Solar-assisted membrane technology for water purification: a review
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ABSTRACT
A shortage of safe drinking water is one of the leading problems in the world. Even in developed countries where water treatment systems are present, safe drinking water may not be always available due to the limitations of advanced water treatment techniques and high energy costs. On the other hand, many rural communities in Asia and Africa situated in semi-arid to arid regions are without reliable access to clean drinking water. It is, therefore, important to explore how solar energy can be linked to water treatment systems for clean drinking water production. Membrane-based water purification technologies play a major role in water purification by utilization of low-cost heat sources to make the process economically and technically viable for small, medium, and large-scale applications. Solar energy can be a viable source of power for water purification facilities in the coming years. Photovoltaic panels and solar thermal collectors are appropriate solar energy collectors for making a solar-powered water treatment system. Solar-assisted membrane-based water purification techniques could have a viable solution to the existing problems in semi-arid and arid regions. Due to the high quality of potable water demand, studies have been carried out on solar-assisted membrane-based technologies in water purification. This review considers basic concepts, specific energy consumption, water production cost, and applications of solar-driven membrane-based water purification technologies such as reverse osmosis, forward osmosis, electrodialysis, membrane distillation, and hybrid membrane systems. This review will allow the researchers to have a wider overview of the effort made by several investigators in the area of solar-assisted membrane-based water purification technology.

Key words | hybrid membrane system, membrane-based technologies, membrane distillation, solar energy, water purification

HIGHLIGHTS
- The recent research boom has been observed in the area of solar-powered membrane-based technologies.
- Solar-powered membrane-based technologies could have a viable solution to the existing problems in Asia and Africa situated in semi-arid to arid regions.
- Membrane-based water purification techniques can produce high-quality freshwater at a competitive cost.
- The past and present status of solar-powered membrane-based technologies has been reviewed.

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INTRODUCTION

Water is one of the most abundant resources on earth, covering three-quarters of the planet’s surface. On the other hand, the abstraction of water by human activities is far above the water available. The amount of available freshwater in natural occurrence is constant. In recent years, freshwater demand across the globe is increasing at an alarming rate due to rapid industrial growth, population growth, and higher standards of living and climate change (Kummu et al. 2013). Therefore, the provision of freshwater is becoming an increasingly important issue in many areas of the world. Water purification is the process of removing undesirable chemicals, biological poisons, suspended solids, and gases from contaminated water. To provide fresh water in an adequate quantity, people are forced to rely on the available water resources treated by thermal-based and membrane-based processes.

The most common thermal-based water purification plants for desalination are multi-stage flash distillation (MSF), multi-effect distillation (MED), and vapor compression (VC). Those conventional water purification methods are energy-intensive, in addition to their complexity and different related operational problems. These shortcomings have forced researchers to search for advanced alternative technologies. One of these alternative technologies is membrane-based water purification technology, which can be coupled with solar energy. Solar water purification can be broadly categorized into two methods. The first one is the direct use of energy collected in a solar still. Direct methods are suitable for small-scale systems. The second one is the indirect usage. Indirect methods can convert solar energy into heat or electricity. These indirect methods are preferable for medium and large-scale desalination systems (Sharon & Reddy 2013).

Solar-powered water treatment units are highly suitable for arid, semi-arid, and remote areas, in developing countries and on islands where no other mode of the power supply is available. Solar-powered membrane-based water purification technologies are currently used in several ways to purify water by reverse osmosis (RO), forward osmosis (FO), electrodialysis (ED), membrane distillation (MD), and hybrid membrane systems. The most commonly used membrane materials for membrane-based water purification technologies are porous hydrophobic and dense hydrophilic membranes. These membranes can be fabricated from organic and inorganic materials. Organic membranes are made of polymeric materials such as polypropylene (PP), polytetrafluoroethylene (PTFE), polyvinylidene fluoride, sulfonated cross-linked polystyrene, cellulosic acetate, and aromatic polyamide. Inorganic membranes are made up of carbon, silica, zeolite, ceramic, various oxides (alumina, titania, zirconia), and metals. Ceramic materials are the most commonly used materials for the synthesis of inorganic membrane for membrane-based water purification technology. When compared with polymeric microporous membranes, ceramic porous membranes can resist severe environments due to their high thermal stability, high...
chemical stability, excellent mechanical strength, biocompatibility, long lifetime, energy efficiency, availability, and sustainability (Gazagnes et al. 2007; Fang et al. 2012). These outstanding properties made inorganic microporous membranes a primary candidate to be used for water purification and desalination applications. Among the membrane-based water purification technologies, MD is an emerging and promising technology for sustainable water purification. This technology can be utilized with low-grade waste heat or solar energy. Therefore, the coupling of MD with solar energy for water purification is an attractive solution for saline water purification (Li et al. 2013a, 2013b).

Thus, compared with other solar-powered membrane-based water purification technologies: solar-powered membrane distillation (SPMD) is an innovative and promising approach for an energy-efficient, cost-effective, robust, and popular solution. MD has received attention in recent years due to its potential advantages regarding energy consumption, simplicity, low maintenance, and its ability to be coupled with solar energy (Al-Obaidani et al. 2008). Novel temperature-driven membrane techniques can produce high-quality freshwater at a competitive price and can be very effective to purify contaminated water (Karagiannis & Soldatos 2008; Hickenbottom & Cath 2014). MD is a combination of thermal distillation and membrane separation driven by a vapor pressure difference due to a temperature gradient across a hydrophobic porous membrane (Ruiz-Aguirre et al. 2017; Sanmartino et al. 2017b).

This paper reviews solar-driven membrane technologies for water purification such as RO, FO, ED, and MD, as standalone processes or as hybrid systems, evaluating energy consumption and water production costs. This review intends to suggest the appropriate solar-assisted membrane-based water purification technology for any given application.

TECHNIQUES AND PROCESSES OF WATER PURIFICATION

Water purification is a process of removing undesirable chemical compounds, organic and inorganic materials (suspended solids and gases), and biological contaminants from raw water to produce safe and clean water for household, agricultural, and industrial use (Othmer 2009). The conventional water treatment process includes physical, chemical, and biological processes. A physical process physically removes unwanted impurities from raw water. The most commonly used physical processes are screening, centrifugal separation, and sedimentation (Rao 2007). A chemical process chemically removes undesirable contaminants from raw water. The most common chemical processes used for water purification are flocculation, coagulation, chlorination, and distillation. Adsorption and filtration are the most common physicochemical process used in conventional water purification technologies.

A biological process effectively removes undesirable contaminants by three main mechanisms: biodegradation, adsorption, and filtration. A biological process is followed by physicochemical processes (adsorption and filtration). The most widely used biological processes are slow sand filters and biologically active carbon. A combination of biologically active carbon units with slow sand filtration is a viable technology for the removal of contaminants from raw water (Dignac et al. 2000). Membrane technology is a category of separation technologies that can be used for separation, concentration, and purification of various mixtures. Membrane technology is the most suitable water purification technologies with wide industrial and commercial applications, due to the following attractive features: some processes can be easily coupled with low-grade waste heat or renewable energy sources, they represent a clean technology with operational ease, yielding high-quality products and a greater flexibility in designing systems (Chen et al. 2011).

SOLAR-POWERED MEMBRANE-BASED WATER PURIFICATION TECHNOLOGIES

Solar energy is an affordable or viable energy source to be utilized in producing freshwater from contaminated water (Al-Kharabsheh 2005). The solar water purification system is a water decontamination system at the household and industrial level based on the direct use of solar energy and indirect use of solar energy to convert it into heat or electricity (Quteishat & Abu-Arabi 2012; Sharon & Reddy 2015).
The application of the solar water purification process has a long history. For instance, Arab alchemists introduced the first solar distillation system in 1,551 to produce fresh drinking water from saline water or contaminated water (Malik et al. 1978).

Among solar-powered water purification technologies, membrane-based water purification technology is the most promising technology due to its environment-friendly nature and economic viability (Ali et al. 2011; El-Sebaii & El-Bialy 2013). Figure 1 provides an outlook, based on the studies reviewed in this contribution, about main membrane-based water purification technologies where such solar-powered reverse osmosis (SPRO), solar-powered forward osmosis (SPFO), solar-powered electrodialysis (SPED), SPMD, and solar-powered hybrid membrane system (SPHMS) have been tested. The figure shows that SPRO technology (38%) has been the most applied technology.

Reverse osmosis

RO is a continuously operating membrane-based separation technology that uses pressure to pass source water through a semipermeable membrane and thereby produce purified water out of contaminated water or seawater (Mona 2010). RO membrane technology is universally adopted and recognized as the leading and the most optimized membrane technology of seawater desalination, drinking water production, brackish water treatment, and wastewater treatment. RO is currently the most mature and commercially available pressure-driven membrane-based separation technology, which can remove suspended solids, dissolved matter, ions, bacteria, all dissolved salts, and organic matter from drinking water using a semipermeable membrane and a high operating pressure.

