 % to 34.55 %. These improvements were conducted using 7929.44 m^3/day of feed flow rate, 59.9 bar hydrostatic pressure and 31.69 °C feed temperature as the RO operating conditions while the MED unit operated at 8 kg/s of steam flow rate and 65 °C of steam temperature.

Shakib et al. [60] appraised the benefits of integrating the hybrid RO-MED/TVC into a gas turbine cycle through a recovery steam generator. The clue behind this integration was to utilise the heat recovery steam generator to absorb the waste heat from the gas turbine exhaust and then supply the steam into the MED/TVC system to produce freshwater besides powering the RO unit via the generated electricity. In this aspect, six configurations of the combined processes were proposed considering two approaches of fixed and variable water productivity of the MED/TVC. By considering several control variables of the RO, MED/TVC and regenerator boiler and reliable constraints, a genetic algorithm optimisation was used to find out the lowest freshwater production cost for the proposed configurations. The results showed the success of using the cooling water of the MED/TVC unit as feed water of RO unit (Fig. 30). Unquestionably, this arrangement distinguished itself by increasing the feed water temperature for the RO process, which was beneficial to accelerate water permeation. The RO unit was powered by the gas turbine cycle's generated electricity, which was the configuration's second benefit. Statistically, this configuration exhibited the lowest freshwater production cost for the first approach of different capacities, US$ 0.77, 0.81 and 0.82 per cubic meter of freshwater for the overall productivity of 105,000, 122,500, and 140,000 m^3/day, respectively. Furthermore, the second approach of the fixed capacity 140,000 m^3/day obtained a value of US$ 0.74/m^3 as the lowest freshwater production cost. It was also claimed that the optimal configuration had the lowest emissions of greenhouse gases.

Al-hotmani et al. [35] proposed a novel design of a double RO unit with two configurations of permeate and retentate reprocessing modes combined to 10-effect of MED to desalinate seawater of 39,000 ppm at 25 °C. Fig. 31 presents a schematic diagram of this integrated system where the first permeate reprocessing RO process contains three blocks of parallel pressure vessels where eight spiral wound modules of Toray membranes were packed inside each pressure vessel in a series. The second retentate reprocessing RO unit contains three blocks of 40, 30, and 16 pressure vessels. The ten effects of MED were designed to operate at 1300 kPa, 8 kg/s, and 70 °C of steam pressure, steam flow rate, and temperature, respectively. The collected brine of the 1st RO unit and the MED unit is treated in the 2nd RO unit, and therefore the 2nd RO unit was designed with a higher number of pressure vessels compared to the 1st RO unit.

The proposed hybrid system of Al-hotmani et al. [35] produced 8521.26 m^3/day with a salinity of 278.66 ppm while consuming 15.7 kWh/m^3. The optimal values of the inlet feed flow rates and feed pressure of the 1st and 2nd RO units, and steam flow rate and temperature have guaranteed an increase of water productivity to 13,786.4 m^3/day (i.e., an enhancement of 61.7 %) besides a significant reduction of the specific energy consumption of the hybrid system to 8.756 kWh/m^3 (i.e., decrease of 44.22 %). The authors manipulated the original design of the hybrid system with the aid of optimisation to provide different grades of water for different applications simultaneously. Specifically, drinking water, distilled water, irrigation water, hospital and lab water, power plant water and water for livestock were produced from seawater

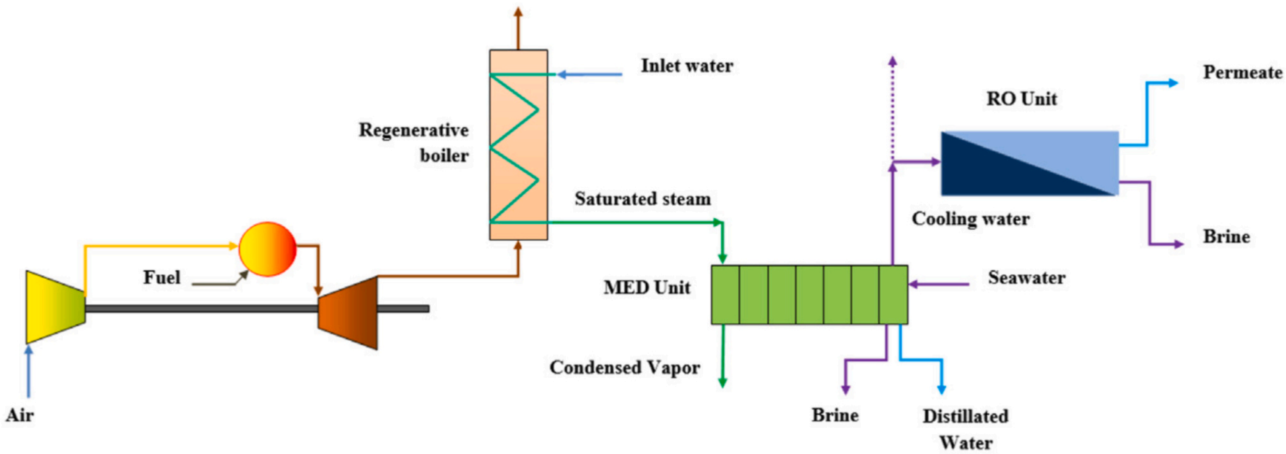

Fig. 30. A representation of the RO-MED system and gas turbine cycle (Adapted from [60]).

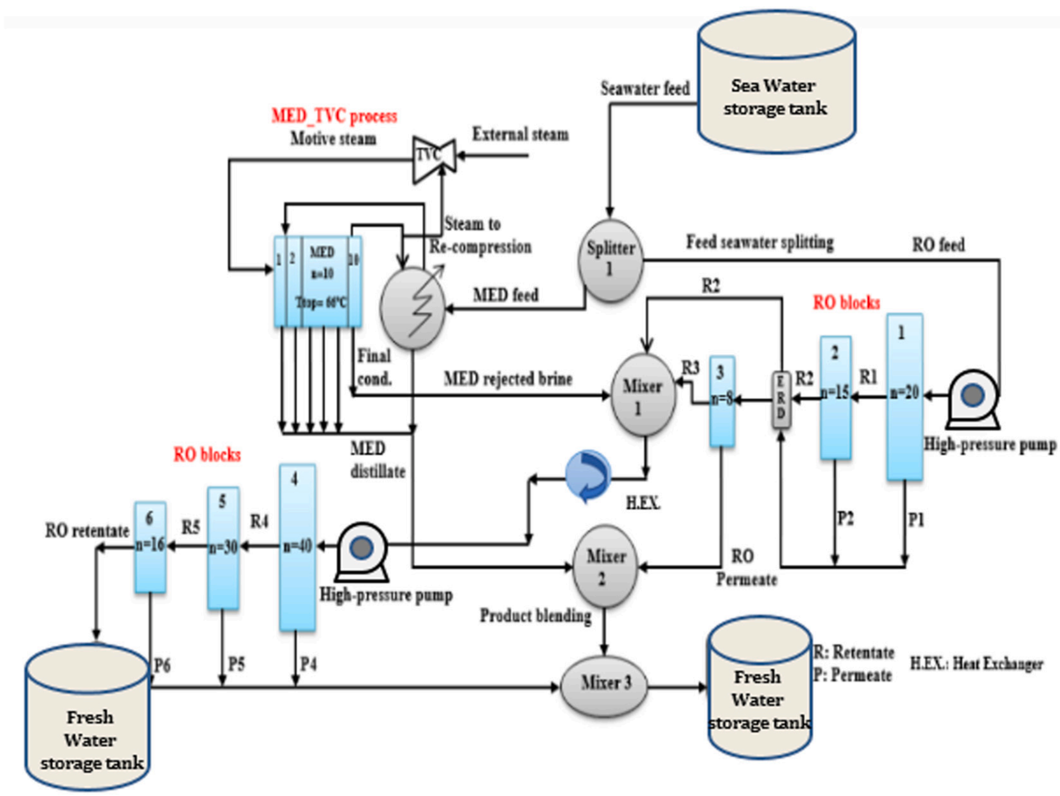

Fig. 31. A representation of integrated system of MED/TVC and double RO units (Adapted from [35]).

