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Review

Current Status and Advancement in Thermal and Membrane-Based Hybrid Seawater Desalination Technologies

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Abstract: Emerging hybrid technologies have better potential than conventional technology for diversifying the desalination industry, which is presently being dominated by thermal and membrane-based desalination. Notwithstanding the technological maturity of the desalination processes, they remain highly energy-intensive processes and have certain disadvantages. Therefore, the hybridization of thermal and membrane desalination processes holds great attention to mitigate limitations of individual processes in terms of energy consumption, quality and quantity of potable water, overall efficiency and productivity. This paper provides an oversight of conventional and developing desalination technologies, emphasizing their existing state and subsequent potential to reduce water scarcity. Conventional hybrid desalination systems (NF-RO-MSF, MED-AD, FO-MED, MSF-MED, RO-MED, RO-MSF and RO-MD) are briefly discussed. This study reveals that the integration of solar thermal energy with desalination has a great potential to substantially reduce greenhouse emissions besides providing the quality and/or quantity of potable water in cost-effective ways. Due to its abundant availability with minimal/no carbon footprint and the ability to generate both thermal and electrical energy, solar energy is considered better than other renewable energy technologies. The findings further suggest that hybrid desalination systems are technically sound and environmentally suitable; however, a significant study of the research process and development is still required to make this technology efficient and economically viable.

Keywords: water scarcity; desalination; hybrid desalination systems; saline water; water treatment

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1. Introduction

Water scarcity is a worldwide problem and increasing at a rapid pace owing to the substantial rise in urbanization and industrialization. Increasing stress of water requirement is a serious issue for humanity and raises both the need for quantity and quality of water supplies [1,2]. According to a United Nations study, water shortage has affected 3.7 billion people worldwide. By 2050, this number could reach 5.7 billion [3]. Freshwater remains a precious global resource due to inadequate supply and scarcity. Figure 1 shows an estimated country-wise water stress in 2040 [4]. Amongst the accessible technologies for freshwater production and conservation, desalination remains the most promising option to reduce water scarcity. Desalination is a process for removing salts from feed water, thus producing freshwater. With the rapid decline in freshwater resources posing a serious threat, the importance of current desalination technology as a way of fulfilling global water demands has never been greater [5,6]. The top drivers for the global desalination market have been described as population growth, industrialization and agricultural advancements. From

2018 to 2022, the worldwide desalination industry grew at 9% annual pace, with Europe, the Middle East, and Africa accounting for 74% [7].

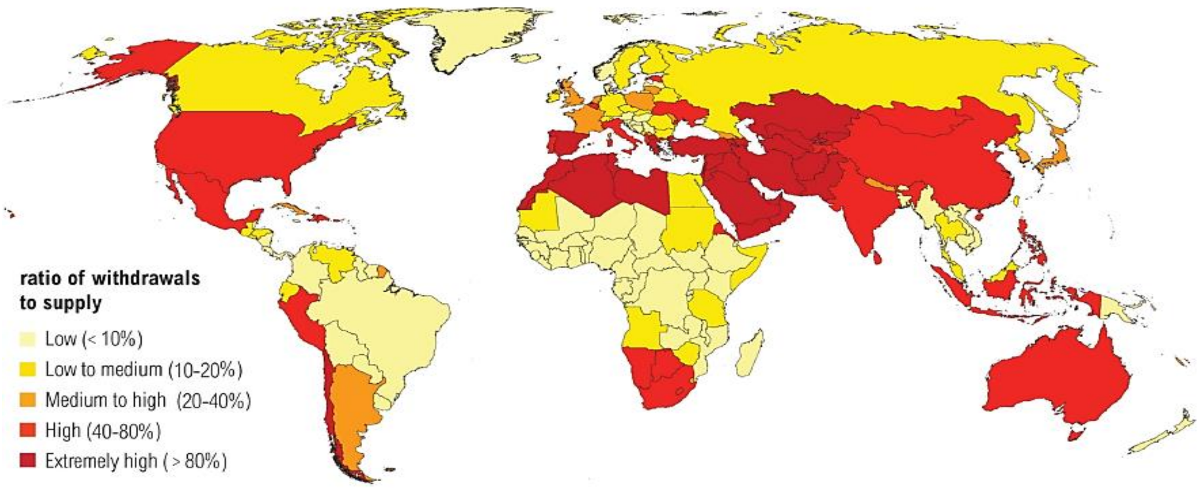

Figure 1. Water stress in 2040 [4].

Notably, thermal and membrane desalination (MD) processes are the two most common forms of desalination and are frequently used by the desalination industry to treat saline water. Thermal desalination, as the name indicates, employs heat to separate distillate from salt water. The most commonly accepted thermal desalination technologies have historically been multi-effect distillation (MED) and multi-stage flash (MSF). However, in recent years, the membrane process has taken over, with around 73% of membrane desalination plants and 27% of thermal plants installed by the end of 2016 [8]. Electrodialysis (ED) is another membrane-based desalination method with a sizable installed capacity. Forward osmosis (FO), another form of membrane-based desalination process, is expected to rise in popularity. Scientific advances in membrane separation technology and the invention of reverse osmosis (RO) membranes have led RO to be the leader in the desalination market. Figure 2 illustrates the global market volume of different desalting technologies [9]. Because of the availability of co-generation plants and lower-cost fuel, the shift from thermal to membrane processes is taking longer in the Middle Eastern and Northern African regions [10].

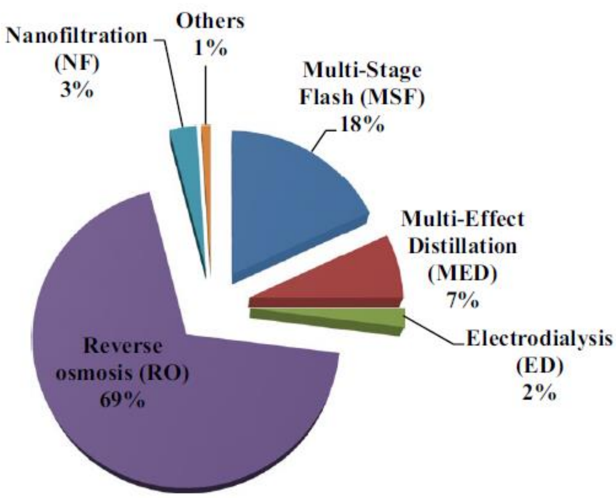

Figure 2. Existing volume of desalination technologies in the global market [9].

Despite the technical sophistication of the abovementioned processes, the energy requirement for desalination processes remains very high. Rising water demand necessitates the construction of an increasing number of high capacity desalination systems, which rely on traditional and expensive fossil fuels and can result in increased emissions of greenhouse gas (GHG) [11]. Despite that the energy necessities of seawater RO have declined by five times over the 50 years due to technological advances, total installed capacity now emits more than 60 metric tons (Mt) of carbon dioxide (CO_2) having a yearly rate of growth between 10–15% [12]. The annual energy requirement of seawater RO installations is about 100 TWh, which translates to 70–100 Mtons of CO_2 per year.

Due to significant heating requirements, thermal desalination units need 40 to 80 kWh/m^3 of thermal energy and an added 2 to 5 kWh/m^3 of electrical energy [12,13]. The high cost and finite existence of fossil fuels are also driving decarbonization in the desalination sector. Desalination with decarbonization is hence a current need and plays a crucial role in combating future climate change while meeting global water demands [12]. Reducing energy demand by developing new materials, optimizing process design or employing renewable energy to reach a pragmatic solution to run desalination plants is the hot discussion in current research. The European Commission has continuously driven policies to elevate the usage of renewable energy while restricting GHG emissions and setting targets [14]. The role of regulatory bodies such as environmentalists, NGOs and policymakers are important in accelerating the transition to desalination powered by renewable energy.

Operational flexibility, meeting potable water quality demands and producing large quantities of water lead to high energy consumption. Water quality demands often necessitate the use of additional phases, placing a strain on a single system's energy costs. Combining the advantages of multiple systems to meet specific water quality objectives is becoming increasingly popular due to low energy consumption. The merging of traditional and contemporary desalination processes has allowed for the development of hybrid desalination systems such as MD, MSF-RO, MED-RO and others [15].