RO can use low-grade waste heat (Tidball & Kadaj 1981; Li et al. 2013a, 2013b) or be integrated with renewable energy such as solar energy (Ghermandi & Messalem 2009; Davies 2011; Delgado-Torres et al. 2011; Mito et al. 2019), wind/wave energy (Diepeveen 2009; Khiari et al. 2019; Leijon et al. 2020), hydro-power (Murakami 1994; Zhou et al. 2020), and geothermal energy (Dipippo 2005; Loutatidou & Arafat 2015; Gnaifaid & Ozcan 2021). It can be driven either by photovoltaic electric generators or by the pressurization energy from solar thermal concentrator systems. RO is a membrane-based separation technology that has lower energy requirements than non-membrane-based separation technologies like MSF, MED, and VC (ElMekawy et al. 2014).

In the last two decades, a total of 37,403 research papers (review articles, research articles, encyclopedia, book chapters, book reviews, conference papers, mini-review, and patents reports) on the focus above-mentioned of the RO has been published since 2000 until the second quarter of 2020 (retrieved from Web of Science database using the search keyword ‘reverse osmosis’, accessed on 29 April 2020).

History and evolution of RO

The concept of the RO process was first described by French physicist Jean-Antoine Nollet in 1748. He carried out experiments by using a pig bladder to study the osmosis process. In 1981, the first SPRO pilot plant was built in Saudi Arabia with a total capacity of 100–400 m3/day of desalted water from seawater or brackish water (Boesch 1982). The first theoretical models and optimization of hybrid wind-solar-powered RO water desalination systems were developed by Mokheimer et al. (2013) in Saudi Arabia. A mathematical model and the computer code for the hybrid photovoltaic–wind electric generation system have been developed. Finally, a recent study by Dong et al. (2017) developed an anti-biofouling commercial polyamide RO membrane.
Solar-powered reverse osmosis

RO is a commercialized membrane-based water purification technology that can be coupled with solar energy systems for economical and energy-efficient desalination of brackish and seawater and water/wastewater treatments to produce freshwater. Solar energy can be used to pump water either through direct conversion or by using the indirect thermodynamic power generation method. The main parts of the SPRO hybrid systems are a solar thermal collector/photo-voltaic module, high-pressure pump, feed and permeate tank, and RO membrane module. Solar thermal collectors have a working fluid that absorbs solar radiation, e.g., oil, water, the refrigerant transfers thermal energy to mechanical work for the generation of mechanical power required by the RO. The general principle scheme of solar thermal driven of RO desalination systems is given in Figure 2.

SPRO has been studied intensively over the last two decades, and more than 4,120 academic documents (review articles, research articles, encyclopedia, book chapters, book reviews, conference papers, mini-review, and patents reports) have been published on the topic since 2000 until the second quarter of 2020 (retrieved from Web of Science database using the search keyword ‘solar-powered reverse osmosis’, accessed on 29 April 2020).

Davies (2011) developed a new system that uses a solar-Rankine cycle to drive RO for high recovery fresh water from saline groundwater. The system used a spiral-wound membrane module with an effective area 2.4 m² and linear Fresnel collectors with a steam turbine (solar collector area 1,000 m²). The final results of the study show that the steam cycle is operated without a vacuum condenser with an output of 350 L/m² day and predicted overall water output of 500 L/m² day. Thus, the proposed system could desalinate 350 m³ from saline water containing 5,000 ppm of sodium chloride with a recovery ratio of 0.7.

Peñate & García-Rodríguez (2012) designed an optimum solar desalination system for nominal capacities of 1,000–5,000 m³/day. The system was used as a parabolic trough collector with a specific energy consumption of 2.14 kWh/m³. Results show that the proposed design would be suitable for a standalone operation because all the energy requirements are supplied by the solar system. Another study on SPRO conducted by Nihill et al. (2018) showed that the recovery ratio was low, i.e., 26%. The authors briefly described the working principle of the new thermal water pump with the help of schematics and thermodynamic curves (P–h and P–h). The pump was a highly compacted heat engine that converted thermal energy directly to pressurized fluid flow. Furthermore, the authors presented the design and experimental analysis of a thermal water pump coupled with an RO desalination system with feed water at a salt concentration of 1,184 ppm, a heat source temperature of 86 °C, and the product water salinity of 111 ppm. The recovery ratio obtained is shown to be 26%. The results indicate that the proposed design has the immediate potential to compete with conventional thermal desalination systems.

In the work of Wu et al. (2018), a multi-objective optimization was used in the design and solar energy of standalone RO desalination driven by a photovoltaic and diesel generator hybrid system in Iran. Furthermore, the effects of varying fuel cost, interest rate, photovoltaic initial cost, and battery initial cost on the economic parameters of the hybrid system are also discussed. The RO units utilized a
specific heat consumption of 4 kWh/m³ with a potential capacity of 10 m³/day. The cost of the desalinated water produced by the proposed hybrid photovoltaic/diesel system ranges between 1.59 and 2.39 $/m³ depending on the costs of the input parameters. From the results, it is seen that the photovoltaic/diesel/battery/RO desalination system is economically and environmentally advantageous to a diesel-only system or a photovoltaic only system.

El Mansouri et al. (2020) presented an RO desalination plant integrated with a salt gradient solar pond with a total capacity of 2,380.8 m³/day and a feedwater salinity of 38,000 mg/L. The result revealed that an autonomous desalination system fully powered by solar energy can produce fresh water at a salinity of 376.6 mg/L with reasonable specific energy consumption, especially with energy recovery (2.1 kWh/m³). The desalination unit is composed of 31 hybrid pressure vessels with a potential capacity of 2,380.3 m³/day and overall specific energy of 2.82 kWh/m³.

A summary of selected studies carried out on solar thermal/photovoltaic-driven RO over the last two decades is given in Tables 1 and 2. This list describes information about the study year, application, feed water type, energy source, system description, daily production, specific energy consumption, and corresponding reference.

**Forward osmosis**

FO is an emerging and promising membrane-based separation technology that uses natural osmotic pressure to transport a solvent (normally water) across a selective permeable FO membrane, as opposed to pressure-driven membrane-based separation technologies like RO.

### Table 1 | Summary of selected solar thermal driven reverse osmosis studies along with their operating conditions

| Year | Application | Feedwater type | Energy source | System description | Capacity (m³/d) | Specific energy consumption (kWh/m³) | Ref. |
|------|-------------|----------------|---------------|-------------------|----------------|--------------------------------------|------|
| 2011 | Desalination | Saline groundwater | Linear Fresnel collectors with the steam turbine | Proposed a new system that uses a solar-Rankine cycle to drive reverse osmosis for high recovery fresh water from saline groundwater with a total RO membrane area of 2.4 m² | 350 | 1.8–7.5 | Davies (2011) |
| 2012 | Desalination | Seawater and brackish water | Solar ponds, thermal collector | Designed recommendations for solar desalination system based on solar organic Rankine cycles-reverse osmosis with RO membrane | – | 2 | Delgado-Torres & García-Rodríguez (2012) |
| 2012 | Desalination | Seawater | Parabolic trough collector (PTC) | Designed an optimum solar-powered reverse osmosis desalination system and compared it with competitor technologies with a total RO membrane area of 37.2 m² | 2,500 | 2.99 | Peñate & García-Rodríguez (2012) |
| 2014 | Desalination | Seawater | Solar field collector | Presented the analysis of the performance of a specific solar desalination organic Rankine cycle system at part load operation | 28.8 | 4 | Ibarra et al. (2014) |
| 2018 | Desalination | Brackish water | Thermal water pump | Designed a thermal water pump coupled with a reverse osmosis desalination membrane with the RO membrane | 0.030 | 45.8 | Nihill et al. (2018) |
| 2020 | Desalination | Seawater | Solar energy/pond | Proposed a reverse osmosis desalination plant integrated with a salt gradient solar pond and numerically investigated with a total RO membrane area of 41 m² | 2380.8 | 2.82 | El Mansouri et al. (2020) |
Table 2 | Summary of selected photovoltaic-driven reverse osmosis studies along with their operating conditions