resources while reducing the disposed brine into the environment. This had introduced a feasible option for a smart city considering the concept of the food-energy-water nexus. Generally, Al-hotmani et al. [35] suggested that the combination of MED and double RO units could provide a more efficient and cost-effective approach for seawater desalination. The optimisation of the hybrid systems reduced the energy consumption and increase the water production rate compared to standalone MED or RO units or the hybrid RO-MED system developed by Al-hotmani et al. [55].

Table 2 summarises the conducted studies of RO-MED units proposed for seawater desalination. These studies provide information on the performance, operational and economic aspects of the hybrid RO-MSF system, as well as the challenges and feasibility of its implementation in seawater desalination.

Interestingly, each of the hybrid configurations mentioned in Tables 1 and 2 has been subjected to a constant feed salinity. The Arabian Gulf experiences different seawater salinity throughout the year [61]. It would therefore be interesting to evaluate the performance of each of these configurations for various feed salinity.

5. Comparison, critical and performance evaluation of RO-MSF and RO-MED hybrid systems proposed for seawater desalination

Various energy needs for both RO-MSF and RO-MED hybrid systems (i.e., thermal energy for MSF and MED units and mechanical energy for RO unit) represent a key distinction between these desalination processes. In general, MED-TVC uses less total electrical equivalent (electrical and thermal) compared to MSF, 6.5–11 kWh/m^3 and 13.5–25.5

Table 2
Proposed studies of the hybrid RO-MED systems for seawater desalination.

Authors and year	Type of study	Design	Inlet seawater conditions	Highlighted results: Productivity, product salinity, water recovery%, specific energy consumption, and freshwater production cost	Challenges and future perspectives
Cardona et al. [49]	Simulation based model	12 effects of MED and a single-stage RO process with a natural gas reciprocate engine. The brine is fed to RO unit	38,000 ppm	2000 m^3/day; 4.5 kWh/m^3; 1.25 \$/m^3	A significantly unbalanced energetic point of view was concluded when it is connected in parallel to the grid. Using an ERD like pressure exchangers or turbine systems, the operation can use less energy by recovering energy from the RO brine stream.
Manesh et al. [50]	Simulation and optimisation-based model	A steam network of site utility connected to 6 effects of MED and RO units to provide electricity via a steam turbine, steam, mechanical power, and cooling water	36,000 ppm	12,6300 m^3/day; 250 ppm; 0.81 \$/m^3; RO: 2.57 kWh/m^3; MED: GOR = 9.1	MED and RO units need to be connected to a steam network, which calls for effective energy integration. Future improvements in energy integration methods, such as those in heat exchanger design, steam management systems, and thermodynamic optimisation, may boost the linked system's total energy effectiveness.
Shahzad et al. [51]	Simulation based model	A tri-hybrid system of a single pass RO spiral wound modules with an ERD and four effects evaporation adsorption system (arranged in a vertical stack). The RO brine is fed into the MED unit while the adsorption bed is used to adsorb the produced vapour of the effects	35,000 ppm; 25 °C	81 %; RO: 3.5 kWh_{elec}/m^3; Adsorption cycle: 1.38 kWh_{elec}/m^3; Hybrid system: 1.76 kWh_{elec}/m^3	The optimal ratio of the recycled brine needs to be addressed to further promote water recovery. The fouling of the RO membranes remains significant challenges and therefore it needs to be addressed for optimal system performance.
Sadri et al. [52]	Simulation and optimisation-based model	Five MED and TVC connected in a series mode to parallel-cross RO unit	42,000 ppm; 25 °C	Exergetic efficiency of RO and MED are 12.8 % and 8.63 %, respectively	It is beneficial to carry out a detailed cost-benefit analysis and assess the integrated system's long-term financial viability.
Filippini et al. [47]	Simulation based model	Different configurations of coupling RO (a series of 20–15-8 pressure vessels, each pressure vessel holds 8 spiral wound modules) and 10 effects of MED/TVC unit	37,000 ppm; 25 °C	Optimum configuration of upstream RO and MED-TVC: 7931.52 m^3/day; 138 ppm; 36 %; 14.51 kWh/m^3	Further simulation is required to systematically evaluate the influence of fouling on the overall performance indicators. An ERD is important to be tested under an optimal configuration
Cao et al. [53]	Simulation based model	Three arrangements of TVC linked to RO in a series combined with a pressure exchanger system. The brine of TVC is used as feed for RO	–	1.38 kWh/m^3; TVC: 0.18 of performance ratio	Simultaneous optimisation of all parameters should have been considered. The recovery of energy from the RO brine stream is made possible by the incorporation of a pressure exchanger system. Additional research studies are needed to engage the turbine systems or isobaric ERD.
Sadri et al. [54]	Simulation and optimisation-based model	RO-MED/TVC with adsorption cycle. The RO brine and a part of feed seawater is the feed of the MED unit while the last effect of the MED/TVC is connected to an adsorption process (silica gel) that uses the vapour of the last effect	–	15,240.96 m^3/day; 0.8 \$/m^3; Hybrid: 19.92 % of exergy efficiency	The most related challenges to the adsorption cycle are the selection of the appropriate adsorbent material and the pre-treatment method to optimise the performance of the hybrid system. The disposal of the spent adsorbent material and the need for proper disposal methods are relevant challenges
Al-Obaidi et al. [32]	Simulation and optimisation-based model	An optimum hybrid system of the upstream RO unit and the MED/TVC unit was presented by Filippini et al. [47].	37,000 ppm; 25 °C	12,398.4 m^3/day; 122 ppm; 32.5 %; 16.37 kWh/m^3; 0.66 \$/m^3	RO membranes are prone to fouling due to the presence of impurities in the feed water. It would be interesting to involve the influence of fouling on the operational parameters especially for a prolonged operation and to ensure a reliable operation of the system.
Al-hotmani et al. [55]	Simulation based model	Five novel configurations of different upstream processes of the hybrid RO-MED/TVC system based on the use of permeate reprocessing model of RO unit	39,000 ppm; 25 °C	7770.816 m^3/day; 10.88 ppm; 30.6 %; 14.259 kWh/m^3	It is viable to evaluate the overall performance of the proposed configurations in case of the MED brine to preheat the feed of RO
Emamdoost et al. [57]	Simulation based model	Two methods of integrated RO-MED system. First, the internal coupling method uses the RO brine as the condenser coolant water of the MED unit. The second method uses the brine of the MED unit to preheat the feed water of RO unit	45,500 ppm; 35 °C	First coupling method: MED: 12000 m^3/day, 2.11 kWh/m^3, 0.9 \$/m^3 RO: 32160 m^3/day, 3.89 kWh/m^3, 1.1 \$/m^3 Capacity ratio of RO-MED: 2.7. Second coupling method: MED: 12000 m^3/day, 3.82 kWh/m^3, 0.9 \$/m^3 RO: 15999.36 m^3/day, 4.6	The study claimed the superiority of the second coupling method, which necessitates further investigation to optimise the decision variables and to mitigate the freshwater production cost and specific energy consumption