Hybridization of various desalination technologies is a major task to achieve several goals, including obviating the requirement for a second pass, lowering brine salinity and increasing the water recovery rate. Hybrid systems are thought to be more ecofriendly and cost-effective than single-use systems because they have a great potential to minimize energy consumption besides improving the quality and/or quantity of potable water [16,17]. Depending on the feed type, the system's mechanism and the target water quality, effective hybridization necessitates the optimization of configuration and operational design.

In recent decades, solar thermal energy has been utilized for desalination. Due to environmental consciousness and the abundant availability of solar energy, much of the research is focused in these directions to reach a practical engineering solution to treat saline water and make it potable in cost-effective ways. The use of concentrated solar power (CSP) in desalination plants has been viewed as an appealing and viable choice for supplying energy in a long-term sustainable manner. Notably, CSP plants create a substantial amount of usable high-temperature heat to meet the demands of various applications in water desalination systems besides generating electricity through power cycles [18]. CSP can be integrated into thermal storage systems and is appropriate for the hybridization of both conventional and nonconventional energy sources [19,20]. These characteristics make CSP the primary choice for large-scale desalination systems for continuous manufacturing of pure water, especially in areas where solar radiation is abundant and seawater is readily available [21]. All recent technologies are very expensive; the high-end level consumption of power requires the development of novel techniques that will minimize energy consumption and cost that would allow the technology to be economically viable and affordable. The majority of studies are attempting to improve the efficiency of desalination systems by reducing energy use. Researchers are looking to areas of development such as chemicals, materials and energy. It is therefore necessary to explore and understand the traditional and modern desalination processes for developing a new technology.

In this study, an extensive review was conducted concerning existing technologies and future directions for the development of integrated technologies such as thermal desalination, membrane desalination and their hybrid systems to treat saline water in cost-effective ways while maintaining the quality.

The following technology section covers the following topics: (i) thermal desalination comprising MSF, MED and VC; (ii) membrane desalination comprising RO, MD, NF, ED and FO; (iii) hybrid desalination comprising NF-MSF, MED-AD, MSF-MED, MSF-BR, MSF-OT, MED-TVC, RO-MSF, ED-Ro, NF-RO and FO-RO-ED; and (iv) hybrid solar desalination systems.

2. Thermal Desalination

Thermal desalination methods are based on the hydrological cycle model in which the saline feed is evaporated and then concentrated to obtain freshwater with low total dissolved solids (TDS). The significant thermal desalination technologies are MED, MSF and vapor compression (VC). Thermal desalination technologies such as MED and MSF are the most widespread technologies for desalination in North Africa (MENA) and the Middle East regions, accounting for about 85% of the total water production capacity there [22]. Higher thermal desalination adaptability in the MENA region, according to Thu et al. [22], is due to higher seawater salinity in the Gulf, frequent algal blooms that could root to extreme fouling of RO membranes, and a large number of power plants having high-capacity that would allow for a lucrative assemblage of power plants with desalination plants.

2.1. Multi-Stage Flash (MSF)

In the MSF process (see Figure 3), the saline feed preheats as it passes through the heat exchanger tubes of flashing stages before entering the brine heater. Although waste heat is not produced during the distillation process, a multi-stage flash distillation system has a high running cost and relatively high rates of corrosion and scale formation because of the high operating temperatures. The process has two main sections: (i) brine heater and (ii) flashing stage [23]. The saline feed is heated in a brine heater with low-pressure bleed steam to a temperature of 900–1100 °C, which is known as the top brine temperature (TBT) [24–26]. The heated saline feed then enters the initial stage, where the ambient pressure is kept lower than that in the brine heater. Because of the lower pressure, salt water evaporates quickly (or flashes). Each stage in MSF is kept at a greater temperature than the one before it, and the pressure is maintained at the boiling point at that specific temperature. Latent heat is lost during condensation to the saline feed as flickering vapor condenses on the tubes of the heat exchanger [23]. Amongst several design structures developed for MSF, brine recirculation (BR) and once through (OT) are the most popular [27]. In MSF-OT, the nonevaporated brine is recycled in the ocean after the last stage and in MSF-BR some of the brine is supplied in the incoming saline water [28]. Recently, MSF-BR has grown in popularity due to its lower maintenance cost and fewer corrosion issues in high-volume plants [29].

Owing to the easy accessibility of low-division heat and co-generation of water and power, MSF desalination accounts for a crucial part of the globally connected desalination capacity and is most widely employed in the Middle East [30]. The amount of energy used in this technology is determined by many different elements that comprise the process configuration, number of steps, design of heat exchanger systems, the maximum temperature at the source of heat and the salt concentration in flashing brine [26]. Another important factor that affects energy requirements in MSF units is fouling or scaling [27]. The energy efficiency of MSF systems is reduced by fouling, scale formation and pipe corrosion. MSF systems use approximately 21 kWh/m^3 of heat equivalent energy in addition to 4 kWh/m^3 of mechanical equivalent energy [31,32]. According to El-Naser [33], the MSF plant consumes between 12 and 24 kWh of electricity/m^3 of water generated. The cost of is also affected by whether thermal energy is provided as exhaust heat or as a distinctive power plant. In the Gulf Cooperation Council (GCC) countries, high-availability steam is used to provide thermal energy to MED and MSF desalination systems in these co-generation plants [31,34]. The number of stages in a typical MSF plant with a water production capacity of 50,000 to 70,000 m^3/day is 18 to 25 [26]. The amount of thermal energy needed in MSF unit capacities between 50,000 to 70,000 m^3/day is between 190 and 282 MJ per cubic meter of water produced, which is equal to 15.8–23.5 kW-h/m^3, given the 30% heat conversion efficiency. Additionally, pumping requires from about 2.5 to 5 kW-h/m^3 electrical energy. As a whole, the cumulative energy consumption of a normal MSF ranges from 18.3 to 28.5 kW-h/m^3 [25].

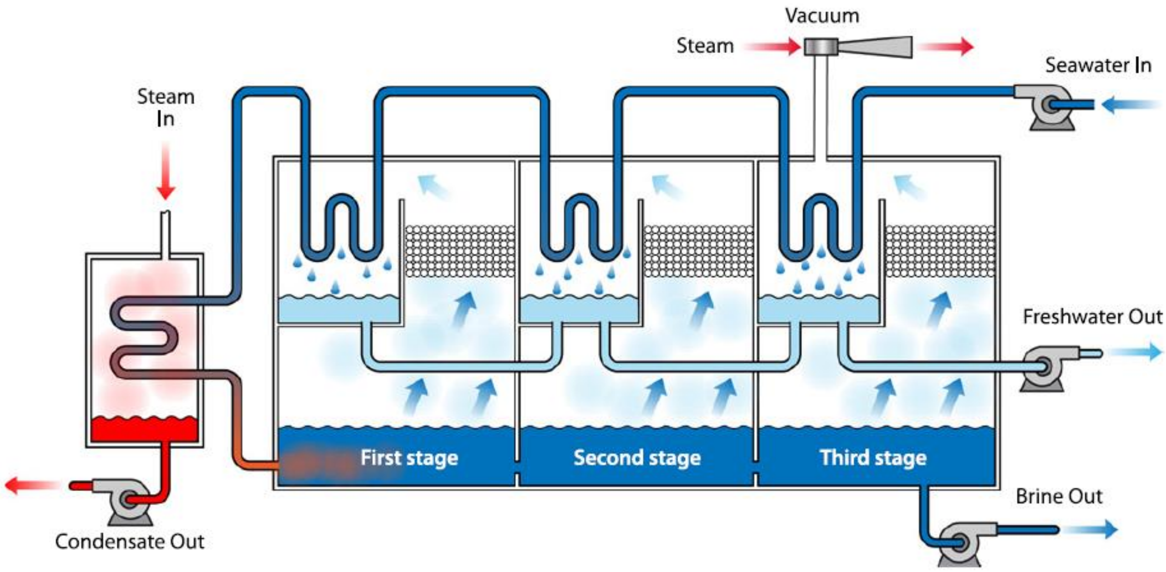

Figure 3. Schematic diagram of an MSF unit [26].