| Year | Application | Feedwater type | Energy Source | System description (flux, rejection, and product water quality) | Capacity (m³/d) | Specific energy consumption (kWh/m³) | Ref. |
|------|-------------|----------------|---------------|---------------------------------------------------------------|----------------|------------------------------------|------|
| 2012 | Desalination | Brackish or seawater | Photovoltaic | Designed and installed a small-scale photovoltaic-driven reverse osmosis desalination plant with RO membrane (TFM-100). Brackish water (1,700 mg/L total dissolved solids (TDS)). Salt rejection 98%. | 0.5 | 19–32 | Banat & Dhabi (2022) |
| 2014 | Desalination | Brackish groundwater | Photovoltaic | Developed photovoltaic-powered reverse osmosis plant with RO membrane (RO 3,8040). Brackish water (4,000–4,500 ppm), product water salinity 300 ppm, recovery rate 70% | 50 | 1.64–3.13 | Peñate et al. (2015) |
| 2016 | Desalination | Brackish water | Photovoltaic | Determined the effect of climatic, design, and operation conditions on the performance and durability of a photovoltaic-powered reverse osmosis system with RO membrane (TW30–4040). A feed TDS of 2,000 mg/l, and a permeate TDS of less than 50 mg/l. | 5.1 | 1.1 | Alghoul et al. (2016) |
| 2016 | Desalination | Seawater | Photovoltaic | Proposed pinch analysis technique for retrofitting the off-grid battery-less photovoltaic-powered reverse osmosis system with a total RO membrane (SW30HR-380) active surface of 33.5 m². Maximum permeate flux 47 L/ m².s, recovery rate (30%), the salinity of the seawater (38,000 ppm) | 10 | 0.375 | Iman & ChangKyoo (2016) |
| 2018 | Desalination | Photovoltaic/diesel generator | Presented the size optimization of a photovoltaic/diesel/battery/reverse osmosis desalination hybrid energy system | 10 | 4 | Wu et al. (2018) |
| 2019 | Desalination | Groundwater | Photovoltaic | Developed an automated design algorithm for a photovoltaic-powered reverse osmosis treatment system and compared it with different geographical locations (Mexico, Ghana, India, and Bangladesh). RO membrane (2.5” × 40”, 4” × 40”) | 1 | 2.6 | Freire-Gormaly & Bilton (2019) |
nanofiltration, and ultrafiltration. The concentrated solution on the permeate side of the membrane (draw solution or sample solution) is the source of the driving force in the FO process (Cath et al. 2006).

Among the concentration-driven membrane-based water purification technologies, FO has multiple benefits: it is energy-friendly and has a lower energy requirement, higher water recovery, and lower membrane fouling tendency. However, this technology has a few critical challenges like internal concentration polarization and reverse salt flux (Tang et al. 2010; Zhao & Zou 2011; Van der Bruggen & Luis 2013). Even though it was introduced back in 1965 (Batchelder 1965), the process has recently gained more attention. This is proved by the increased number of publications from 2000 until the second quarter of 2020 (retrieved from Web of Science database using the search keyword ‘forward osmosis’, accessed on 29 April 2020), with a total number of 6,851 of research papers (review articles, research articles, encyclopedia, book chapters, book reviews, conference papers, mini-review, and patents reports) covering FO topics.

History and evolution of FO

The first method for the generation of electric power by mixing fresh and salt water was invented by a British engineer named Pattel in 1954. It can be used for salinity gradient power, FO, pressure-retarded osmosis, and reverse ED processes (Pattle 1954). Eleven years later, in 1965, Batchelder first proposed an FO separation process for the demineralization of water by using sulfur dioxide as a volatile draw solute (Batchelder 1965).

In 1996, the world’s first FO system was established by hydration technology innovations water in Canada for dewatering and producing blue-green algae. The first commercial thin-film composite FO membrane was introduced in 2010. In the same year, a hybrid FO/RO system was built for water purification and desalination application (Cath et al. 2010). Zhang et al. (2013) developed the first photovoltaic-powered hybrid system by combining FO and ED for the production of freshwater from secondary wastewater effluent or brackish water. Finally, a recent study by Phuntso et al. (2016) established a pilot-scale FO desalination plant for fertigation.

Solar-powered forward osmosis

A schematic diagram of a solar-driven FO system is shown in Figure 3. The main parts of the solar-driven FO system are the solar thermal collector/photovoltaic module, feed, permeate and brine tank, FO membrane module, and pumps. The energy required for an FO system is lower than for an RO system of the same capacity; therefore, FO is competitive in energy terms (Zheng 2017).

SPFO has been explored intensively over the last two decades, and more than 1,186 research papers (review articles, research articles, encyclopedia, book chapters, book reviews, conference papers, mini-review, and patents reports) have been published on the topic since 2000 until the second quarter of 2020 (retrieved from Web of Science database using the search keyword ‘solar-powered forward osmosis’, accessed on 29 April 2020).

Schrier (2022) developed a simple, low-cost, and scalable alternative method for ethanol concentration by FO with solar-regenerated draw solution. The draw solution was an aqueous brine that was regenerated by solar evaporation. The author found that the proposed system produced 95, 50, and 50% (w/w) ethanol solutions. The mean production rate in Ethiopia was 0.69 and 1.41 kg/m² day for 50 and 50% product, respectively. In comparison, the main production rate in Brazil was found to be 0.74 and 1.54 kg/m² day for 50 and 50% product, respectively.

Razmjou et al. (2015) studied the thermodynamic feasibility of bilayer polymer hydrogels as draw agents for the continuous production of fresh drinking water using SPFO. Thermodynamic analysis results show that the bilayer hydrogel-driven FO process requires a specific heat

Figure 3 | General scheme for solar-driven FO system.
consumption between 1.12 and 3.57 kWh/m³. The feed solution was 2,000 ppm sodium chloride solution and dewatering flux rose from 10 to 25 L/m² h. They concluded that the hydrogel-driven FO process required a minimum of energy compared with other well-established desalination techniques such as RO.

Khayet et al. (2016) used the response surface methodology and statistical experimental design to model a solar FO pilot plant and to optimize different responses such as the water permeate flux, the reverse solute permeates flux, and the FO-specific performance index. Then, a Monte Carlo simulation method was employed to determine the optimum operating conditions that maximize both permeate flux and thermal efficiency of the FO pilot plant. The obtained optimum parameters were confirmed experimentally. The results obtained in the pilot plant show that the specific heat consumption for a hybrid membrane system (FO–RO) and an FO system was 0.62–25.79 and 0.086–3.6 kWh/m³, respectively. An optimum FO-specific performance index range from 25.79 to 0.62 L/g kW h was achieved under optimum FO operating conditions, 0.83 L/min feed flow rate, 0.31 L/min draw solution flow rate, and 32.65 °C temperature.

Monjezi et al. (2017) also presented a novel process for the regeneration of dimethyl ether as a draw solute in FO using thermal energy from a solar pond in Chabahar, Iran. The authors conclude that the proposed process is a viable option for solar desalination. The average daily desalinated water was 2,450 m³ with a given solar pond size of 10,000 m². Recently, Amjad et al. (2018) developed and tested a combination of FO with solar energy for water desalination using as draw solution potassium doped carbon nanofibers in tri-ethylene glycol, which has high osmotic pressure and efficient absorption of solar energy. It was found that the osmotic pressure and water flux of the novel draw solution are directly related to the concentration of potassium/carbon nanofibers and tri-ethylene glycol. The specific solute flux of this work was 0.031 g/L. The quality of produced water was superior compared with potable water standards. Some selected references based on their study year, application, feed water type, types of draw solute(s), energy source, system description, specific energy consumption, and corresponding reference are presented in Table 3.

**Electrodialysis**

ED is one of the most commonly used membrane-based water purification technologies using semipermeable membranes to remove an undesirable ionic substance from an aqueous solution by applying an electric field. The process uses a driving force to transfer ionic species from the source water through anion exchange membranes and cation exchange membranes to a concentrated wastewater stream, creating a more dilute stream (Valero et al. 2011). Parameters such as current density, pH, flow rate, feed water ionic concentration, cell compartment geometry, and membrane properties determine the overall performance of the ED process (Mohammadi et al. 2004; Chang et al. 2009). Similarly, reverse ED is a promising membrane-based water purification technology to extract renewable energy from salinity gradients (Tufa et al. 2018).

A total of 3,038 ED-related academic documents (review articles, research articles, encyclopedia, book chapters, book reviews, conference papers, mini-review, and patent reports) were published during the period of 2000 to the second quarter of 2020 in the Web of Science database using the search keyword ‘electrodialysis’ (accessed on 29 April 2020). The annual publications almost quadrupled over the past 20 years, increasing from 205 in 2000 to 820 in 2020.

**History and evolution of ED**

The concept of ED was first reported by Maigrot and Sabates in 1890 (Maigrot & Sabates 1890). Ten years later, the first ED process patent was taken by Schollmeyer in 1900 (Schollmeyer 1902). Morse and Pierce published the first scientific article on ED in 1903 (Morse & Pierce 1903). The fundamental theory of membrane equilibrium and membrane potential was proposed by Donnan (1911). In the 1950s, the first commercial ED equipment was introduced by Ionics Corporation for water purification and desalination (Juda & McRae 1950; Winger et al. 1953). In 1954, the first commercial ED desalination plant was constructed in Saudi Arabia to produce fresh water from brackish water (Shaposhnik & Kesore 1997).