(continued on next page)

Table 2 (*continued*)

Authors and year	Type of study	Design	Inlet seawater conditions	Highlighted results: Productivity, product salinity, water recovery%, specific energy consumption, and freshwater production cost	Challenges and future perspectives
				kWh/m^3, 0.82 $/m^3 Capacity ratio of RO-MED: 0.33	
Al-hotmani et al. [58]	Simulation based model	Two novel designs of double RO units including permeate and retentate reprocessing modes integrated to the MED/TVC unit	39,000 ppm; 25 °C	8467.5456 m^3/day; 14.253 kWh/m^3	The simulation introduced only a marginal improvement in the specific energy consumption compared to the configuration presented by Al-hotmani et al. [55]. Optimisation is vital to reduce the specific energy consumption and improve the water recovery
Al-hotmani et al. [59]	Simulation and optimisation-based model	An integrated system of permeate reprocessing RO mode and the MED/TVC unit	39,000 ppm; 25 °C	9464.77 m^3/day; 7 ppm; 34.55 %; 11.685 kWh/m^3	Despite the good results achieved compared to those claimed by Al-hotmani et al. [55] and Al-hotmani et al. [58], further boost of the energy savings can be made in conjunction with a renewable energy source
Shakib et al. [60]	Simulation and optimisation-based model	Six different configurations of a gas turbine cycle are integrated to the RO-MED/TVC through a recovery steam generator. Optimal configuration: Cooling water of the MED/TVC unit used as feed water of RO unit	–	105,000 m^3/day, 0.77 $/m^3; 122,500 m^3/day, 0.81 $/m^3; 140,000 m^3/day, 0.82 $/m^3	Maximising the integrated system's overall energy efficiency is one of the main difficulties. Gas turbines produce waste heat that can be used in the RO-MED system while also producing electricity. Due to variations in operating conditions and the requirement for efficient heat transmission, attaining optimal energy integration among various systems can be challenging.
Al-hotmani et al. [35]	Simulation and optimisation-based model	Hybrid system of MED/TVC unit and double RO units (permeate and retentate reprocessing modes)	39,000 ppm; 25 °C	13,786.4 m^3/day; 278.66 ppm; 8.756 kWh/m^3	Limitations include the complexity to maintain a steady water productivity from the related processes for long-term operation due to fouling, especially for RO process, which reduces water productivity and overall performance. Finding a better way to limit high salinity brine from spreading is crucial to learning about an appealing and eco-friendly approach to keep the environment safe. The current study made the assumption that the salinity and temperature of seawater were fixed, and as a result, it did not discuss how these variables vary seasonally.

kWh/m^3, respectively. Considering the nominal specific energy consumption of RO process, which is between 5 and 9 kWh/m^3 (electrical only), it can be said that the RO-MED/TVC hybrid systems use less specific energy consumption than RO-MSF systems [62]. This is due to the lower operating temperatures required by the MED/TVC combined system, while the integration with TVC further improves the whole efficiency. In the same context, it should be noted that the integration of RO-MSF and RO-MED has positively impacted the specific energy consumption and performance ratio. For instance, Al-hotmani et al. [55] ascertained the superiority of utilising hybrid system of permeate reprocessing mode of RO with an ERD and MED/TVC that enables to have 14.259 kWh/m^3 of energy at a productivity of 7770.816 m^3/day and 10.88 ppm product water salinity leading to an overall water recovery of 30.6 %. Expectedly, the integrated RO-MSF would operate with a bit higher specific energy consumption due to having a greater top brine temperature.

Due to the simple geometry, easy operation and the existence of TVC, the MED has a reduced initial investment and maintenance cost, a lower rate of corrosion, a higher lifetime, and a lower pumping energy consumption compared to standard MSF thermal units [63].

The MED technology exhibits a lower freshwater production cost compared to MSF technology (i.e., 0.52–1.01 US $/m^3 compared to 0.52–1.75 US $/m^3). Accordingly, the hybrid RO-MED system has a lower freshwater production cost compared to the integrated RO-MSF system [64]. This is due to the lower energy consumption and lower capital cost of the MED system.

High water recovery rates are possible with both RO-MSF and RO-MED hybrid systems. The RO coupling in both hybrid systems enable greater recovery of freshwater from the rejected brine and higher quality produced water. The actual amount of water recovered depends on a number of variables, including the operating conditions such as the pumping pressure, feed flow rate and temperature, and system design such as the configuration type, number of stages, number and types of RO modules, RO membrane characteristics (permeability, rejection factor, fouling resistance, etc.), and feed water quality, which varies widely depending on the location of the installed hybrid plants [65].

Systems like RO-MSF and RO-MED/TVC both provide the highest quality freshwater. Potable water is produced as a result of the efficient removal of dissolved salts and contaminants by the RO process.

In general, thermal processes produce high purity water compared to membrane-based processes. Salinity up to 500 ppm is tolerated for potable water in many countries. However, hybrid processes allow production of different grades of water required for different purposes in smart cities [35].

Because of its superior efficiency, which is obtained from low operating temperatures, lower energy consumption, cheap capital cost, and high distillate recovery, MED desalination technology is preferred over MSF one for the utilisation of thermal energy in RO hybrid systems. However, because the MSF technology is currently in use and presents around 21 % (Fig. 1) of the total installed capacity, several scientists have investigated the hybridization proposal centred around MSF. However, the MED can be considered as an ideal option to be integrated with RO process as a result to its low sensitivity to treated water salinity compared to MSF. In other words, the efficiency and performance indicators of MED process are less affected by variations in the salt content of treated water due to its lower operating temperature in a comparison to MSF process. Specifically, the treated water in MSF process is rapidly flushed to vapour at high temperature which leads to a sudden increase in salinity of remaining liquid, which makes it more sensitive to any change in treated water salinity. However, the treated water in MED process is subjected to evaporation in multi effects and condensed vapour is used to heat the subsequent effects. Thus, the water salinity increases gradually in the subsequent effects and therefore the process is less affected to any variation in the incoming water salinity.

In addition to the increasing energy efficiency with excellent recovery yields, MED enables RO processes to discharge zero liquid to the environment (i.e., brine salinity discharge near to salt saturation conditions) [66,67]. Furthermore, the utilisation of the RO-MSF with crystallisation (i.e., salt production step) and adsorption system has enabled to reach zero liquid discharge and high water recovery [38,68]. To achieve it, nevertheless, is challengeable due to scale formation on heat exchanger surfaces brought on by the precipitation of calcium, magnesium, and silica salts.

The economic and freshwater production cost analysis revealed that the hybrid RO-MSF and RO-MED systems could produce freshwater at a lower cost than either the stand-alone MSF, MED and RO systems. This is attributed partly to the higher water recovery achieved by the hybrid systems. In general, both hybrid systems could provide a reliable and cost-effective solution for large-scale seawater desalination, and the proposed modelling and optimisation frameworks could be applied to design and optimise such systems.

The RO-MSF hybrid systems are well suited for high-capacity applications because they have been frequently used in large-scale desalination plants. Additionally, for scalable and usable in medium- to large-scale facilities the RO-MED/TVC hybrid system exhibits more industrial potential.