2.2. *Multi-Effect Distillation(MED)*

MED as presented in Figure 4 is one of the most widely used desalination methods today where waste heat is not available for the distillation process [26]. MED systems have issues including high running costs and high temperatures that promote corrosion and scaling. A condenser and cells classified as effects make up the bulk of MED. From first to last, these cells are at lower temperatures and pressures, with temperatures ranging between 65 and 90 °C [35]. The saline feed water is preheated before entering the condenser. The multiple effects are then fed with heated feed water in equal proportions. Evaporator tube bundles are housed in each effect and the saline water is sprayed over these evaporator tubes. Low-pressure steam passing through the evaporator tubes vaporizes the feed water doused onto them in the first instance. In the following effects, the vapor formed is utilized as an energy source from the evaporated water. The vapor from the previous effect is used to heat the condenser's saline water. Because the boiling temperature of water decreases with pressure, decreased pressure effectively evaporates water at low temperatures [36]. External steam is utilized only in the first stage of the MED unit, while the heat extracted during cooling is utilized as a source of energy for heating in subsequent stages [37].

The amount of freshwater generated is determined by the number of effects and increases in proportionality with the number of effects. It is, however, constrained by the minimal temperature differential between effects and the overall temperature range of the process [27]. Thermal energy between 145 and 230 MJ/m^3 is needed in a standard MED device with capacities falling between 5000 to 50,000 m^3/day, corresponding to range of electrical energy from 12.2 to 19.1 kWh/m^3. Pumps can use an additional 2 to 2.5 kWh/m^3 of electricity [23]. As a result, in a standard MED, the overall SEC is between 14.2 and 21.6 kWh/m^3. Due to lower operating temperatures, MED consumes less thermal energy than MSF and is thermodynamically the most effective process [38,39].

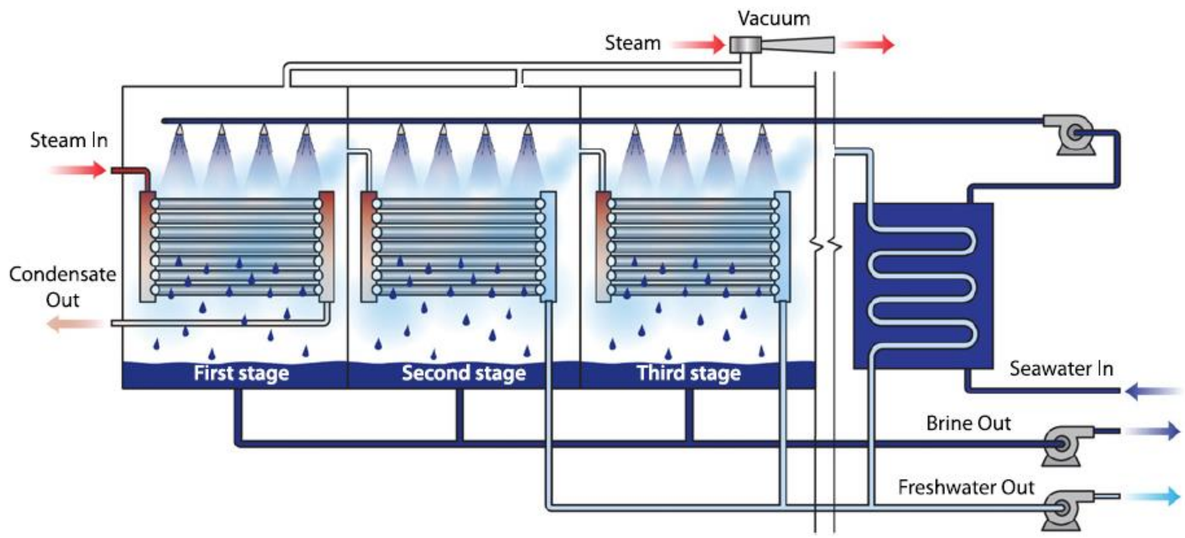

Figure 4. Schematic diagram of an MED unit [26].

2.3. Vapor Compression (VC)

The VC desalination system utilizes initially pressurized vapor from saline feed water to evaporate additional feed water. In VC, incoming saline feed water is evaporated at the first stage and the formed vapor is compressed either mechanically (MVC) or thermally (TVC). Additional saline feed is then evaporated using this pressurized vapor as a heat source. The capacity of MVC units is typically up to 3000 m^3/day with a single stage, whereas TVC capacity is about 20,000 m^3/day with several stages [40]. The reason being, the same specific energy consumption of the MVC unit irrespective of the stages count, while the thermal efficiency of TVC increases with the addition of stages [41].

For small- and medium-capacity installations, VC processes are usually realistic [42]. It is small and lightweight. The capital investment required is fair, and its operation is straightforward and consistent. The VC plant, rather than the RO plant, can produce higher quality water from low-quality feed. Since the components of the evaporator are exposed to the saline feed water directly, they require massive and costly steam compressors while scaling and corrosion are major concerns [40]. To improve overall performance, VC is frequently combined with MSF or MED processes [43]. Vapor compression distillation systems need to address (i) maintenance on compressors and heat exchangers, which is more extensive than for other systems; (ii) high energy consumption; and (iii) expensive capital expenditures.

3. Membrane Desalination

In membrane desalination processes, salts having larger radii are restricted to pass through the semi-permeable membranes. As a result, low-TDS freshwater is obtained as a product and high-concentration brine is rejected. Reverse osmosis, membrane distillation and electrodialysis are major membrane desalination technologies. Other evolving membrane technologies, including nanofiltration (NF) and forward osmosis (FO), are still in the early stages of development.

3.1. Reverse Osmosis (RO)

Reverse osmosis-type desalination technology is well established and a leading membrane desalting process. It works by reversing the osmosis principle. The salt solution is pressed against the semi-permeable membrane. RO works by experiencing a higher hydraulic pressure than the hydrostatic potential of the solution to push the liquid from a higher concentration region to a lower concentration area through a semi-permeable, nonporous membrane. Since RO technology does not use a phase-change method to generate freshwater, the theoretical energy consumption is much lower than that required by thermal processes. RO has become a commonly accepted technology in recent decades, with large-scale plants deployed worldwide [44]. This desalination has now exceeded thermal desalination in terms of overall power capacity in many regions of the world. RO is an appealing technology for SW desalination because of the extensive information available on optimizing RO systems and the recovery of RO plants is low.

According to the laws of thermodynamics, the minimum energy required to generate freshwater from seawater at a 50% rate of water recovery is 1.14 kWh/m^3 [45]. Without energy recovery, RO plants run at 10 kWh/m^3, and with energy recovery, they run at 2 to 5 kWh/m^3 [46]. According to data obtained by Nikolas Voutchkov from approximately 20 desalination plants and a daily output of more than 40,000 m^3/day from 2005 to 2010, the estimated energy usage of seawater RO desalination plants is 3.1 kWh/m^3 [47]. The amount of energy needed by RO systems is finalized by several factors, including feed characteristics, pump performance, membrane permeability, recovery rate, RO configuration and, if necessary, the type of energy recovery device used. Solid particles larger than one Angstrom can be retained by RO membranes. It shows that protozoa, bacteria, viruses, suspended solids and other contaminations in drinking water can be absorbed by the membrane [48]. Seawater systems have an operating pressure of 54 to 80 bar, while brackish water systems have a pressure of 15 to 25 bar [38]. RO membranes are costly and have a two- to five-year lifespan.

Preliminary treatment of the salty or saline feed water is needed to eliminate particulates and extend the life of the membranes. For RO membrane oxidizers, a wide range of organics, algae, pH, bacteria, particles and other foulants are troublesome [49]. Hence, preliminary treatment of the salty feed water remains critical and has a substantial influence on the cost of RO [50].

It is observed that using RO with an electrodialysis integrated system improves the recovery of deionized products or reduces concentrate volumes [51]. Another approach attempted by Zhu Chongqin et al. [52], using a low-pressure high-recovery multi-stage RO system, showed more than 70% recovery.

3.2. Membrane Distillation (MD)

MD is a form of separation that involves contacting a porous membrane at one side with a heated aqueous feed solution. The difference in temperature between the hot solution and the cold permeate flowing through the membrane induces a vapor pressure difference. As a result of the pressure difference, more toxic compounds vaporize and move through the membrane pores. It is a robust separation process which can be employed for separation of anything like juice, dairy compounds, pharmaceutical compounds, oily wastewater treatment and desalination as well [53]. Figure 5 presents the schematic diagram of the solar MD unit [26]. In recent years, MD has discovered its niche in desalination applications, where it could compete with traditional processes. Brine concentration or small-scale are examples of desalination systems in rural areas [54,55]. This system suffers from high energy consumption and heat-induced deterioration of sensory (color changes, off-flavor production) and nutritional features.