The first reverse ED pilot-scale plant was installed and tested in 2014 in Trapani, Italy, for the production of fresh water from real brackish water and brine (Karabelas et al.
Table 3 | Summary of selected solar-assisted forward osmosis studies

| Year  | Application            | Feedwater type                  | Draw solute(s)                          | Energy source               | System description                                                                                                                                                                                                 | Specific energy consumption (kWh/m³) | Ref.     |
|-------|------------------------|---------------------------------|-----------------------------------------|-----------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------|----------|
| 2012  | Dewatering             | Ethanol–water mixture           | NaCl, CaCl₂, K₂HPO₄, and K₄P₂O₇        | Solar energy collected from a shallow pool of brine | Developed a simple, low-cost, and scalable alternative method of removing water from ethanol with a tabular forward osmosis membrane                                                                 | –                                   | Schrier (2012) |
| 2013  | Desalination           | Saline water or wastewaters     | Bilayer polymer hydrogels              | Concentrated solar energy   | Investigated the feasibility of bilayer polymer hydrogels as forward osmosis draw agents with a total FO membrane area of 1.77 cm². Feed solution: 2,000 ppm sodium chloride solution                                             | 1.12–3.57                           | Razmjou et al. (2015) |
| 2016  | Water treatment/desalination | Saline aqueous solute          | NaCl                                    | Solar thermal and photovoltaic | Optimized a solar thermal and photovoltaic-powered forward osmosis pilot plant by using a statistical experimental design and RSM. Spiral-wound membrane module: effective membrane area of 0.35 m² | FO–RO: (0.62–25.79) FO: (0.086–3.6) | Khayet et al. (2016) |
| 2017  | Desalination           | Seawater                        | Dimethyl ether                          | Thermal energy              | Presented a novel process for the regeneration of dimethyl ether as a draw solute using thermal energy from a solar pond with the FO membrane                                                                 | 0.46                                | Monjezi et al. (2017) |
| 2018  | Desalination           | Deionized and brackish water    | Potassium doped carbon nanofibers in triethylene glycol | Photo-thermal               | Developed and tested a combined novel forward osmosis with solar energy with a total FO membrane-active surface area of 42 cm²                                                                                             | –                                   | Amjad et al. (2018) |
A technically and economically attractive energy-neutral ED process was developed by Luo et al. (2021). Finally, a recent study by Shah et al. (2018) developed the cost-optimal design of the ED process for domestic use.

Solar-powered electrodialysis

A schematic diagram of a solar-driven ED system is shown in Figure 4. The main parts of the solar-driven ED are a photovoltaic module, feed, permeate and brine tank, ED membrane module, and circulating pumps. The solar radiation on the surface of the solar panel is transformed into electric energy, which is required by the ED.

As has been mentioned above, studies on ED have a long history. In the last two decades, several ED systems across the globe have been designed, installed, and tested using solar energy. For example, more than 1,181 academic documents (review articles, research articles, encyclopedia, book chapters, book reviews, conference papers, mini-review, and patents reports) have been published on SPED since 2000 until the second quarter of 2020 (retrieved from Web of Science database using the search keyword ‘solar-powered electrodialysis’, accessed on 29 April 2020).

Uche et al. (2013) analyzed the feasibility of brackish water desalination by on-grid and off-grid batch ED for modeling and experimental tests supplied with an alternative current-direct current-controlled rectifier or a photovoltaic array. An ED stack model was developed and experimentally validated. Results showed that a specific heat consumption of 0.9–1.7 kWh/m³ with a potential capacity of 4.32 m³/day was obtained for brackish water solutions of about 3,000 ppm. It is important to note that batch ED presented similar results to continuous reversal ED in terms of specific energy consumption.

Fernandez-Gonzalez et al. (2015) discussed the sustainability of a photovoltaic-powered ED system for the desalination of brackish water. Besides, they analyzed the energy efficiency of the system to determine the specific energy consumption. The system required a specific heat consumption of 0.49–0.91 kWh/m³ with a potential capacity of 1–200 m³/day for brackish water (2,500–5,000 mg/L). They identified the main barriers of photovoltaic-powered ED system, which are preventing a larger market penetration of the system.

Gonzalez et al. (2017) tested a pilot-scale SPED brackish water purification module. They analyzed the electricity consumption of a standalone water purification module. The results showed that a salt removal efficiency of 95% and an arsenic removal efficiency of >99.9% was reported. The system required the lowest specific electricity consumption of 2.16 kWh/m³ for the ED and 5.46 kWh/m³ for the global system. In the overall process, desalinated water with TDS concentrations between 102 and 284 mg/L was obtained in all experimental tests.

Xu et al. (2020) developed an ED desalination model and solved this model using MATLAB to evaluate the influences of voltage, flow rate, and electrolysis compartment size on system performance. In addition to that, a small-scale photovoltaic ED desalination system was built to verify the validity of the model. Under three typical weather conditions (overcast, cloudy, and sunny day), the system performances were characterized. The results show that the salinity at the exit of the ED chamber decreases with the increase in the voltage and the ion membrane area, and increases with the increase in the flow rate. On a typical sunny day, the salinity at exit reaches below the standard (<1,000 ppm) earlier than in overcast and cloudy days. The cumulative freshwater was, respectively, 0.4, 1, 1.6, and 2.2 L within 2 h at the flow rate of 200, 500, 800, and 1,100 mL/h.

Some selected references based on the study year, application, feed water type, energy source, system description, daily production, specific energy consumption, and corresponding reference are listed in Table 4.

Membrane distillation

MD is a membrane-based water purification technology in which the separation process takes place by a difference in
| Year   | Application                  | Feedwater type | Energy source | System description                                                                 | Capacity (m³/d) | Specific energy consumption (kWh/m³) | Ref.                          |
|--------|------------------------------|----------------|---------------|-------------------------------------------------------------------------------------|-----------------|-------------------------------------|-------------------------------|
| 2010   | Desalination                 | Brackish water | Photovoltaic  | Analyzed the feasibility of batch-electrodialysis technique for modeling and         | 4.32            | 0.9–1.7                             | Uche et al. (2015)            |
|        |                              |                |               | experimental tests. ED membrane stack: ten 0.02 m²                                    |                 |                                     |                               |
| 2013   | Desalination                 | Brackish water | Photovoltaic  | Designed a photovoltaic electrodialysis system with two membranes (cation and anion) | 192             | 0.618                               | Peñate et al. (2015)          |
|        |                              |                |               | stacks                                                                               |                 |                                     |                               |
| 2015   | Desalination                 | Brackish water | Photovoltaic  | Analyzed the energy consumption of a photovoltaic-powered electrodialysis system    | 1–200           | 0.49–0.91                           | Fernandez-Gonzalez et al. (2015). |
|        |                              |                |               | with a total anionic and cationic membranes area of 0.3 m²                           |                 |                                     |                               |
| 2017   | Water purification           | Brackish water | Solar power   | Designed a pilot-scale solar-powered electrodialysis water purification module       | –               | Electrolysis: 2.16–2.86, overall process: 5.46–6.98 | Gonzalez et al. (2017).       |
|        |                              |                |               | with a total anionic and cationic membranes area of 200 cm²                         |                 |                                     |                               |
| 2018   | Production of freshwater and | Saline         | Photovoltaic  | Photovoltaic bipolar membrane electrodialysis and added feedback control for a      | –               | 4.4 kWh/kg HCl (variable current system) 7.3 kWh/kg HCl constant current system | Herrero-Gonzalez et al. (2018) |
|        | valorization of waste        | concentrates   |               | circuit for acid production. Heterogeneous polyethylene-based anion (AM-PP RALEX) and |                 |                                     |                               |
|        |                              |                |               | cation (CM-PP RALEX) exchange membranes                                             |                 |                                     |                               |
| 2020   | Desalination                 | Saltwater      | Photovoltaic  | Developed an electrodialysis desalination model and solved using MATLAB to evaluate | 0.0048–0.0264   | –                                    | Xu et al. (2020)              |
|        |                              |                |               | the influences of voltage, flow rate, and electrolysis compartment size on system    |                 |                                     |                               |
|        |                              |                |               | performance and validated a model using experimental data. Used ion-exchange membrane |                 |                                     |                               |
volatility. It is a thermally driven separation process making use of a microporous hydrophobic membrane. It appears to be a promising solution for water purification and desalination whenever cheap, and abundant energy like low-grade waste heat or solar energy is available (Bouguecha et al. 2015). The driving force for MD is the vapor pressure difference across the membrane due to the temperature gradient between the feed, and permeate side of the membrane interface (Al-Obaidani et al. 2008). It results from the temperature difference between the two sides of microporous hydrophobic membrane water vapor condensates on the permeate side of the membrane.

Four types of MD configurations are commonly used in the MD process: direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), sweeping gas membrane distillation (SGMD), and vacuum membrane distillation (VMD) (El-Bourawi et al. 2006; Souhaimi & Matsura 2011) (Table 5).