Specific research should be conducted to solve scale deposition as a result to precipitation of Calcium and Magnesium salts on heat exchanger tubes of MSF units. Furthermore, efforts should be exploited to mitigate the propensity of corrosion in the flash chambers and condensers of MSF due to the existence of non-condensable gases such as CO_2 and O_2 in an aggressive environment. The same concerns also exist in the MED units.

Research should focus on creating cutting-edge distillation methods for MED systems. To increase the energy efficiency and thermal performance of the distillation units and to lower the energy consumption and operating expenses of the integrated RO-MED systems, advanced heat exchanger designs, unique topologies, and optimised process control algorithms should be considered.

The energy efficiency can be enhanced through the effective use of the produced waste heat during the MSF and MED distillation technologies (i.e., high temperature brine). By recovering and reusing waste heat from distillation units, techniques including heat integration, heat recovery, and heat exchange techniques can be used to lessen the dependency on external energy sources and increase the ecological viability of the RO-MSF and RO-MED desalination systems. For instance, the overall energy usage can be decreased by pre-heating seawater prior to RO treatment using waste heat from MSF and MED distillation units. The majority of designs employ the reject stream from the MSF plant's heat rejection section as the RO feed water. Specifically, this arrangement has the maximum water productivity of RO process. This arrangement offers reduced chemical use, decreased membrane replacement rates, and increased membrane service lifetime. Thus, further investigations are required to optimise the operational design of this configuration and look at the optimal ratio of brine recycling for further improvement of water recovery. Furthermore, it is vital to test and investigate the possibility of using high-temperature brine that exits the MED units as a feed for the RO plants during the cooler seasons. Such a combination will boost plant productivity and lower the energy needs of the RO process. Special care must be taken to use adequate RO membrane modules capable to withstand the desired temperatures.

Enhancements in cost and energy efficiency have been made to the standard RO system design by using innovative RO membrane module designs, including large diameter spiral wound modules (increase in surface area of a higher productivity), high RO performance membranes (i.e., high permeate flux and salt rejection factor) and reduced fouling/scaling tendencies. Additional advancements in cost reduction will be probable with more study and technological improvement in system design and energy recovery.

Significant improvements in energy recovery have been made possible through the advancement of energy recovery technologies. Thanks to the transfer of hydraulic energy from the high-pressure RO brine to the seawater, which reduces the energy consumption of high-pressure pumps of RO technology. Using the new conversion of energy recovery devices, called Pressure Exchanger (PX) devices, which are designed with an energy efficiency greater than 95 % [14] will allow a considerable reduction of the specific energy consumption of RO process combined with MSF and MED units.

The development of enhanced membrane materials, including graphene oxide, nanocomposites, thin-film nanocomposite membranes, and membranes capable to withstand high temperatures and pressures with high chemical and mechanical resistances builds on the idea of innovative materials for membranes and offers promise for better RO performance. Some of these membranes exhibit reasonably high salt rejection factors, improved water permeability, and good fouling/scaling resistance, resulting in effective RO desalination membranes with long life-time [69,70]. This would then have the significant benefit of increasing the water production rate and recovery of the RO-MSF and RO-MED hybrid systems.

Complex optimisation procedures such as particle swarm methodology, genetic algorithm, and species-conserving genetic algorithm are hardly used to hybrid RO and thermal technologies-based seawater desalination. In this sense, greater efforts must be made, especially for multi-objective optimisation, to assign the best cost-effective design of a multi-stage RO process and MSF or MED processes under optimal energy and environmental impact options.

The permeate reprocessing mode of RO process integrated to MSF thermal desalination has not been investigated in the open literature. Thus, there is a need to explore the feasibility of this design.

The naturally occurring element boron, which is present in saltwater, can provide problems for some applications because of its toxicity and potential negative influences on the environment and human health [71,72]. A specific study is required to investigate the performance of hybrid RO-MSF and RO-MED systems towards the specific removal of boron from sweater.

The integration of the RO-MSF and the RO-MED systems to the adsorption system is valuable to be developed and analysed in a systematic research studies. There is a high possibility of significantly mitigating brine disposal via improving the operation of such hybrid systems.

The MSF and RO have been combined to maximise the benefits of mixing the by-products of the two technologies. This is specifically conducted by using some of the saltwater remaining after heat rejection as a make-up for the RO process and combining the RO brine discharge with the MSF brine recycling (see for example, Figs. 9 and 10) [40,42]. There is therefore a necessity to explore the advantages of such design in the hybrid RO-MED system.

Cogeneration of power plants for a hybrid system of multistage RO and MSF presents challenges in terms of efficiency optimisation, integration complexity, system sizing, and water treatment considerations. However, it also maintains exciting potential in terms of energy efficiency, sustainability, operational flexibility, and integration with energy storage technologies [45,73]. To achieve smooth operation and effective energy use, the operating conditions, such as temperature, pressure, and flow rates, must be optimised.

A viable direction for future development is the integration of forward osmosis (FO) with MED and RO systems. Utilising a draw solution (such as wastewater, RO brine) to desalinate seawater, FO can assist as a pre-treatment step before MSF [15] and RO [74–76] are used to further treat the water. This integration can rise water recovery while dropping energy usage.

The combination of adsorption mode of activated carbon to RO system has acknowledged essential advantages including the enhanced removal of organic matter, reduced fouling, and boosted overall performance [77]. It would be valuable for the horizon of this design to be connected to MSF and MED units and appraise the consequences.

Integrated systems, which optimise energy use and lessen the ecological effects of seawater desalination, offer encouraging solutions to the rising worldwide concern for environmental sustainability. The hybrid systems joining thermal and RO membrane techniques can mitigate greenhouse gas emissions and the overall carbon footprint linked to desalination by increasing energy efficiency. For example, the exergy analysis and energy optimisation of the hybrid RO-MSF and RO-MED systems would offer an opportunity to lessen the overall specific energy consumption.

Intelligent process optimisation approaches hold the key to the success of integrated systems in the future. By using available data of different types of desalination plants and by adjusting factors like feed flow rates, temperature, pressure, brine recycling, top brine temperature, steam mass flow rate and temperature, etc., artificial intelligence (AI) algorithms, machine learning, and advanced control systems can optimise the operation of both RO-MSF and RO-MED desalination plants, leading to improved energy efficiency, increased water production, and decreased maintenance needs.

Most studies covered in Tables 1 and 2 considered a fixed water demand for both hybrid RO-MSF and RO-MED systems. However, real-world water demand fluctuates throughout the day and seasons. Thus, the future research should emphasis on the challenge of adapting operational and design parameters to meet variable water demands. To resolve this issue, it is vital to develop adaptable hybrid systems that can effectively alter their operation to accommodate changing water needs and assuring a continuous and dependable water supply throughout the year. Another critical issue is the maintenance of the hybrid RO-MSF and RO-MED systems, that is crucial for continuous water production. This difficulty can be minimised by utilising strong control methods and creative maintenance techniques. Al-Obaidi et al. [78] introduced a specific study to simulate and optimise four designs of multi stage RO process to compute the production of different grades of water in terms of salinity. The results showed optimal operating conditions without plant shutdown besides preserving the membrane modules throughout the year.

While RO-MSF and RO-MED systems may suffer from fluctuating feed water conditions, system stability, control, and reliability issues arise when the integrated system is exposed to transient operations, such as start-up, shutdown, or variable water demand. Therefore, the adoption of sophisticated control and optimisation algorithms should be developed to improve the integrated system's performance and functionality.