Sweeping gas membrane distillation (SGMD), direct contact membrane distillation (DCMD), air-gap membrane distillation (AGMD) and vacuum membrane distillation (VMD) are the four basic MD configurations. All of these configurations require direct membrane interaction with a heated feed. They vary in the way they induce vapor pressure gradients and how they absorb transported vapor on the permeate side [53]. The energy consumption is largely dictated by the type of configuration.

One of the most distinguishing features of the MD process is that its permeate content and flux are unaffected by feed water salinity up to 200,000 mg/L [23]. The method may use waste heat or low-grade heat energy to treat high-salinity water, demonstrating its importance at the energy–water nexus. Membrane properties, MD configuration, plant capacity and operating conditions are all factors that affect MD energy efficiency [56,57]. MD has much promise for treating brines with salinities above 80,000 mg/L, which are nearly impossible to treat with RO [58]. MD is also appealing for desalination because of the advantages in operating the device on renewable energy sources and the compactness of the setup.

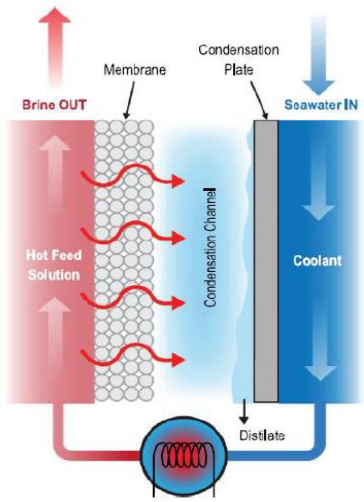

Figure 5. Schematic diagram of a solar MD unit [26].

3.3. Nanofiltration (NF)

Nanofiltration (NF) shares the same concept of separation technology driven by pressure as RO and ultrafiltration (UF). NF has proven to be a promising and robust pressure-driven separation method with several applications. Due to the lower pressure requirement, NF consumes less energy than RO [59]. Tiny organic molecules and multivalent inorganic salts can be separated from feed sources using NF, with rejection rates ranging from 75 to 99% for divalent salts and 30 to 50% for monovalent salts [60]. Since the capability of NF desalination to reject small organic pollutants is minimal, it is often combined with separation processes, e.g., adsorption, to achieve equivalent micropollutant removal [55]. Since NF membranes work at comparatively low pressure, their energy requirements are low as well, varying from 0.6 to 1.2 kWh/m^3 [61]. Membrane fouling, poor isolation of micropollutants and some of the problems pertaining to nanofiltration indicate the need for better knowledge of mass transport [62,63].

3.4. Electrodialysis (ED)

Although ED was first patented in 1890, it took nearly 50 years for it to become a commercially available process for the desalination of brackish water [64]. Being an electromembrane process, ED removes both nonionic and ionic components using an electric field. Cation and anion exchange membranes (CEM and AEM) are arranged alternately in an ED unit. As an electric current is passed through electrodes, the ionic current forces cations to travel toward negative electrodes and anions to travel toward positive electrodes, as seen in Figure 6 [65].

This transfer of ions, when combined with the selective isolation of ions by stacks of CEMs and AEMs, results in channels with low and high concentration of solutions [66]. Low electrical resistance and high selectivity are two characteristics of ion exchange membranes used in ED. These membranes, like all membranes, are vulnerable to fouling. The polarity of the ED mechanism is inverted to reduce membrane fouling [67–69]. In ED schemes, this reduces the need for acid or antiscaling chemicals [70].

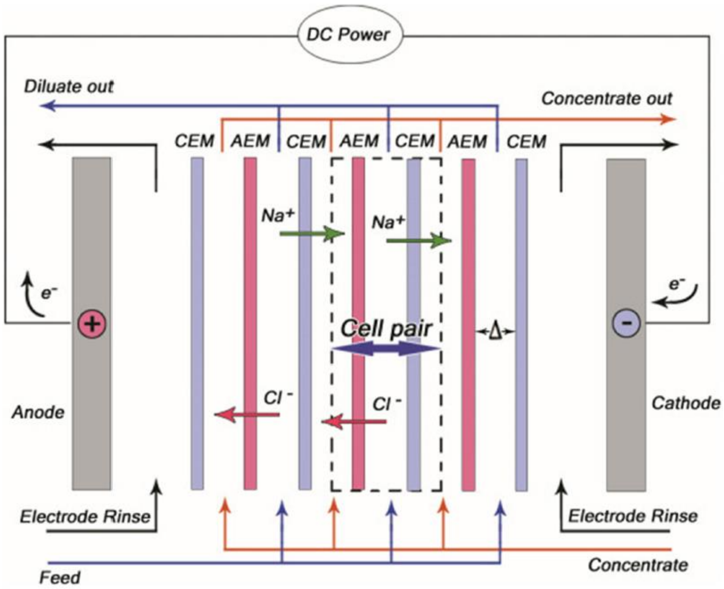

Figure 6. Schematic of electrodialysis desalination [65].

Owing to the enormous number of ions in seawater, the necessary electrical energy for desalination by an ED system would be prohibitively high, making it appropriate for brackish water (BW) desalination with a total dissolved solids concentration of less than 5000 mg/L [71]. The energy required by an ED unit to produce water with an approximate concentration of 800 mg/L is theoretically 26 kWh/m^3 for SW and 3.3 kWh/m^3 for BW desalination [72]. Low-pressure circulation pumping consumes 0.5_1.1 kWh/m^3. Every 1000 mg/L TDS removal consumes 0.7 kWh. Energy losses in the BW ED desalination system are about 5% of the total energy [73]. An ED unit can consume up to 10 kWh/m^3 of electrical energy, dependent on the water salinity [46]. An ED machine, for example, would consume around 1.5 kWh/m^3 of power to decrease the TDS from 1500 to 500 mg/L.

3.5. Forward Osmosis (FO)

In the past decade, forward osmosis technology has grown significantly, with numerous studies focusing on improving FO membrane efficiency and drawing solutions. In FO, an osmotic pressure gradient difference causes the separation of solutes from water. Saline feed is forced to flow through a membrane that is impermeable to salts from a low-side pressure saline feed solution to a high-side pressure draw solution.

The draw solution of concentration, which has a higher osmotic pressure, attracts water molecules from the supply solution via the membrane, requiring very little hydraulic pressure for separation in FO [74]. Separating the draw solute from the distilled water is performed after the diluted draw solution has been collected. The membranes used in FO are less susceptible to scaling and fouling than membranes used in RO since they work at low pressure [30]. The efficiency of an FO system is greatly affected by the feed characteristics, the membrane properties and the draw solution selected [75]. The draw solution must meet two criteria: (i) it must produce high osmotic pressure, and (ii) it must be quickly reproduced [76]. The energy requirement for the complete process is determined by the draw solution recovery stage. To offset the pressure decrease in the feed channel during the osmosis stage, a low-pressure circulation pump is required, with an estimated energy usage of 0.10–0.11 kWh/m^3 at 50% water recovery [77,78]. The osmosis step was also reported to use 0.2–0.55 kWh/m^3 of energy [79]. According to Moon and Lee, energy consumption for FO desalination varies between 3 and 8 kWh/m^3, dependent on the amount of energy required to regenerate the draw solute [80].

McGovern et al. [78] examined and evaluated the real and theoretical energy efficiency of FO and RO. Their study illustrated that RO uses much less energy than FO. They also argued that FO research efforts should be focused on alternative FO applications. In 2007, Khyadarov [81] proposed a solar-powered FO system that included thermal exchangers, solar batteries, a pretreatment unit and several fluids for the FO device. Solar-driven FO is a promising field for desalination–decarbonization because it consumes substantially lesser energy than conventional techniques [82].

4. Hybrid Desalination Systems

A hybrid desalination system that incorporates two or more systems for desalination, and it has been found to be more efficient. Hybrid desalination systems were first introduced as thermal/RO systems, highlighting the benefits of RO's low energy usage and MSF's strong separation performance. Hybrid desalination systems now cover a diverse variety of applications, including membrane–membrane, thermal–thermal and membrane–thermal processes, among others.