MD is extremely useful for some applications (desalination, water purification/treatment, and resource concentration) and has been used for many purposes. Some of the most common applications are wastewater treatment, drinking water purification, production of chemicals, crystallization of salts, milk and fruit juices concentration, removal of water from blood and treatment of protein solutions in biomedical industries, treatment of pharmaceutical wastewater containing taurine, treatment of textile wastewater contaminated with some special types of dyes such as methylene blue, aqueous solutions, treatment of water contaminated with boron, arsenic, and some heavy metals, ammonia, the concentration of coolant liquid, such as glycols (Wang & Chung 2015).

There has been a rapid surge in MD studies in the last two decades. For example, more than 29,114 academic documents (review articles, research articles, encyclopedia, book chapters, book reviews, conference papers, mini-review, and patents reports) have been published on MD from 2000 until the second quarter of 2020 (database obtained from Web of Science with the term ‘membrane distillation’ as on 29 April 2020). Research interest in MD has grown exponentially with the total number of publications approximately doubling with each 10 years (e.g. ~8,743 in 2010 to ~20,371 in 2020).

Figure 5 shows a comparison between the numbers of gathered papers published in the peer-reviewed journals for each MD configuration over the last two decades. It can be seen that among the published academic documents, VMD is the most studied MD configuration, and as the figure shows more than 49% of the MD is focused on the VMD configuration. On the contrary, sweep gas membrane distillation (SGMD) is the least studied configuration, which contains only 6.2% of the MD published papers.

History and evolution of MD

MD as a water purification technology was first introduced in 1963 by Bodell. He carried out experiments on MD for desalination by using silicon rubber membrane material, and then he received the first MD patent (Bodell 1965). The first scientific work on DCMD was published by Findley (1967). Weyl suggested suitable hydrophobic MD membranes (Weyl 1967). Bodell (1968) introduced the first SGMD and VMD configuration. In 1982, Cheng and Wiersma fabricated composite membranes having porous hydrophobic and non-porous hydrophilic layers for MD applications (Cheng & Wiersma 1982). This specific type of membranes used for the MD application was patented.

A few years later, the first MD device for desalination purposes was manufactured by Gore et al. in 1985. In 1988, a flat plate AGMD system was developed by the Swedish Company (Alklaibi & Lior 2004). A hybrid SPMD system with a total installed capacity of 0.12 m³/day was tested in Saudi Arabia to produce freshwater (Chafidz et al. 2016). Finally, a recent study by Lienhard et al. in 2018 established an energy-efficient conductive gap MD system for desalination and water purification.

Solar-powered membrane distillation

MD is a membrane-based desalination technology that can be coupled with solar energy systems (Al-Obaidani et al. 2008). The SPMD system is a hybrid and a standalone system. The system is an off-the-grid electricity system. A schematic diagram of the solar standalone DCMD system is shown in Figure 6. The main parts of the solar standalone DCMD system are a solar thermal collector/photovoltaic module, feed and distillate tank, MD module, and circulating pumps. The hybrid system here is defined as an off-the-
### Table 5 | Types of MD configurations and their advantages and disadvantages

| Configuration                              | General scheme | Description of the system | Advantages                                                  | Disadvantage                              |
|-------------------------------------------|----------------|----------------------------|------------------------------------------------------------|-------------------------------------------|
| Direct contact membrane distillation      | ![Diagram](image) | Both feed and permeate liquids are in direct contact with the membrane. The driving force, the vapor pressure difference across the membrane. Condensation takes place within the membrane module itself | • Simple operation  
• Requires the least equipment  
• High permeation flux  
• Lower permeation flux  
• Lower mass transfer resistance  
• Possible internal heat recovery | • Lower thermal efficiency  
• Higher heat loss by conduction and low-temperature polarization  
• Permeate contamination risk |
| Air gap membrane distillation             | ![Diagram](image) | Introduced an air gap between the membrane and condensation surface. Condensation takes place within the membrane module itself | • Low heat loss by conduction and low-temperature polarization  
• Higher thermal efficiency | • Low permeation flux  
• High mass transfer resistance  
• Required large membrane surface area |
Sweep gas membrane distillation (SGMD)

Sweep gas is used in the permeate side for sweeping the vapor molecules. Condensation takes place in an external auxiliary unit.

- Low heat loss by conduction
- Lower mass transfer resistance
- High permeate flux
- High operational cost
- Difficult to handle the sweep gas
- Difficult heat recovery
- Required large size external condenser

Vacuum membrane distillation (VMD)

The vacuum is applied on the permeate side of the membrane with the help of the vacuum pump. Condensation takes place in an external auxiliary unit.

- Negligible conductive heat loss
- High permeate flux
- Better thermal efficiency
- Difficult heat recovery
- High risk of pore wetting
- Required external condenser
grid energy generation system with the end-use energies in the form of heat and electricity.

For the last two decades, several research works have been carried out on designing, installing, and testing SPMD. For example, more than 3,306 academic documents (review articles, research articles, encyclopedia, book chapters, book reviews, conference papers, mini-review, and patents reports) have been published on SPMD from 2000 until the second quarter of 2020 (retrieved from the Web of Science database, accessed on 29 April 2020).

Figure 5 shows a comparison between the numbers of gathered papers published in journals for each SPMD configuration. It can be seen that among the published academic documents, solar-powered VMD is the most studied SPMD configuration, as the figure shows more than 35.5% of the SPMD is focused on the solar-powered direct contact membrane distillation (SPDCMD) configuration. In contrast, solar-powered sweep gas membrane distillation (SPSGMD) is the least studied configuration, which contains only 6.8% of the SPMD published papers.

Wang et al. (2009a, 2009b) synthesized a novel type of mixed matrix hydrophobic hollow fiber membrane with nanosized pores to improve the desalination performance in DCMD and VMD with a total membrane area of 0.09 m² and potential capacity of 0.02 m³/day. Moreover, their study also investigated the effect of additives (Cloisite clay particles and ethylene glycol) on membrane structure and performance. The system required a specific heat consumption of 7,850 kWh/m³ with a permeate flux of higher than 79.2 kg/m² h. The experimental results showed that the synthesized membranes with nanoscale pores used in MD yielded a 100% salt rejection without sacrificing the permeation flux. The addition of ethylene glycol enhanced pore formation during phase inversion and the addition of clay
particles enhanced the tensile modulus and improved long-term stability compared with those fibers without particles.

Chen & Ho (2010) tested DCMD with a solar absorber for saline water desalination with an effective membrane area of \(6.09 \times 10^{-2} \text{ m}^2\). The system used a PTFE membrane with a pore size of 0.1 \(\mu\text{m}\), a porosity of 0.72, and the thicknesses of 130 \(\mu\text{m}\) and feed temperature (between 35 and 50°C). This study also presented a two-dimensional mathematical model and a general numerical method to obtain water productivity, absorber plate, and flow conduit temperature distributions. The results show that the theoretical predictions agree fairly well with the experimental results using a combination of Knudsen diffusion and viscous flow models for membrane coefficient estimation.

Similarly, Bouguecha et al. (2015) evaluated the performance and thermal energy efficiency of solar energy powered PP hollow fiber DCMD plant with a potential capacity between 0.24 and 0.34 m\(^3\)/day, a membrane thickness of \(30 \times 10^{-6} \text{ m}\), a porosity of 40\%, and the temperature of the hot feed stream between 62.1 and 64.9°C. The specific heat consumption of the pilot plant with a heat recovery arrangement was 1,609 kWh/m\(^3\). This value is 31.3\% less than that that reported in the work of Bouguecha et al. without a heat recovery arrangement. Moreover, a permeate flux of 212.88 kg/m\(^2\) day was reported in the same study.

Shim et al. (2015) proposed and experimentally tested a solar-assisted DCMD system for seawater desalination with a total membrane area of 0.06 m\(^2\) and a potential capacity of 0.058 m\(^3\)/day. The system used a PTFE membrane with a thickness of 110–120 \(\mu\text{m}\), a porosity of 88\%, a feed flow rate of 4.5 L/min, and the feed and permeate temperature of 60°C and 20°C, respectively. Results showed that the system requires a specific heat consumption of 896–1,453 kWh/m\(^3\) with a permeate flux of 981.6 kg/m\(^2\) day and salt rejection rate >99.8\%.

SPDCMD was also adopted in a recent study of Kabeel et al. (2017). The pilot plant was installed by using a PP tubular membrane with a total membrane area of 1 m\(^2\), thickness of 1.5 mm, and average pore size of \(0.2 \times 10^{-6} \text{ m}\), which aims to produce potable water after desalination of saline water. Their study also investigated the effect of the cooling unit on system productivity, the effect of feed water flow rate on the pressure drop across the membrane, and measured thermal performance of the system by the gained output ratio with daytime. The authors found that the pressure drop was 158.89 N/m\(^2\) at a feedwater flow rate of 10 L/min. While in cases of feed water flow rate of 15 L/min, the pressure drop was about 336.61 N/m\(^2\). This indicates that the pressure drop across the membrane increases with the increase in the feed water flow rate. The use of the cooling unit significantly increased the system productivity by 1.25 times. A potential capacity of 0.033 m\(^3\)/day and a gain output ratio (GOR) of 0.49 was also obtained.