Although considerable work has been achieved in cost reduction through the hybridization of desalination technologies, it is believed that there is more room for improvements through design modifications. Different configurations can be examined for more efficient desalination process (e.g. Optimum number of stages, full use of rejected heat from cooling water and blowdown brine, location, etc.).

There is an immediate need to develop efficient desalination technology in a world where freshwater is becoming progressively scarcer. The earlier sections have discussed the integrated RO-MSF and RO-MED systems in detail, demonstrating how well they work when using fossil fuels to desalinate seawater. However, an abundance of new technologies is on the horizon, and the desalination scene is changing quickly. These creative strategies, which combine thermal and membrane desalination technologies and are fuelled by fossil fuels, present promising answers to the urgent problems associated with water scarcity. Now, we are going to take a brief look at these state-of-the-art hybrid systems that have the potential to influence seawater desalination in the future.

6. Other hybrid membrane and thermal desalination processes with fossil fuel as energy sources

6.1. Hybrid RO-MD

Membrane distillation (MD) can be partially tagged as thermal desalination. In MD, feed water is heated using thermal energy (fossil fuel based) and a porous hydrophobic membrane is placed in between the hot feed on one side and colder permeate on the other side. The temperature difference between the two fluids leads to vapour pressure difference across the membrane and results in evaporation of more volatile compounds on the hot side, which is transported through the membrane. Four different MD configurations have been cited in the literature [12,79]. It is a highly energy intensive process, yet to find wide commercial application. Use of hybrid energy systems (i.e., combining fossil fuel and renewable energy systems) would be a way forward but significant amount of research will be required. Zaragoza et al. [80] concluded that although MD is an attractive technology for solar-powered decentralized desalination it is yet to find itself commercially viable due to high energy consumption and cost.

Choi et al. [13] considered simulation based study on the economic viability of hybrid RO-MD system for seawater desalination with fossil fuel based energy system. However, the freshwater production cost hybrid system was found to be the same as that obtained using RO process only.

6.2. Hybrid FO-MD

Forward Osmosis (FO) desalination harnesses the natural osmotic pressure difference across a membrane to drive water movement. Compared to RO process, FO does not necessitate applying hydraulic pressure to overcome the feed solution's osmotic pressure. Instead, FO uses a highly concentrated salt solution (draw solution) with high osmotic pressure to attract water molecules from a feed solution with lower osmotic pressure [81].

Kim et al. [14] intended to develop and improve a new FO-MD integrated module for water treatment applications that is both thermally and osmotically isolated. The purpose of the FO tests was to determine how temperature in the draw solution (DS) affected the water flux, specific reverse salt flux RSF (SRSF), and reverse salt flux (RSF). Additionally, MD experiments were conducted to look at how DS concentration affected salt rejection and water vapour flow. The model based simulations were run in order to maximise the recovery rates for FO and MD, the initial DS concentration, and the initial DS flow rate. The findings demonstrated that a rise in DS temperature was associated with an increase in water flux and a decrease in SRSF, indicating improved membrane stability and pure water extraction. Statistically, water flux of FO was found to increase exponentially by more than 55 % when temperature was raised from 20 °C to 50 °C. The authors reported that higher initial DS flow rate and lower initial DS concentration can attain a greater permeate rate of the FO−MD system. For a high stability and promoted water flux, it was suggested to operate FO at 40 °C as the ideal DS temperature. Although it had no effect on salt rejection, higher DS concentration led to a tiny reduction in water vapour flux.

To provide an effective solution for brine management of seawater desalination based fossil fuel and enhances crystallisation efficacy for a zero-liquid discharge application, Son et al. [82] examined a circular three-process hybrid system of seawater RO, MD, and FO (Fig. 32). The suggested system has been designed to improve the water productivity of seawater RO using MD while diluting the brine of seawater RO using

FO unit before disposing into surface water. A thorough experimental investigation was conducted to assess the hybrid system's performance in various operational scenarios. Furthermore, examined were the effects of anti-scalant content and MD operating temperature on membrane fouling and water quality. The seawater volumetric concentration factor (VCF) of the hybrid system spans from 1.0 to 2.2, enabling feasible and long-term full-scale operation. Concentrated saltwater and seawater RO brine from a full-scale desalination plant within the targeted VCF range were used to test a variety of MD and FO operation conditions.

In comparison to saltwater concentrate, the results show that the anti-scalant in SWRO brine improved MD flux stability by minimising flux drop. This demonstrates how anti-scalants help to reduce scaling and fouling in the MD process. In comparison to saltwater concentration, anti-scalants in SWRO brine decreased MD flux decline by 68.3 %. Nevertheless, neither membrane fouling nor osmotic driving force interference was brought on by the anti-scalant during the FO process.

6.3. Hybrid FO-MSF-MED

Altaee and Zaragoza [15], Altaee et al. [74,75], Thabit et al. [16] considered hybrid forward osmosis (FO) and thermal desalination processes of MSF and MED where FO unit was utilised as a pre-treatment step to remove scale contributing ions from the seawater. For instance, Altaee et al. [74,75] investigated the efficacy of FO as a pre-treatment step to eliminate scale-forming ions (sulfate, magnesium, and calcium) from saltwater before MED and MSF processes. With an emphasis on higher Top Brine Temperatures (TBTs), the investigation was precisely sought to evaluate how FO pre-treatment impacted thermal desalination plant performance. Altaee et al. [74,75] deployed a set of various salinities in the simulation to appraise the influence of seawater TDS on the performances of FO pre-treatment and thermal plant efficacy in terms of freshwater recovery rate and scale formation. This is exactly achieved using different seawater salinities, ranging between 32,000 to 45,000 ppm. To appraise the influence of elevated TBTs on distillate flow rate, scale formation, and the general efficacy of the hybrid systems, the TBTs of the MSF and MED plants were increased above standard operating temperatures. The consequences indicated that the calcium, magnesium, and sulfate ion concentrations in the thermal plant's feed solution were effectively lowered by the FO pre-treatment, which in turn reduced the likelihood of scale formation. Additionally, raising the TBTs in the thermal plants increased the plant's capacity overall and the distillate flow rates. Higher TBTs did, however, also raise the possibility of scale build-up on heat exchanger tubes. Fig. 33 shows the simulation results that introduces the progressive of productivity as a result to increasing the TBT from 111 °C to 130 °C and decreased with increasing the seawater salinity.

Darwish et al. [83] considered FO as a pre-treatment step of the heat recovery section of the MSF process (Fig. 34). The primary goal of this study was to determine whether adding FO as a pre-treatment to already-existing MSF desalting units would be a feasible way to improve their efficiency and capacity. The study put up a novel plan to pre-treat MSF desalting units with FO. The flashing brine from the final stage with the highest concentration of brine salt would be sent to the FO unit as the draw solution (DS), and the FO system would use the cooling saltwater exiting the heat rejection section as the feed solution. The outcomes indicated that when the FO recovery ratio rose, the likelihood of scale development mitigated. This was described by the FO pre-treatment's improved removal of divalent ions (sulfate, magnesium, and calcium) from the MSF feed water. The investigation also revealed that at a TBT of 135 °C and a FO recovery ratio of 40 %, the MSF unit could run securely without the production of calcium sulfate scale. Larger membrane surface areas would be essential to attain higher FO recovery ratios.