In this section, a critical review of the different combinations of desalination is covered, such as NF-MSF, MED-AD, MSF-MED, MSF-BR, MSF-OT, MED-TVC, RO-MSF, ED-Ro, NF-RO and FO-RO-ED. Hassan et al. [83] suggested a hybrid NF-MSF unit to extract scale-forming ions from seawater prior to it reaching the MSF unit. They also suggested an NF-MSF-SWRO hybrid system, in which the SWRO reject was fed to the MSF unit. Pilot-scale tests on the hybrid system revealed that the MSF unit in NF-MSF would work successfully at 130 °C TBT without adding an antiscalant, resulting in a GOR of 13 and improved water recovery. In a similar study, Hamed et al. [84] also demonstrated that coupling MSF with NF enables MSF to work at 130 °C TBT. The water recovery from the NF-MSF hybrid system was 70%, which is substantially higher than that for standard MSF systems (35%). The FO-performance of MED at high TBTs was investigated by Altaee et al. [85], who used the Ryznar scale index (RSI) to investigate the propensity for scale formation, wherein RSI 5 indicates a strong tendency to form scales and RSI 6–7 indicates a weak tendency [86]. To prevent scaling problems, the optimal FO recovery for various TBTs was determined using RSI estimates. According to the results, the MED process is healthy to work at 85 °C TBT with a 40% FO recovery rate and a feed salinity of approximately 45,000 ppm.

Thu et al. [22] were the first to suggest a hybrid MED-AD method. The researchers used this model for assessing the efficiency of the MED-AD system in their research. GOR increased by 40%, and the rate of water production was doubled, according to the findings. Shahzad et al. [87] established a simulation model to equate the efficiency of MED-AD to that of traditional MED units. The temperature of the final impression was recorded to be less than 3 °C, which is significantly lower than that for stand-alone traditional MED. The broad range of temperature and TBT in the final result of MED-AD hybridization allows for the inclusion of more effects while maintaining the same heat supply. This leads to higher water output and improved efficiency. Furthermore, even though both systems used the same amount of heat, the hybrid system generated three times more water than the MED system. Thu et al. [88] looked into the impact of hybridization with AD on the MED process. They ran several MED-AD scenarios with a variety of MED effects and water inlet temperatures. Without adjusting the number of effects in the MED, which was presumed to be eight, the average rise in total water output in the MED-AD hybrid device was 89% greater than in the MED unit. The MED unit's water production rate increased as the number of impacts increased. Furthermore, since the source of heat in the adsorption cycle was held constant in all simulating tests, when supply temperature rises it proportionately raises the water output as new effects to the MED unit decrease.

An MSF-MED hybrid arrangement was studied by Nafey et al. [89]. Each module in this device contained one boiling evaporator and one flash evaporator. The two streams of hot brine discharged from the brine heater were isolated. One of the streams was drawn into the first MED effect, which produces vapor. Brine exiting the first MED effect was combined with brine from the next progressive effect of MED. The first MSF stage then received it. The brine from this step was split into two streams, one of which was supplied into the second MED cell and the other of which was blended with the brine from the second MED cell. The method was reiterated until the final result was achieved. The hybrid system's water cost was 9% lower than MED and 31% lower than MSF-BR, according to the findings. Mabrouk and Fath [90] conducted a technoeconomic review of the MED-MSF hybrid system in relation to traditional systems, viz., MED, MSF-BR and MSF-OT, and MED-TVC in a more recent report. Each of the three MSF phases was combined with three MED effects in the hybrid MSF-MED method. In comparison to MED-TVC and MSF-BR, the hybrid system reported a 16% and 58% decrease in pumping power consumption, respectively. The hybrid device, on the other hand, had a GOR that was 9% higher than MED-TVC and 3% lower than MSF-BR.

The RO-MSF hybrid system is now used in many commercial plants. As compared to stand-alone methods, coupling RO with MSF has several advantages including combined pre- and post-treatment, lower SEC and lower construction costs [17]. Typically, two RO stages are needed in RO plants to produce a high-quality product. Single-stage RO can be used in a hybrid RO-MSF system because the products from RO and MSF are mixed [91]. Furthermore, by mixing products, RO can work at reasonably high TDS levels. As a result, membrane replacement becomes less frequent, affecting device economics [92]. Mahbub et al. [93] investigated the impact and efficiency of integrating RO and MED in a single power plant. The outcome demonstrated a rise in thermal efficiency from 44% to 63%. Furthermore, the SEC of the plant when integrated with MSF-RO was 17% higher than when integrated with MED-RO.

In 1981, Schmoldt et al. [94] suggested a hybrid electrodialysis–reverse osmosis device. They suggested using ED as a secondary step for infiltrating quality control. However, the absence of high-selectivity membranes and high flux at that time resulted in a large energy requirement of 7.94 kWh/m^3 for a 45,000 mg/L RO unit [95]. It was concluded that for a unit capacity of 1000 m^3/day with saline feed TDS less than 4000 mg/L, the expenditure for ED is less corresponding to the RO process of the same capacity. Currently, the amount of energy needed for RO is comparatively very small to what was previously estimated. According to the study, increased salt rejection membranes and the creation of strong flux would not only decrease the price of the RO unit but would also lower the TDS content of the intake of saline feed water and therefore the energy demand of the ED unit.

Turek et al. [95] compared single-stage stand-alone RO, NF-RO hybrid system, NF-SWRO-ED hybrid system and a hybrid ED-RO system for seawater desalination plants. They assessed the recovery rate and SEC of the four systems. At 7 kWh/m^3, the hybrid NF-SWRO-ED system achieved a strong recovery of 69%. Even though the SEC of the single traditional RO was much lower (2.76 kWh/m^3), the RO system only recovered 43% of the water. Choi et al. [96] investigated the commercial viability of an RO-MD hybrid seawater desalination scheme. When the flux and recovery rates exceed those of RO, they discovered that the proposed hybrid system or just a stand-alone MD can compete with RO. In addition, the cost of the thermal energy used in MD remains low [96].

SEC for hybrid FO systems was assessed by Bitaw et al. [97]. They developed a hybrid FO-RO-ED approach that used ammonium chloride (NH_4Cl) as the desired draw reagent. Once this solution was recovered by ED, the existing solution from ED was used as the RO feed. They found that the relative energy consumption by RO and ED is proportional to the average concentration between the ED exit and the RO inlet, given that a higher concentration increases energy input to RO. Kim et al. [98] numerically tested the output of an RO-MD-PRO hybrid method using earlier validated models of RO, MD and PRO systems. Rejected brine from RO is partially fed to MD in the proposed hybrid system, and the MD concentrate is blended with residual RO brine to be used as the PRO draw mixture. The study focused on how the size of the RO unit, the thermal energy price for MD and the brine division ratio affected the efficiency of the hybrid plant. They concluded that with a plant capacity of 2000 m^3/day, the proposed hybrid configuration would deliver produced water at an SEC of 1.60–1.79 kWh/m^3, compared to 1.9 kWh/m^3 for stand-alone traditional RO, almost neglecting the thermal energy cost for MD component. A hybrid MD-MSF system for recovering freshwater from rejected MSF brine was studied by Laval et al. [99]. The hybrid method also lowers environmental risks by minimizing the volume of heated, concentrated, processed, and de-aerated MSF-rejected brine. The summary of conventional hybrid technologies is provided in Table 1.

Table 1. Summary of the main features in conventional hybrid technologies.