Ben Abdallah et al. (2015) experimentally and numerically investigated solar-powered VMD for seawater desalination and further determined daily productivity. The system was used as a hollow fiber polyvinylidifluoro membrane module with a membrane thickness of 0.4 mm, an internal fiber diameter of 2.6 mm, a length of 1 m, and a maximum feed temperature of 80°C. The model shows that the daily production throughput can reach 38 kg/day with a permeate flux between 256.32 and 490.08 kg/m\(^2\) day. The integration of solar energy with the hollow fiber module allows the improvement of the desalination plant productivity.

Chafidz et al. (2016) tested portable and hybrid solar-powered vacuum multi-effect MD systems with a total membrane area of 5.12 m\(^2\) and potential capacities between 0.27 and 0.38 m\(^3\)/day for producing fresh water in Saudi Arabia. The average distillate output rate was 11.53 L/h with a maximum of 15.94 L/h at noontime, whereas the distillate flux was in the range of 1.5–2.6 L/m\(^2\) h. The solar energy converting efficiency from the two tests was low (33.6\%).

Ma et al. (2018) evaluated the feasibility of small-scale solar VMD unit for seawater desalination. The effects of various solar and VMD parameters on daily water production, energy consumption, and gained output ratio were analyzed through several series of simulations. Results showed that lower operating temperatures were more favorable. A permeate flux of 8 kg/m\(^2\) day, a potential capacity of 0.008 m\(^3\)/day and GOR of above 0.7 with a specific heat consumption of 121–239 kWh/m\(^3\), which is quite comparable to single-effect single-stage MD systems driven by indirect supplied heat was achieved at the specified operating temperatures.

Banat et al. (2017) designed and manufactured a small-scale standalone solar-powered spiral-wound AGMD module with an internal heat recovery function. In these experiments, PTFE ethylene membrane was used with a total membrane area of 10 m\(^2\), a porosity of 80\%, a pore size of 0.2 \(\mu\text{m}\), a
thickness of 35 μm, and a temperature level between 60 and 80 °C and potential capacity of 0.19 m³/day. The plant integrated solar thermal and photovoltaic energy. A permeate flux of 60 kg/m²·day was obtained. The specific thermal energy consumption calculated for this system is less than that for conventional solar stills (640 kWh/m³). This suggested that MD is better in energy saving than solar stills.

Guillén-Burrieza et al. (2011) tested a solar-driven AGMD desalination pilot plant. In their work, flat sheet PTFE membrane with a total membrane surface area per module of 2.8 and 8.4 m², a porosity of 80%, a thickness of 0.2 mm, a pore size of 0.2 μm, and a feed temperature up to 85 °C was used. The system required a specific heat consumption of 810–2,220 kWh/m³ with a permeate flux of 156–168 kg/m²·day. The authors conclude that a multi-stage concept is required to improve the performance and thermal efficiency of the system.

Similarly, Guillén-Burrieza et al. (2012) also analyzed and compared the performance of two different pre-commercial AGMD desalination modules with a total membrane surface area of 9 m² each in terms of distillate production and quality, thermal efficiency, and recovery ratio. Minimum specific thermal energy consumption was in the range of 1,805 kWh/m³ for the compact prototype and around 294 kWh/m³ for the multi-stage one. Distillate quality was excellent (in the range of 2–5 μS/cm) and practically not affected by feed flow rate, hot inlet temperature, or feed salt concentration. The performance ratio of a compact prototype was never larger than 0.53, while for multi-stage, the performance ratio reached a maximum of 1.96. Finally, the multi-stage analysis showed that by increasing the number of modules not only the heat recovery is greater but also the distillate throughput is to some extent better; therefore, multi-stage concept shows better features for scaling of the system. The authors conclude that the best specific distillate production and heat consumption results were as high as 5.09 L/m²·h and as low as 294 kWh/m³, respectively.

Selected studies relevant to MD showing the study year, system scale, energy source, system configuration (flux and rejection), daily production, specific energy consumption, water production cost, and corresponding reference are presented in Table 6.

As can be seen in Table 6, the specific energy requirement of MD systems has been mainly attributed to the membrane properties, module configurations and dimensions, operating conditions, plant type, and size (capacity) (Wang et al. 2009a, 2009b; Bouguecha et al. 2015; Li et al. 2019; Karanikola et al. 2019; Ma et al. 2020). Based on the above-mentioned attributes, it is difficult to figure out the actual energy required to operate an MD system and the energy cost of the system. In general, MD systems consume energy for three main functions: heating the feed aqueous solution, cooling the permeate aqueous solution or condensing, and running the circulation pumps, vacuum pumps, or compressors based on the design and configuration of the system. Heat energy utilized for heating the feed aqueous solution occupies the largest fraction, which is more than 90% of the total energy requirement of the MD system (Wang et al. 2009a, 2009b; Khayet & Matsuura 2011). Moreover, heat and mass balance calculations show that the specific thermal and electricity demands for MD systems lie around 4.0–5.0 and 1.5–4.0 kWh/m³, respectively (Liu & Martin 2005).

**Hybrid membrane systems**

A membrane-based hybrid water purification technology is a combination of two or more membrane-based separation techniques that results in a better technique compared with these processes used alone. By using hybrid membrane systems, benefits in product quality, environmental and energy impacts, and plant footprint can be obtained (Drioli & Fontanova 2004). By using hybrid membrane processes, the combinations of water purification techniques are considered to provide an opportunity to exceed the limitations of conventional processes (Buonomenna 2013). Such systems often target reducing weaknesses of a certain conventional process. They are characterized by flexibility in operation, less specific energy consumption, high water productivity, low construction cost, high plant availability, and better power and water matching.

Hybrid membrane processes are expected to offer new innovative solutions and they offer new possibilities for sustainable industrial growth (Drioli et al. 2011). In the last two decades, a great deal of research has been conducted on the hybrid membrane system. For example, more than 5,143 academic documents (review articles, research articles, encyclopedia, book chapters, book reviews, conference papers,
| Year      | Plant type               | Energy source                     | System configuration, flux, rejection, and product water quality                                                                                   | Capacity (m³/d) | Specific energy consumption (kWh/m³) | Water production cost (US$/m³) | Ref.                           |
|----------|--------------------------|-----------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|-----------------|--------------------------------------|-------------------------------|--------------------------------|
| 2007     | Small scale              | Solar thermal collector           | Air gap membrane distillation, a distillate quality of $< 5 \mu S/cm$, distillate flux (19 L/m² day)                                            | 0.12            | 200-300                              | –                             | Banat et al. (2007)            |
| 2008     | Small scale              | Solar thermal collector           | Air gap membrane distillation The electric conductivities for feed and distillate water were 670 and 3 $\mu S/cm$, respectively, and salt rejection (99.5%) | 0.064           | 647                                  | –                             | Fath et al. (2008)             |
| 2009     | Laboratory scale         | Solar thermal collector           | Vacuum membrane distillation, the conductivity of feed water (230 $\mu S/cm$) and produced water (4 $\mu S/cm$), pure water flux (32.19 kg/m² h) | 4.16            | Overall: 127.54                      | –                             | Wang et al. (2009a, 2009b)     |
| 2015     | Pilot plant              | Solar thermal collector plus photovoltaic | Direct contact membrane distillation. The maximum permeate flux of the plant was 8.87 L/m³ h Without heat recovery (0.079) With heat recovery (0.11) | 0.365           | Overall: 8.75                        | –                             | Bouguecha et al. (2015)        |
| 2018     | Small scale              | Thermal/photovoltaic collectors   | Sweep gas membrane distillation Brackish groundwater (500 mg/L total dissolved solids)                                                                 | 0.24            | –                                    | 85                            | Moore et al. (2018)            |
| 2019     | Prototype                | Solar thermal collector           | Air gap membrane distillation, permeate flux (4-10 L/m² h), A salinity level of 10–200 ppm of water can be produced from a 33,000 ppm feed water (seawater) | 0.004           | 0.018                                | 10                            | Li et al. (2019)               |
| 2019     | Laboratory scale         | Solar thermal collector plus photovoltaic | Direct contact membrane distillation, yield productivity (10.5 L/m². day) Without heat recovery (0.079) With heat recovery (0.11) | 0.365           | –                                    | 8.75                          | Zarzoum et al. (2019)          |
| 2019     | Small scale              | Solar thermal collector           | Direct contact, sweeping gas, and vacuum membrane distillation, feed water salinity of 3.5% or 15% DCMD: 1017–1536 SGM: 719–729 VMD: 650–660 | 10              | DCMD: 10.26–37.99 kg/m² h            | 38.9                          | Soomro et al. (2020)           |
| 2020     | Pilot plant              | Concentrated solar power          | Direct contact membrane distillation (10.26–37.99 kg/m² h) DCMD: 1017–1536 SGM: 719–729 VMD: 650–660 For a tiny scale: 0.017 For a bigger scale: 0.449 | 38.9            | –                                    | 0.314                         | Ma et al. (2020)               |
| 2020     | Small scale              | Solar thermal collector           | Vacuum membrane distillation Small scale (0.18 m²): 0.0037 Big scale (3 m²): 0.096 For a tiny scale: 0.017 For a bigger scale: 0.449 | 0.365           | Overall: 8.75                        | –                             | Soomro et al. (2020)           |
| 2020     | Small scale              | Solar thermal collector plus photovoltaic | Sweep gas membrane distillation configuration with 0.6 m² membrane area, product purity (8–10 $\mu S/cm$) Without heat recovery (0.079) With heat recovery (0.11) | 0.022           | Overall: 8.75                        | –                             | Li & Lu (2020)                |
mini-review, and patents reports) have been published on hybrid membrane system since 2000 until the first quarter of 2020 (retrieved from Web of Science database using the search keyword ‘solar-powered hybrid membrane system’, accessed on 29 April 2020). The number of publications on the hybrid membrane system was limited to three journals, i.e., Journal of Membrane Science, Desalination, and Chemical Engineering Journal. The above-mentioned three journals were the core journals in a hybrid membrane system.