6.4. Hybrid MED-AD

To maximise the implication of energy input in seawater desalination, Son et al. [84] exhibited an integrated system of four effects MED and adsorption desalination (AD) of four beds silica gel-water and solar thermal energy system (a collector array of evacuated tubes and thermally-stratified water tanks for energy storage) (Fig. 35). The aim of the study was to optimise the desalination process's energy input consumption while evaluating the hybrid system's performance in a range of operative scenarios. The integrated system performed better by integrating two thermal desalination processes and used energy synergistically. This work constructed the synergetic thermodynamic model and confirmed it using experimental findings from the pilot unit at the King Abdullah University of Science and Technology (KAUST) in Saudi Arabia, which has a notional production capacity of 10 m^3/day and freshwater salinity of 236 ppm from seawater salinity of 34,718 ppm. In order to enable vapour extraction by the AD beds during the MED-AD

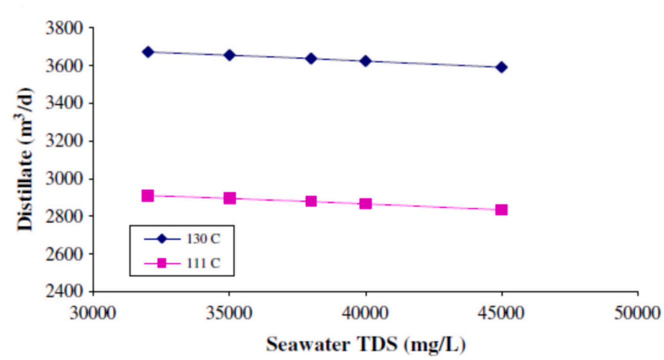

Fig. 33. Impact of seawater salinity on distillate production.

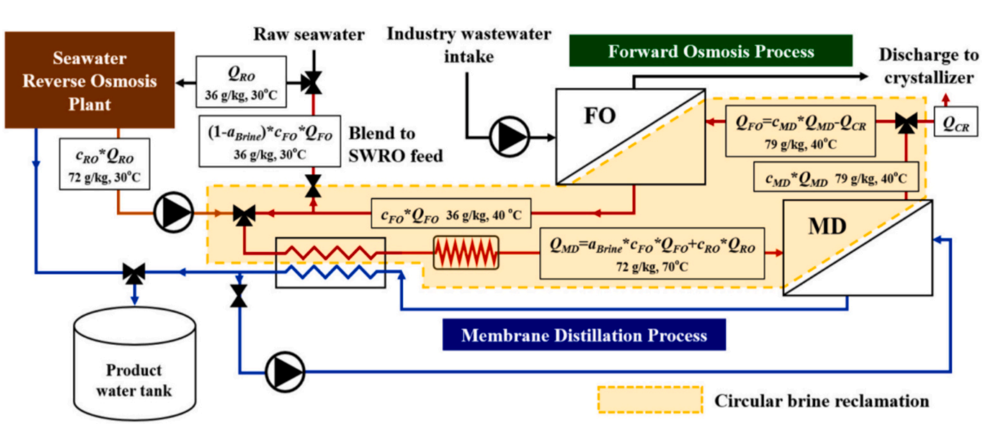

Fig. 32. SWRO-MD-FO brine reclamation hybrid system flow diagram [82].

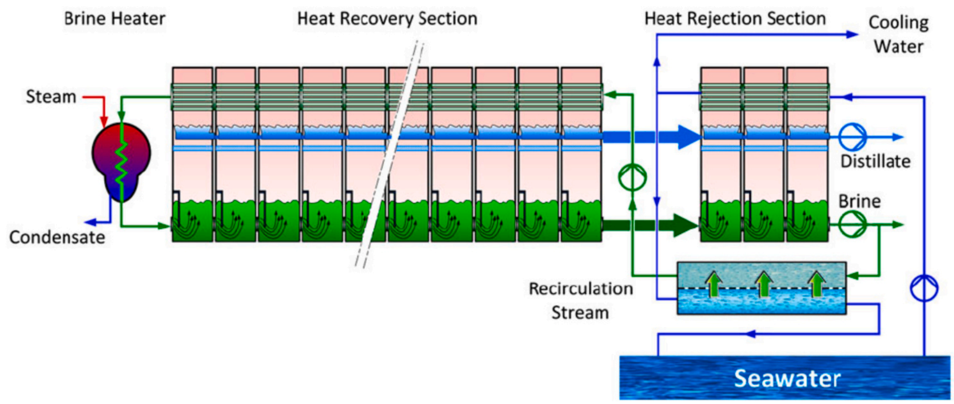

Fig. 34. A representation of MED and FO pre-treatment unit [83].

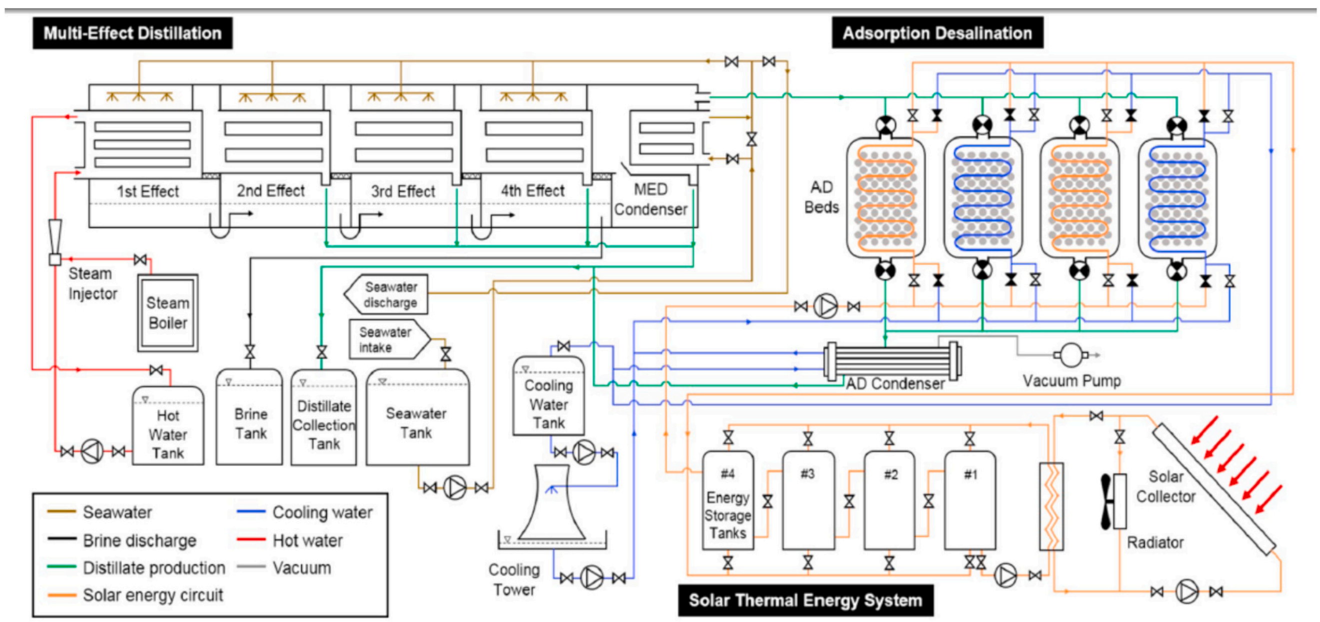

Fig. 35. An integrated system of MED-AD-Solar thermal energy unit [84].

hybrid operation, the MED condenser was bypassed. The distillate output, energy input, and universal performance ratio (UPR) of the MED-AD hybrid system were evaluated. The outcomes were contrasted with the MED system's performance when it was working alone.