Author	Hybrid Configuration	Water Production Capacity	Outcome
Hassan et al. [83]	NF-MSF, NF-SWRO-MSF	20 m^3/day	NF-MSF and NF-SWRO-MSF systems in which MSF was operated using reject from SWRO as feed. The pilot-scale experiment showed that a hybrid system can operate at a TBT of 130 °C, which led to the GOR of 13 and enhanced water recovery.
Hamed et al. [84]	NF-MSF	20 m^3/day	MSF can be operated at a TBT of 130 °C. A water recovery rate of 70% was obtained.
Altaee et al. [85]	FO-MED	---	The hybrid system was investigated at high TBTs. The RSI was used to investigate the scale-forming tendency. MED operated at 85 °C TBT with a FO recovery rate of 40% or less when the feed salinity was 45,000 ppm.
Thu et al. [86]	MED-AD	Hot water flow rate 7.14 kg/s	First hybrid MED-AD system. GOR increased by 40% and the water production rate doubled.
Shahzad et al. [87]	MED-AD	Hot water flow rate 0.8 kg/s	MED-AD was compared with standard MED using a numerical model. In the last effect, the broad range between TBT and temperature allowed for the addition of more effects in MED. This led to enhanced performance and water production was increased by three times.
Thu et al. [88]	MED-AD	Hot water flow rate 7.14 kg/s	Maximum enhanced water-rate production in the hybrid system was 89% compared to stand-alone MED. Water production rate increased with the number of effects in MED.
Nafey et al. [89]	MSF-MED	5000 m^3/day	Each module consisted of a boiling evaporator and one flash evaporator. The designed configuration showed a decline in water production by 9% and 31% compared to MED and MSF-BR, respectively.
Mabrouk and Fath [90]	MSF-MED	56,781 m^3/day	Technoeconomic investigation of combined MSF and MED systems and conventional systems was conducted. For pumping, the power consumption of the hybrid system was 16% and 58% lower than MED-TVC and MSF-BR, respectively, whereas, GOR was higher by 9% and lower by 3% than MED-TVC and MSF-BR, respectively.
Mahbub et al. [93]	MED-RO, MSF-RO	MED-RO-47.96 MIGD, MSF-RO-36.61 MIGD	Combining MED-RO in the same plant resulted in a thermal efficiency increase of 19%. SEC of the plant combined with the MSF-RO system is significant compared to the MED-RO system by 17%.
Turek et al. [95]	NF-SWRO-ED	---	The results were compared among four different configurations, namely RO, NF-RO, NF-SWRO-ED and hybrid ED-RO. At 7 kWh/m^3, the hybrid NF-SWRO-ED achieved a high recovery rate of 69%.
Choi et al. [96]	RO-MD	50,000 m^3/day	While the flux and recovery rate are higher than those of RO, the RO-MD hybrid system could compete with RO. Furthermore, the price of supplying thermal energy for MD remains low.
Kim et al. [98]	RO-MD-PRO	2000 m^3/day	The price of thermal energy, the RO unit size, and the brine division ratio were all considered factors influencing hybrid plant efficiency. The proposed hybrid configuration could produce freshwater at 1.6–1.79 kWh/m^3 of SEC for a 2000 m^3/day plant capacity, compared to a 1.9 kWh/m^3 needed for a single RO.
Lawal D.U. et al. [99]	MD-MSF	75 to 200 m^3/day	The average expense for freshwater from a hybrid MD-MSF is between 1.085333 and 1.08638 $/m^3.

Based on this attempt to review the available literature, it is clear that there are a variety of ways to potentially hybridize traditional desalination processes. Conjoining thermal and membrane-based desalination processes allow for benefiting from individual processes and mitigating their limitations. For the MED-AD hybrid configuration, water production capacity and GOR increased significantly compared to a single MED. The NF-RO-MSF trihybrid integration also led to increased GOR and water recovery. Moreover, the performance of MED-AD was shown to increase three times relative to a stand-alone MED. The MSF and MED thermal desalination systems were individually integrated with RO to identify the significant hybrid model. The SEC of MED-RO was observed to be significantly better than MSF-RO.

Hybrid desalination plants are theoretically conceivable for the long-term generation of freshwater, but there is still a huge possibility for significant research and development in the field to make such technologies efficient and economically more feasible. Additionally, this review study also includes renewable solar as a thermal source of energy for desalination.

5. Hybrid Solar Desalination Systems

Solar desalination can be either directly or indirectly accomplished, depending on the manner in which the technology is powered by solar radiation. Freshwater is generated directly in solar collectors in direct desalination systems, termed solar stills, and solar energy is collected as electrical or thermal energy in ancillary solar desalination systems, which is then used to drive the desalination device. Despite numerous technological attempts to raise the water production rate in solar stills, the designs now available are not suitable for large-scale water production [100]. Nevertheless, research into novel materials for direct methods has progressed rapidly in recent decades.

The available literature concentrates on developments in solar still productivity, such as design configurations, operational conditions [101–104] and also incorporating latent heat storage for use when there is no sunlight [105]. While solar stills are affordable and easy to maintain, they lose a significant amount of heat and are inefficient, even in small systems [106].

The compatibility of the chosen desalination method determines whether to use solar energy directly or convert it into electrical power for desalination. The conversion effectiveness of heat from solar irradiance produced more accurate estimates of the energy requirements of a solar still. A higher conversion from sunlight to heating in direct desalination has been made possible due to the development in a range of novel materials. In a similar study, Kim et al. [107] investigated a 3D graphene network-coated wood with a solar-to-water vapor conversion efficiency of approximately 91% at 1 kW/m^2 power density of solar simulation. Shang et al. [108] used a porous CuS/polyethene hybrid membrane to achieve 63.9% conversion efficiency. Low thermal conductivity and good regeneration capability were also demonstrated by the membrane, resulting in reduced thermal losses. Inspired by nature, Finnerty et al. [109] developed a method that deployed a synthetic leaf made using graphene oxide. A hygroscopic coating was placed on the synthetic leaf, and water was transferred by capillary action from bulk to leaf. It was possible to reach a level of efficiency of 78%. This attempt was stated to have much potential for solar desalination without liquid output. In addition, different novel materials and methods for utilizing solar energy directly in desalination have been identified for improved energy efficiency [110–112]. Solar thermal and photovoltaic (PV) technologies are two types of hybrid solar desalination technology. For energy generation, the former can be further categorized into concentrated solar power (CSP) and direct heating for low-temperature applications. Solar PV has dominated other renewable energy options including wind and hydropower in recent years [113]. PV module prices have fallen by 80% in the last decade as a result of technical developments with average costs projected to fall from 0.05 to 0.06 $/kWh in the near future [114]. PV with RO is the most popular combination. Owing to the high heat losses in smaller desalination systems, larger desalination systems are more appropriate for photovoltaic hybridization. In addition to PV systems, solar collectors having 60 to 75% thermal efficiency are attracting much interest in addition to solar PV. Their levelized cost ranges from 0.05 to 0.09 $per kWh, depending on the type of collector, price and performance [115]. CSP is a method for extracting solar thermal energy that uses mirrors to focus sunlight and produce a large volume of heat. This heat is then converted to a fluid, which generates electricity. The (i) parabolic trough collector (PTC), (ii) linear Fresnel reflector (LFR), (iii) solar power tower (SPT) and (iv) parabolic dish systems (PDS) are the four CSP technologies currently accessible. Figure 7 depicts a variety of hybrid CSP desalination technology configurations that can be formed [114]. Three mature CSP technologies are the solar tower, parabolic and linear Fresnel, which can be paired with various power cycles such as air Brayton, Rankine, CO_2 supercritical Brayton, organic Rankine cycle (ORC), and transcritical-CO_2 Rankine. Using a membrane desalination device, the energy produced by power cycles may be used to produce freshwater in part or completely. Furthermore, the waste heat released by the given cycles might be used in thermal desalination units. Such processes may make use of waste heat from a Brayton cycle's exhaust gas, a CO_2 power cycle's condensation/heat sink condition or a Rankine cycle's extraction/condensation phases. Instead of producing electricity, the heat produced by CSP may be utilized to power a desalination facility. Due to the likelihood of steam within a 500_4500 kPa pressure range at high temperature, TVC-MED could be the most viable alternative among the current desalination technologies [116].

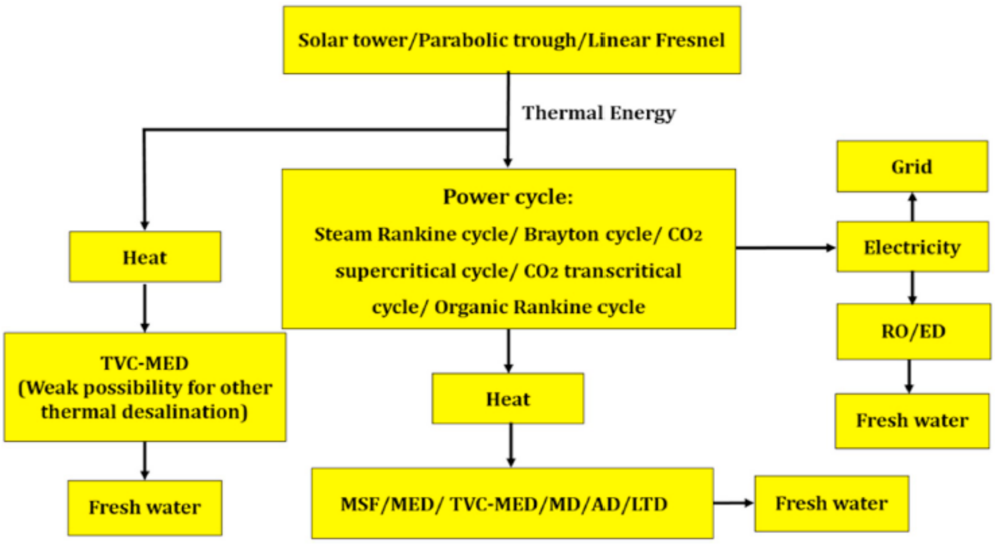

Figure 7. Various possible arrangements for hybridizing CSP units with desalination technologies [116].