**History and evolution of hybrid membrane systems**

The concept of hybrid membrane processes was first introduced by Rautenbach and Gröschl in 1990 (Rautenbach & Gröschl 1990). Two years later, the first hybrid FO–RO desalination system was patented by Yaeli (1992) to produce purified or potable water from seawater and brackish water. A tri-hybrid RO–MD–nanofiltration system with a total installed capacity of 20,064 m$^3$/day was developed and first performed an exergy and energy analysis of an integrated membrane system for water purification (Criscuoli & Drioli 1999). A hybrid multi-stage flash–RO desalination plant with a total capacity of 454,000 m$^3$/day was designed and built-in Saudi Arabia (Jong et al. 2005; Rovel et al. 2005).

A hybrid desalination system was patented by Al-Mayahi & Sharif (2006) for the production of fresh drinking water from brackish and seawater. Similarly, a hybrid RO–pressure-retarded osmosis pilot plant mega-ton scale was built and operated in Japan (Salto et al. 2012). In the work of Zhang et al. (2015), a solar energy-driven FO–ED hybrid system was developed for the production of potable water from secondary wastewater effluent or brackish water. Recently, the first novel concept of tri-hybrid RO–membrane capacitive deionization–reverse ED was developed and tested for improving the energy efficiency of RO seawater desalination system (Choi et al. 2019).

**Solar-powered hybrid membrane systems**

The hybrid membrane system is a combination of membrane-based and/or non-membrane-based water purification technologies that can be coupled with low-grade waste heat or solar energy systems for economical and energy-efficient desalination and water/wastewater treatments. Zhang et al. (2015) tested an SPED and FO hybrid system for producing high-quality water from secondary wastewater effluent or brackish water and regenerating the draw solution simultaneously. The authors show that the water produced from this system contains a low concentration of total organic carbon, carbonate (ionic carbon), and cations derived from the feedwater; had a low conductivity, and meets potable water standards without needing additional treatments.

Weiner et al. (2015) designed a hybrid SPRO–MED desalination system for treating agricultural drainage water. Based on energy and capital cost, a concentrated solar-powered hybrid RO–MED plant provides significant savings over a concentrated solar-powered standalone MED system. It indicates that the hybrid RO–MED system compares favorably to the standalone MED system. Subramani & Jacangelo (2015) proposed an FO system combined with an MD system for the treatment of high salinity wastewater.

Suwaileh et al. (2019) developed an integrated FO–solar-powered AGMD system for brackish water desalination based on an experimental and theoretical approach. The experimental results showed that for the modified FO, a membrane water recovery of 53.3% was obtained. In a solar-powered AGMD system, a water flux of 5.7 L/m$^2$/h and a rejection of 99.55% were obtained at a feed temperature of 60 °C with an energy consumption of 1.1 kWh. The total energy consumption of a hybrid system was reduced by 67%. It concludes that the total energy consumption of the hybrid FO–AGMD was lower than that for the RO technique for brackish water desalination.

A thorough survey has been executed of peer-reviewed published articles (review articles, research articles, encyclopedia, book chapters, book reviews, conference papers, mini-review, and patent reports) related to the hybrid membrane system over the last two decades. A total of 1,159 peer-reviewed articles have been published on SPHMSs from 2000 until the first quarter of 2020. The presented database has been acquired from the Web of Science database using the search keyword ‘solar-powered hybrid membrane system’, accessed on 29 April 2020. The number of publications on SPHMS was limited to four journals, i.e., Renewable and Sustainable Energy Reviews, Desalination, Energy, and Renewable Energy.
A summary of selected studies carried out on integrating/hybrid membrane-based/non-membrane-based water purification technologies is given in Table 7.

**ECONOMIC EVALUATION OF SOLAR-POWERED MEMBRANE-BASED SEPARATION TECHNOLOGIES**

Techno-economic assessment is necessary to evaluate the economic feasibility of membrane-based separation technologies for desalination (seawater, brackish water, and groundwater), wastewater treatment (municipal and industrial waste), and food processing (concentration of fruits and vegetable juices, pre-concentration of milk and whey, and dealcoholization of alcoholic beverage). Membrane-based separation technologies that can operate using different energy sources including renewable sources like solar energy, geothermal energy, hydroelectric power, and wind energy, and conventional energy sources, including uranium and fossil fuel like coal, crude oil, and natural gas.

Water production costs of solar-powered membrane-based separation technologies were assessed based on their investment (capital) cost and operation cost. Energy is the largest segment of the water production cost of all desalination systems (Saffarini et al. 2012). It is important to note that energy consumption and water production cost estimates are site-specific and vary from membrane-based separation technology to membrane-based separation technology primarily due to differences in system boundaries, site-specific salinity, site-specific economic indexes, and a lifetime of the plant (Karagiannis & Soldatos 2008). Several studies have presented a techno-economic assessment of solar-powered membrane-based separation technologies and reported their energy consumption and water production costs.

Saffarini et al. (2012) presented an economic evaluation of three standalone SPMD systems (VMD, DCMD, and AGMD). Water production costs were calculated for the three configurations: DCMD ($12.7/m^3), AGMD ($18.26/m^3). The results show that DCMD is the most cost-effective configuration, and AGMD is the most expensive configuration.

Alsheghi et al. (2015) designed a cost-effective solar photovoltaic-powered RO desalination plant in Abu Dhabi. The specific energy consumption of produced water was around 6.99 kWh/m^3. They also presented a cost analysis framework and reported a cost of US$0.825/m^3 for 200 m^3/day solar photovoltaic-powered RO desalination plant, which could be compared with other membrane-based separation technologies. Their study indicated that solar photovoltaic-powered RP can be an economically and technically viable option for large-scale desalination plants.

Macedonio et al. (2014) studied the performance of a laboratory-scale DCMD for the desalination of oilfield produced water. They reported a permeate production rate achieved of 0.14 m^3/day and specific energy consumption of produced water around 0.06 kWh/m^3 with a cost of 0.72 US$/m^3 (produced water at 20°C) and 1.28 US$/m^3 (produced water at 50°C). Results suggest that the laboratory-scale DCMD is the least energy-intensive and conclude that water produced from laboratory-scale DCMD is economically competitive with solar-powered membrane-based separation technologies. This study also discovered that the permeate flux and water production costs were highly dependent on feed temperature and concentration.

Guillén-Burrieza et al. (2015) presented a techno-economic assessment of a pilot-scale plant for solar desalination based on the existing plate and frame MD technology with a potential production capacity of 100 m^3/day. The results showed that a water production cost in the range of 12.5–14.12 US$/m^3 for solar-driven MD and 8.98 US$/m^3 for fossil-driven option. Soomro & Kim (2018) also presented performance and cost evaluation of a solar power tower plant integrated with a DCMD system with a potential production capacity of 40.75 m^3/day. The specific energy consumption of produced water was around 0.06 kWh/m^3 with a cost of 0.392 US$/m^3.

A summary of selected studies carried out on membrane-based separation technologies and their specific energy consumption and water production cost is shown in Table 8. This list describes available documented information about the study year, system scale, energy source, system description, daily production, specific energy consumption, and water production cost.