When compared to the MED system alone, the distillate production of the MED-AD integrated system showed an impressive rise. Because of the additional flash evaporation in the hybrid system, distillate production rose by 3–5 times at the same heat source temperatures (40–60 °C) at fixed inlet feed flow rate of 0.475 m^3/h for all operations. This is due to a higher efficiency of adsorbing the vapour via the adsorption system, which signifies an outstanding thermodynamic synergy of MED and AD cycles. It was possible to desalinate even at heat source temperatures lower than the surrounding air temperature thanks to the wider operating range of the MED-AD hybrid system. The use of low-grade energy sources was made possible by lowering the bottom brine temperature (BBT) to as low as 9 °C. However, the water production reduces by reducing the inlet seawater temperature.

6.5. Hybrid MED-MD

Due to a high energy consumption of MD, a hybrid desalination system of MED and MD was introduced by Ali et al. [85]. The significance of the suggested integrated system is the possibility of harnessing thermal energy of the brine of MED which could alleviate the high energy consumption of MD. Using a comprehensive mathematical model for the hybrid MED-MD system, Ali et al. [85] examined the impact of MD input flow rate, different configurations (MED with and without TVC) (Figs. 36 and 37), on techno-economic viability of integrated MED with MD including the performance indicators and freshwater production cost. The outcomes proved the hybrid system's financial feasibility by showing that integrating MD with MED may drastically lower water costs when compared to standalone MED. In particular, the water cost of the integrated system is 2.05 \$/m^3, 17 % less than that of the individual MED system. Additionally, the trade-off between capital and operating expenses determines the ideal value for the MD feed flow rate, which reduces the cost of water. TVC enhances performance ratio (PR) from 7.4 to 9 and lowers water costs from 2.05 to 1.84 \$/m^3 when added to the hybrid system. This is specifically an improvement of water recovery up to 52 %, which signifies a decrease of water production cost down to \$1.84/m^3. This configuration characterises by having a single seawater intake which utilises the thermal energy of the last effect vapour for powering additional MD vessels by heating consecutive brine effluent streams (Table 3).

Referring to the established results of the emerging technologies to MSF and MED thermal desalination processes, the following summary can be presented:

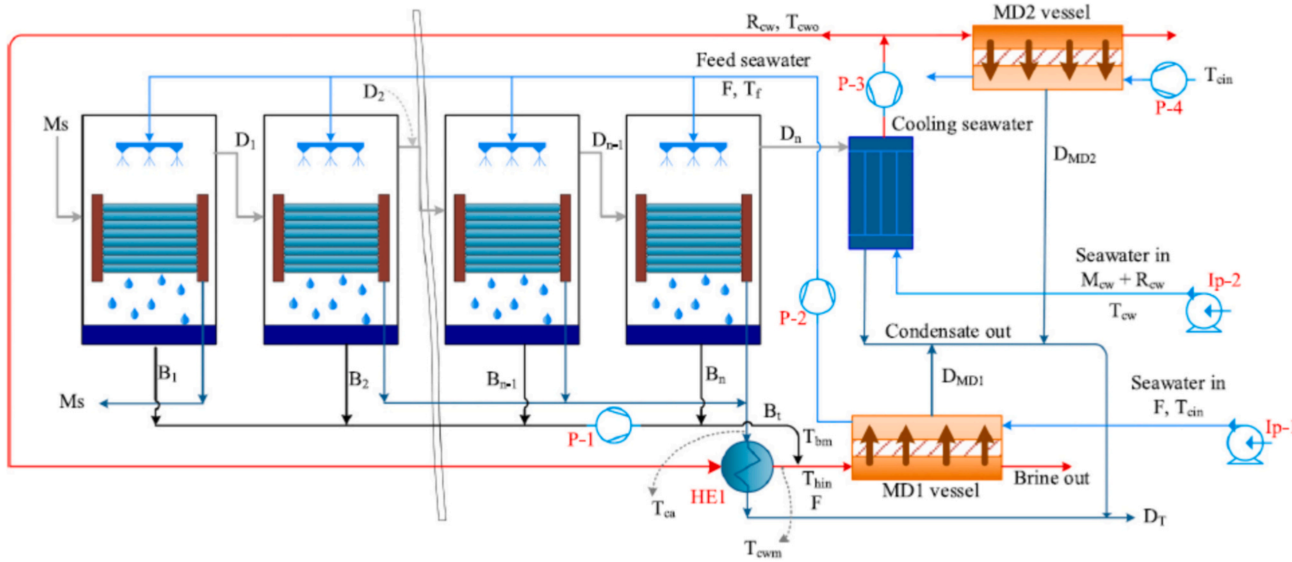

Fig. 36. Integrated MED and MD without TVC.

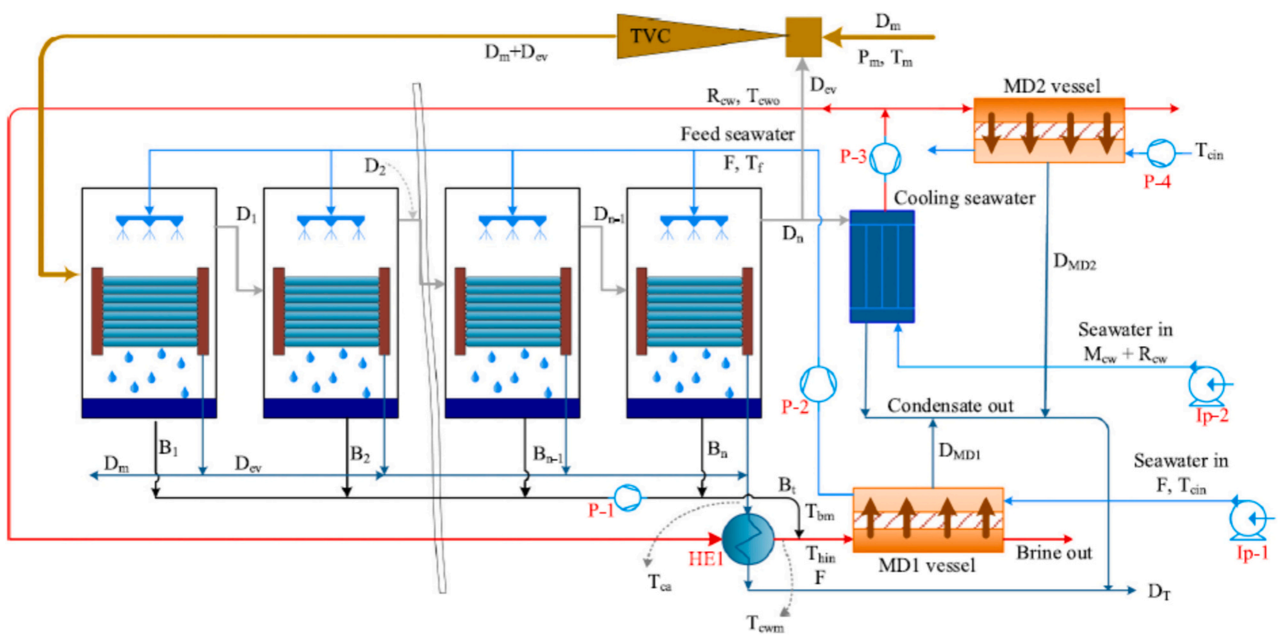

Fig. 37. Integrated MED and MD with TVC.