The efficiency of a novel CSP desalination unit was evaluated by Blanco et al. [117], as part of the AQUASOL experiment. The proposed plant was planned to generate 3 m^3/h of freshwater at a nominal volume. A PTC solar area incorporated with storage of thermal energy, a TVC-MED hybrid configuration and a dual-effect absorption heat pump was deployed in this model. These improvements resulted in a 12% reduction in electricity usage (from 3.3 to 2.9 kWh/m^3) and a 44% decrease in requisite of the thermal energy (from 63 to 36 kWh/m^3).

Experimental findings for a pilot plant with a hybrid MED-AHP powered by a PTC solar field were presented by Stuber et al. [118]. They found that using the AHP efficiency increased dramatically. The same reduced the requisite thermal energy of the unit from 261.87 to 133.2 kWh/m^3, as opposed to a stand-alone MED. Due to the reduction in thermal energy demand, the needed capacity of solar fields was decreased by 49%. The thermal energy consumption for an integrated hybrid MED-AHP unit with 10 stages was decreased by 34.0 kW/m^3 based on the simulation results. Hassabou et al. [119] used unsteady analysis to determine the technoeconomic efficiency of a PTC-operated MSF system in

MersaMatruh, located in Egypt, which was planned to generate 5000 m^3/day of freshwater. They performed a simplistic economic study and contrasted the efficiency of a CSP-MSF system to that of a CSP-RO system and fossil-fueled desalination systems. They found the water production price of the CSP-RO hybrid system competed with traditional fossil fuel-operated desalination systems; on the other hand, the cost of water production is about three times greater than CSP-MSF system than that of the fossil fuel-driven systems.

In Almeria, Spain, Ibarra et al. [120] examined the output of a 5 kW ORC-CSP-based RO hybrid plant for clean water processing. In their study, they discussed the thermodynamic output at partial load to estimate clean water processing potential under various operating conditions. Pentafluoro propane was taken as a functioning solution for an ORC unit and a thermal energy storage system was planned to justify the ORC's requirements. According to their findings, the device provided about 1.2 m^3/h of clean water, making the system ideal for remote places. The efficiency of a combined CSP-RO-MED desalination device in Egypt was evaluated by Iaquaniello et al. [121]. The machine consisted of two components: (i) a steam Rankine cycle with an integrated gas turbine cycle, which used a backup energy supply and a molten salt PT CSP plant to operate the Rankine cycle; and (ii) a combination RO-MED desalination system with energy recovery equipment. They indicated that the CSP-RO-MED hybrid system has numerous advantages including versatile water and power output and less than 1 €/m^3 LCOW.

In the California's Central Valley, Weiner et al. [122] established a PTC-driven RO-TVC-MED hybrid system to generate 7600 m^3/day of clean, pure water from brackish water and agricultural runoff. They discussed that the proposed hybrid system is more effective than a discrete TVC-MED in terms of cost and energy use. They demonstrated that the hybrid system's LCOW was 41% lower than a stand-alone TVC-MED system, and LCOW was reduced by 48% when the planned hybrid system was fueled by grid energy and natural gas. Li et al. [123] developed a CSP-RO hybrid unit for freshwater and electricity co-generation. In this, a PTC-driven supercritical ORC powered the RO system. At design circumstances, the hybrid unit generated 200 kW of electric power, with 100 kW going to the RO unit, which produced 40 m^3/h of freshwater, and the remainder going to the grid. According to their findings, running the ORC under subcritical circumstances is advantageous for low solar irradiation intensity, whereas supercritical ORC performed effectively for medium to high solar irradiation intensity. ORC acting over a full spectrum of solar radiation was determined to have an optimal thermal efficiency of 18–20%, although it was just 14% in low solar radiation settings.

In southern Italy, Casimiro et al. [124] compared and analyzed the performance of a hybrid CSP-RO and a hybrid CSP-MED unit for combined freshwater and power generation. The hybrid CSP-RO plant produces about 14% more freshwater and 20% more energy than the hybrid CSP-MED design, according to the researchers. In Abu Dhabi, Soomro and Kim [125] assessed the economic and thermodynamic efficiency of a new hybrid solar tower–MD unit for co-generation. Along with solar tower components, the system had a 111 MWe-capacity Rankine cycle, thermal storage and a direct contact MD unit. The warm saline water from the Rankine cycle's condenser was supplied to the MD unit in the hybrid system. Their findings showed that increasing the DCMD feed water temperature decreased real thermal energy consumption. For a mean freshwater processing volume of 40.75 m^3/day, the LCOW was 0.392 $/$m^3$ and the LCOE was 0.1303 USD/kWh. They concluded that the current configuration is both environmentally and economically favorable. Ishimaru [126] announced a solar PV-ED hybrid system installed in Nagasaki, Japan, with a water generation capacity between 200 and 375 m^3/day. The hybrid system performance ranged from 6.0 to 8.2%, and the power usage was lower than the 1.92 kW-h/m^3 built value.

Worldwide, several hybrid solar PV-RO desalination systems have been constructed. A water processing plant having a 1.2 gal/min water production capacity constructed in Jeddah, Saudi Arabia, is adequate to fulfill the demand for drinking water for roughly 250 people. According to Al-Suleimani and Nair [127], the solar PV-powered RO system was cost-effective compared to the RO unit run by diesel for a comparable size, with a water output cost of 6.52 $/m^3$ versus 8.68 $/m^3$ for the latter. Raval and Maiti [128,129] proposed a revolutionary idea for the performance of both PV and RO by using solar PV panel thermal energy to heat the moving saline feed water while raising the temperature of the flowing RO supply and decreasing the temperature of the PV module. They determined that by modifying the RO productivity and PV modules, they could reduce energy usage by 28%. As feed water temperature rises, the membrane flux increases by 3% per °C.

Mathias et al. [130] investigated the impact of hybrid PV-RO systems, including single and double RO modules, PV area, power and battery consumption on recovery rate. Using dual-stage plants with capacities greater than 5 m^3 might achieve a recovery rate of about 65% on the higher side. They illustrated that as capability grew, production costs decreased. From a financial standpoint, the authors concluded that using batteries with capacities less than 5 m^3/day was not cost-effective. From the convergence of PV-RO with the grid, Alsheghri et al. [131] demonstrated the likelihood of reducing government subsidies for water production by 84%. When compared to thermal-based systems, this technology has a much smaller environmental effect. According to the report, the fixed-PV limited installed system costs 1.39 $/m^3$, whereas the high-installed-capacity unit with a one-axis monitoring device cost 0.85 USD/m^3. The large-capacity unit with one-axis monitoring saved 33,579,763 L of diesel per year, whereas the mounted PV limited capacity unit saved 1,158,987 L of fuel per year, and CO_2 emissions were reduced by 90,241 and 3115 tons per year, respectively.

In the climate circumstances of Abu Dhabi, the possibility of using heat retrieved from solar PV modules through the cooling stage of HDH desalination was explored [132]. According to their findings, the device built could generate freshwater at a rate of 2.28 L/m^2 surface area. When compared to the traditional PV-RO, this should result in an 83.6% reduction in environmental effects.

Based on the work presented here, the summary of significant characteristics of hybrid solar desalination technologies is shown in Table 2.

Table 2. Summary of the significant characteristics of hybrid solar desalination technologies.

Authors	Hybrid Configuration	Water Production Capacity	Outcome
Blanco et al. [117]	CSP –TVC-MED-Double effect AHP	72 m^3/day	A solar PTC region is used in conjunction with a TVC-MED/MED double-impact absorption heat pump. As compared to a system without an AHP component, the electrical energy consumed and thermal energy requirements were decreased by 12% and 40%, respectively.
Stuber et al. [118]	CSP-MED-Single effect AHP	Variable from 5.73 m^3/day to 11.28 m^3/day	Due to a decrease in the quantity of thermal energy required, the integration of a single-effect AHP resulted in a significant reduction in the surface area of the PTC region.
Hassabou et al. [119]	CSP with MSF	5000 m^3/day	The cost of producing freshwater from a CSP-RO hybrid unit was comparable with traditional fossil fuel-driven desalination systems, whereas, the water production price of a CSP-MED hybrid unit was determined three times higher than that of a fossil fuel-driven unit.