An essential change in the management of the world's water scarcity problems is signified by the combination of traditional desalination techniques of MSF and MED with pioneering technologies of FO, MD, and AD. When integrated, the distinct advantages of each technology advance the desalination operations' overall efficiency and sustainability. FO is a low-energy technique of purifying water that works by using osmotic pressure differences to draw water through a semi-permeable membrane. MD offers noteworthy benefits in energy effectiveness as well as adaptability to different water sources by using temperature gradients to evaporate water molecules via hydrophobic membranes. AD is an environmentally friendly technique of extracting fresh water from saline solutions by taking benefit of the adsorption-desorption cycle of adsorbent materials. These approaches enhance energy efficiency, lessen the effect on the environment, and boost desalination performance when combined with MSF and MED. This comprehensive strategy opens the door for sustainable water solutions in the face of rising global water demand by demonstrating the revolutionary potential of combining established and cutting-edge desalination technology. Despite these advantages, the following critical disadvantages need to be considered:

- In FO, MD, and AD systems, scaling, fouling, and membrane deterioration can happen, affecting long-term performance and necessitating regular maintenance. One crucial challenge with membrane-based systems is scaling.
- Large-scale adoption has been hindered by a lack of established processes and field experience with developing technologies that are integrated into MSF and MED.
- The performance of FO, MD, and AD systems may be impacted by changes in the content and quality of the feed water. As a result, particular optimisation studies are needed to determine the ideal operating settings.

Table 3
Proposed studies of the hybrid emerging technologies and membrane and thermal seawater desalination technologies.

Authors and year	Type of study	Design	Inlet seawater conditions	Highlighted results: Productivity (m^3/day), product salinity (ppm), water recovery (%), specific energy consumption (kWh/m^3), and freshwater production cost ($/$m^3$)	Challenges and future perspectives
Altaee et al. [74,75]	Analytical	FO pre-treatment in the removal of divalent ions from feed solution to MSF and MED	32,000 to 45,000 ppm	From 111 °C to 130 °C, the distillate rises with the TBT and falls with the salinity of the seawater.	The influence of membrane fouling on the FO process's performance was not taken into account in the study. Subsequent research ought to examine the fouling capacity of seawater and devise tactics to alleviate fouling. It is also necessary to assess the energy usage of the FO pre-treatment process and how it affects the hybrid desalination system's overall energy efficiency.
Darwish et al. [83]	Analytical	FO pre-treatment in the removal of divalent ions from feed solution to MSF	32,000 and 45,000 ppm	MSF unit could operate safely without producing calcium sulfate scale at a TBT of 135 °C and a FO recovery ratio of 40 %.	It is necessary to assess the energy usage of the FO pre-treatment process and how it affects the hybrid desalination system's overall energy efficiency. The effect of membrane fouling on the FO process's performance was not taken into account in the study. Subsequent research ought to examine the fouling capacity of seawater and devise tactics to alleviate fouling.
Kim et al. [14]	Experimental and analytical	An integrated system of FO-MD	Variable DS feed temperature between 20 and 50 °C	A statistical analysis revealed that when the temperature was raised from 20 °C to 50 °C, the water flux of FO increased exponentially by more than 55 %.	The economic viability of the suggested module, cleaning techniques, and membrane fouling require more study. Energy recovery and reuse within the system cannot be ignored to keep the freshwater production cost at an acceptable level.
Son et al. [84]	Experimental	A desalination technology that combines adsorption with multi-effect distillation (MED).	34,718 ppm, 33 °C	By using a variety of heat sources ranging from 40 to 60 °C, the MED was able to increase water output and the universal performance ratio (UPR) by a factor of 2 to 5.	The optimisation of the number of effects, feed flow rate, and timing of the AD cycle, was not investigated in this work. Research on optimisation can aid to determine the ideal circumstances for enhancing the hybrid system's performance.
Ali et al. [85]	Experimental and Analytical	A desalination system that combines MD with MED (with and without TVC)	25 °C	The hybrid system's water cost of 2.05 $/$m^3$ is competitive when compared to previously reported results and 17 % less expensive than the solo MED system.	The effect of membrane fouling on the MD unit's performance is not taken into account in this investigation. The overall economics of the hybrid system can be impacted by membrane fouling, which can dramatically lower the permeate flux and raise the energy consumption of the MD process. The main emphasis of the study is how the system's performance and economics are affected by the MD feed flow rate and unit cost. Not enough research has been done on other crucial factors such feed salinity, temperature, and membrane properties. An extensive sensitivity study would offer a deeper comprehension of the functioning of the system under various operating scenarios.
Son et al. [82]	Experimental	Comprehensive system that incorporates a three-process hybrid of seawater RO MD, and FO.	50, 60, 70, and 80 °C.	When compared to operations that used seawater concentrate, the flux reduction in MD operations was reduced by 68.3 % due to the anti-scalants found in SWRO brine.	Further investigation is essential to evaluate the hybrid system's total energy efficiency and financial viability, as well as to optimise operative conditions and look into long-term system performance. The efficacy and long-term feasibility of the hybrid system may also be upgraded by examining the use of different anti-scalants or anti-scalant mixtures created especially for it.

7. Conclusions

The hybrid seawater desalination system, which combines thermal distillation and RO membrane applications, has been the focus of various recent studies. As a result, RO, MED, and MSF have been integrated into several configurations. This study attempted to appraise the performance indicators of the integrated systems while covering several aspects including the design, operation, performance, techno-economic, challenges and future prospects. In general, it is fair to admit that the interconnected RO-MSF and RO-MED systems have the potential to improve global water security. These technologies are essential for guaranteeing a sustainable and reliable water supply.

This review shows how combining RO with MSF and RO with MED technologies can improve the overall effectiveness, water recovery rate reducing energy consumption and minimising the environmental impact of seawater desalination process. In order to address the growing demand for drinking water, hybrid systems can offer a trustworthy and high-quality source of freshwater. This study also highlights some technical, financial, and environmental constraints/difficulties with hybrid systems, such as scaling, corrosion, and fouling, as well as the high initial and ongoing expenditures.

The decision between the RO-MSF and the RO-MED/TVC hybrid systems ultimately come down to project-specific needs, like required capacity, energy accessibility, and cost concerns. To choose the best technology for a certain saltwater desalination project, thorough economic analyses and feasibility studies are required. This paper suggests some future research areas in hybrid systems.

Referring to the integrated membrane-based processes and traditional distillation methods of membrane distillation and absorption distillation, it can be said that the ongoing research should critically analyse the possible techniques to improve the overall efficiency of these systems as they provide sustainable solutions to global water challenges.

CRediT authorship contribution statement

Mudhar Al-Obaidi: Writing – original draft, Methodology, Investigation, Formal analysis. **Alanood A. Alsarayreh:** Writing – original draft, Investigation, Formal analysis. **Farhan Lafta Rashid:** Writing – review & editing, Investigation. **Md Tanvir Sowgath:** Writing – review & editing, Investigation. **Salih Alsadaie:** Writing – review & editing, Investigation, Formal analysis. **Alejandro Ruiz-García:** Writing – review & editing, Investigation. **Mohamed Khayet:** Writing – review & editing, Investigation, Formal analysis. **Noreddine Ghaffour:** Writing – review & editing, Investigation, Formal analysis. **Iqbal M. Mujtaba:** Writing – review & editing, Supervision, Formal analysis.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

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