Table 2. *Cont.*

Authors	Hybrid Configuration	Water Production Capacity	Outcome
Ibarra et al. [120]	CSP with RO	28.8 m^3/day	Only CSP-ORC that is capable of powering an RO unit was developed for the 5 kW solar unit. With a 1.2 m^3/h water-generation capacity, the system was found to be ideal for remote areas.
Ianquaniello et al. [121]	CSP-hybrid MED-RO	1224 m^3/day by MED and 19,372 m^3/day by RO	A hybrid MED-RO with a combined CSP was developed. The proposed CSP-RO-MED hybrid concept provides scalable water and power cogeneration with lower than 1 EUR/m^3 LCOW.
Weiner et al. [122]	CSP-hybrid TVC-RO-MED	7600 m^3/day	A hybrid TVC-RO-MED system was used in the system, which was powered by a PTC solar field. With a 41% lower LCOW, the hybrid TVC-RO-MED system was found to be significantly efficient compared to a single TVC-MED. The LCOW for a single TVC-MED unit was 0.75 $/$m^3$, and the LCOW for a hybrid TVC-RO-MED system coupled with a CSP area was 0.45 $/$m^3$.
Li et al. [123]	CSP-RO	960 m^3/day	A PTC-driven supercritical ORC and an RO unit were combined in a hybrid CSP-RO configuration. The system provided 200 kW of power at design conditions, with 100 kW going to the RO unit to generate pure water and the remainder flowing to the grid.
Casimiro et al. [124]	CSP-RO and CSP-MED	---	The authors compared and analyzed the efficiency of CSP-integrated RO and CSP-integrated MED systems in terms of water and power co-generation. They found that the CSP-RO hybrid system yields 14% more product water and 20% more electricity than the CSP-MED hybrid system.
Soomro and Kim [125]	CSP-DCMD	40.75 m^3/day	DCMD unit and solar tower operated Rankine cycle were integrated with a new hybrid system. Warm water from the condenser of Rankine cycles is supplied to the DCMD unit. The LCOW and LCOE of the proposed system were 0.392 and 0.1303 $/$m^3$, respectively. According to the authors, freshwater development under the proposed scheme is both environmentally and economically favorable.
Ishimaru [126]	PV-ED	200–375 m^3/day	A hybrid PV-ED system was described. The average performance ranged from 6.0 to 8.2%, and the energy utilization was lower than the 1.92 kW-h/m^3 built value.

Table 2. *Cont.*

Authors	Hybrid Configuration	Water Production Capacity	Outcome
Raval and Maiti [128,129]	PV-RO	---	An innovative concept was developed by authors to increase the performance of PV and RO. It was found that energy consumption was reduced by 28% due to the utilization of thermal energy of PV panels to perform the preheating of the incoming saline of the RO unit.
Mathias et al. [130]	PV-RO	With reference to 5 m^3/day	RO modules, solar-PV area, capacity and usage of batteries were considered to study the effect of hybrid PV-RO. For a capacity higher than 5 m^3/day, a recovery rate of about 65% was obtained by using double-stage RO plants. For a capacity lower than 5 m^3/day, the use of batteries was not economically viable.
Alsheghri et al. [131]	PV-RO	---	The proposed system had a significantly reduced environmental impact compared to the thermal desalination system. Significant energy saving in terms of diesel usage was determined. A net reduction in CO_2 emission for both single-axis tracking systems and fixed PV small capacity was determined.
Giwa et al. [132]	PV-HDH	2.28 kg/m^2 PV area	Under Abu Dhabi's environmental conditions, heat retrieved from the PV module during the cooling phase of HDH desalination was investigated. When compared to the PV-RO model, the proposed system reduced environmental damage by 83.6%.

According to the research carried out, it is possible to infer that integrating solar thermal with desalination offers significant potential for both water production and co-generation of power and water. The potential of solar energy to generate both electrical and thermal energy, together with its abundant availability and no carbon footprint, makes solar energy the most promising hybridization option for desalination. Numerous technologies were presented in this study to recognize the viability of solar energy use in desalination. CSP-RO hybrid unit with low water production capacity was found to be suitable for remote regions. The RO-TVC-MED hybrid system was observed to be more significant than a single TVC-MED having lower LCOW. Various hybrid PV systems were also evaluated. The overall performance of both solar PV and RO can be improved by employing PV panels and using generated energy to preheat the flowing saline of the RO unit.

The CSP and PV desalination plants are environmentally friendly and more efficient, but the water production cost of CSP/PV-driven desalination remains higher than the conventional systems. The literature revealed that there is still significant progress required for hybrid CSP/PV desalination system development to make them economically more feasible.

6. Conclusions

In technological advancement, both cost and energy-effective desalination technologies are critical for sustainable development. Scientific progress is essential for developing desalination technologies to compete with traditional processes. In this review, commercialized and emerging desalination technologies were discussed in detail. Hybridization of various desalination processes, on the other hand, would help to minimize energy consumption and efficient recovery of potable water and acts as a panacea in the desalination process. The following research direction has been drawn from this study:

- In the available literature, only a few embedded system designs have indeed been proposed and optimized, with far few implementations. In certain circumstances, one mechanism was configured independently, but the impact on the overall system was not been examined.
- Integration of MED with AD poses many advantages (e.g., increased GOR and water production capacity) and needs further attention. Results from theoretical studies have shown that the maximum increase in water production rate was 89% compared to a stand-alone system.
- Comparison of RO with MSF and MED individually presents higher thermal efficiency of MED-RO by 17%. The SEC was also lower for MED-RO than MSF-RO by 19%.
- Separate PV-RO desalination plant units show promise for ensuring pure water in remote and arid regions where there is little access to an electricity grid. The effectiveness of the PV-RO desalination unit is possible using a correctly organized PV array, solar monitoring system, tilt angle correction and panel cleaning device.
- Using the thermal energy of PV panels to preliminary heat the incoming saline feed of the RO unit showed a reduction in energy consumption by 28%. For capacities higher than 5 m^3/day, the PV-RO system achieved (a recovery rate of 65% and also has low environmental impact) remarkable performance and thus upgrading these technologies could be helpful to achieve sustainable development goals (SDGs).
- A pilot-scale study needs to be explored and conducted to understand the commercial applicability and scalability of hybrid technology with respect to energy consumption, increase in the quality and/or quantity of water, and resource recovery.
- System design optimization and cost analysis of upscaling is required to make the hybrid system economically viable.

Hybrid desalination systems pose technoeconomic advantages over conventional systems and further research is required to evaluate the pursuit of identifying the most suitable technology. Many of the hybrid desalination studies are analytical. Numerical and experimental validation of the proposed hybrid configurations is required to realize the economic feasibility. It also requires incorporating renewable sources and cavitation phenomena for making them more viable.

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Abbreviations

AD	Adsorption desalination
MED	Multi-effect distillation
MSF	Multi-stage flash
RO	Reverse osmosis
ED	Electrodialysis
MD	Membrane distillation
FO	Forward osmosis
AHP	Absorption heat pump
HDH	Humidification–dehumidification
NF	Nanofiltration

GHG	Greenhouse gases
TWh	Terra watt-hour
DCMD	Direct contact membrane distillation
VMD	Vacuum membrane distillation
AGMD	Air-gap membrane distillation
SGMD	Sweeping gas membrane distillation
RSI	Ryznar scale index
SEC	Specific energy consumption
PV	Photovoltaic
PTC	Parabolic trough collector
SPT	Solar power tower
ORC	Organic Rankine cycle
SWRO	Seawater reverse osmosis
CSP	Concentrated solar power
TDS	Total dissolved solids
MENA	Middle East and North Africa
TBT	Top brine temperature
OT	Once through
BR	Brine recirculation
GCC	Gulf Cooperation Council
VC	Vapor compression
MVC	Mechanical vapor compression
TVC	Thermal vapor compression
CEM	Cation exchange membrane
AEM	Anion exchange membrane
SW	Seawater
BW	Brackish water
GOR	Gain output ratio
3DGN	3-dimensional graphene network
kWh_{th}	Kilowatt hour
LFR	Linear Fresnel reflector
PDS	Parabolic dish systems
LCOW	Levelized cost of water
LCOE	Levelized cost of energy

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