As can be seen in Table 8, the unit cost of water production from saline water by membrane-based desalination technologies is around $0.79/m^3 of permeate for RO (Choi et al. 2016), $1.59 and $2.39/m^3 of permeate for RO...
| Hybrid process                  | Application               | Schematic diagram                                                                 | Description                                                                                                                                                                                                 | References                           |
|--------------------------------|---------------------------|------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------|
| Electrodialysis-forward osmosis | Desalination              | ![Diagram](image1)                                                                  | Developed a solar-powered hybrid system (forward osmosis-electrodialysis) for produced high-quality water and regenerated the concentrated draw solution simultaneously. The capacity of 0.13 m$^3$/day, initial draw solution is 1.0 or 0.5 M, and a final draw concentration of 0.2 M | Zhang et al. (2015)                   |
| Forward osmosis-membrane distillation | Treatment of industrial wastewater | ![Diagram](image2)                                                               | Proposed forward osmosis system combined with a membrane distillation system for the treatment of high-salinity wastewater. Water recovery of up to 80%. rejection (>99.5%) of organic contaminants (TrOCs) | Xie et al. (2013); Subramani & Jacangelo (2015) |
| Reverse osmosis-membrane distillation | Treatment of industrial wastewater | ![Diagram](image3)                                                               | Proposed reverse osmosis system combined with air gap membrane distillation system for wastewater treatment. RO recovery (89%) and MD recovery (80%), giving a total water recover of 98% for the combined system | Martinetti et al. (2009); Subramani & Jacangelo (2015) |
desalination system driven by a photovoltaic and diesel generator, respectively (Wu et al. 2018), $4.34/m^3 of permeate for solar-powered RO (Ghafoor et al. 2020), $0.825/m^3 of permeate for solar photovoltaic-powered RO desalination plant (Alsheghri et al. 2015), $4.15–6.15 for a solar-powered ED-FO hybrid system (Zhang et al. 2015), $5.66/m^3 for photovoltaic ED (Ali et al. 2011), $16.02/m^3 for VMD, $12.7/m^3 for DCMD, $18.26/m^3 for AGMD (Saffarini et al. 2015), $0.72–1.28/m^3 for DCMD (Macedonio et al. 2014), $0.392/m^3 for SPMD (Soomro & Kim 2018), $12.5–14.2 and $8.98/m^3 for MD driven by solar energy and fossil fuel, respectively (Guillén-Burrieza et al. 2015), $0.74/m^3 for MD integrated with waste heat (Tavakkoli et al. 2017), and $0.59–1.16/m^3 for an FO–RO hybrid membrane system (Choi et al. 2016). The large variation in cost estimates across studies is attributable to several factors including plant type (small, medium, large scale), production capacity, system configuration, feed water salinity, and energy sources, so the available studies are hardly comparable.}

**APPLICATION AREAS OF SOLAR-POWERED MEMBRANE-BASED SEPARATION TECHNOLOGIES**

In the past two decades, solar-driven membrane-based separation technologies including RO, FO, ED, MD, and hybrid membrane systems have been increasingly used for a wide range of applications including in a variety of water desalination, food, and pharmaceutical industries, power generation and water treatment industries. The most common applications and uses of SPRO include desalination of seawater, brackish water, and groundwater (Helal et al. 2008; Ghernandi & Messalem 2009; Qiblawey et al. 2011; Salcedo-Díaz et al. 2011; Alsheghri et al. 2015; Kumarsamy et al. 2015; Peñate et al. 2015; Tigrine et al. 2016; Freire-Gormaly & Bilton 2019), and wastewater treatment (Muniaraj & Samuel 2017).

SPFO membrane-based technology is an emerging technology in the field of energy, desalination, and water. Some of its applications include seawater/brackish water desalination (Wang et al. 2014; Khayet et al. 2016; Monjezi et al. 2017; Amjad et al. 2018), ethanol–water separation (Schrier 2012), food processing, power generation, and wastewater
| Year    | Plant type       | Energy source       | System description (flux, rejection, and product water quality)                                                                 | Capacity (m³/d) | Specific energy consumption (kWh/m³) | Water production cost (US$/m³) | Ref.                  |
|---------|------------------|---------------------|-------------------------------------------------------------------------------------------------------------------------------|-----------------|-------------------------------------|------------------------------|-----------------------|
| 2011    | –                | Photovoltaic        | Photovoltaic electrodialysis system for seawater desalination                                                               | –               | –                                   | 5.66                         | Ali et al. (2011)       |
| 2012    | Pilot plant      | Solar energy        | A presented economic evaluation of three standalone solar-powered membrane distillation systems                               | –               | –                                   | $16.02/m³ (VMD), $12.7/m³ (DCMD), $18.26/m³ (AGMD) | Saffarini et al. (2012) |
| 2013    | Small scale      | Photovoltaic        | Solar-powered electrodialysis and forward osmosis hybrid system                                                            | 0.13            | –                                   | 4.15–6.15                    | Zhang et al. (2013)     |
| 2014    | Laboratory scale| Electric energy     | Evaluated the potentiality of direct contact membrane distillation for desalting and reuse of oilfield produced water. Overall salt rejection >99%; total carbon rejection >90%; 70% recovery. | 0.146           | 0.06                                | Produced water at 20 °C = 1.28 Produced water at 50 °C = 0.72 | Macedonio et al. (2014) |
| 2015    | Small scale      | Photovoltaic/grid   | Designed a cost-effective solar photovoltaic-powered reverse osmosis desalination plant                                        | 200             | 6.99                                | 0.825                        | Alsheghri et al. (2015)  |
| 2015    | Pilot scale      | Thermal collector   | Presented techno-economic assessment of a pilot-scale plant for solar desalination based on the existing plate and frame membrane distillation technology and compared the results with fossil-driven option. The specific flux of the unit was 5.1 L/m² h | 100             | 374.8                               | Solar-driven (12.5–14.12) fossil-driven (8.98) | Guillén-Burrieza et al. (2015) |
| 2016    | Mathematical model| Electric grid      | Evaluated the performance and economic feasibility of the reverse osmosis alone, and forward osmosis–reverse osmosis hybrid process and developed also a model to predict the performance of this hybrid system. Feed (seawater): 35,000 mg/L, produced water: 200 mg/L, permeate flux 15 L/m² h | 64,444–208,333  | RO: 2.92 FO–RO: 2.26 | RO: 0.79 FO–RO: 0.59–1.16  | Choi et al. (2016)       |
| 2017    | Plant scale      | Waste heat          | Presented techno-economic assessment of direct contact membrane distillation for treatment of high-salinity shale gas produced water and developed also the model based on a combination of experimentally determined membrane distillation performance. Feed water salinity (100,000 mg/L), recovery factor of 66.7% | 1893            | 1.25                                | MD: 5.70 MD integrated with waste heat: 0.74 | Tavakkoli et al. (2017) |
| 2018    | Pilot plant      | Photovoltaic/diesel | Presented the size optimization of a photovoltaic/diesel/battery/reverse osmosis desalination hybrid energy system          | 10              | 4                                   | Photovoltaic (1.59) diesel (2.39) | Wu et al. (2018)        |
| Year | Location | Energy Source | Key Findings | MD Cost | MVC Cost | Authors |
|------|----------|---------------|--------------|---------|----------|---------|
| 2018 | Lab scale| Electric      | Presented technological design and economic analysis of air gap membrane distillation and vacuum air gap membrane distillation for application in a zero liquid discharge and compared also the cost with mechanical vapor compression. Feed solution (70,000–250,000 ppm), 75% more cost-effective if the MD is driven with free waste heat. | 10 MD (11.5) | 100 MVC (31) | Schwantes et al. (2018) |
| 2018 | Pilot plant| Solar energy | Presented performance and cost evaluation of solar power tower plant integrated with a direct contact membrane distillation system. Permeate flux at a feed temperature 40 °C (7.31 kg/m² h) and 70 °C (37 kg/m² h) | 40.75 MD (11.47) | 0.06 MVC (22.4) | Soomro & Kim (2018) |
| 2020 | Pilot plant| Photovoltaic | Presented techno-economic feasibility of photovoltaic-reverse osmosis desalination system under a tropical environment. The plant obtained 60% permeate productivity and 40% brine | 10.8 MD (5.5–6) | – MVC (7.6) | Ghafoor et al. (2020) |
CONCLUSIONS AND FUTURE PERSPECTIVES

TECHNOLOGIES

Water and energy play an important role in sustainable development and are essential for the socioeconomic development of many countries in the world, particularly in Asia and Africa. Membrane-based technologies play a vital role in both water purification and sustainable energy generation either individually or in combination with other membrane-based techniques. These technologies could be coupled with renewable energy sources, like solar energy (thermal collectors and photovoltaic panels), geothermal energy, hydroelectric power, and wind energy to make the process more economical, easier to control, and viable for industrial applications.

Solar-powered membrane-based water purification technologies are more energy-efficient and generally economical than solar-powered non-membrane-based water purification technologies. Among solar-powered membrane-based water purification technologies, RO is the most widely investigated water purification technology for small, medium, and large-scale water treatment systems and very well suited to be driven by solar energy systems. Solar power integrated with the most notable emerging separation technology such as MD has also seen a powerful revival recently with improved performance. As indicated in Tables 1, 2, 4 and 8, SPRO and SPED have the most favorable economics and lowest energy consumption in membrane-based technologies.

It can be concluded that more theoretical and experimental studies in the field of solar-driven membrane-based water purification technologies are needed to optimize the systems to become more energy-efficient, cost-effective, and environmentally friendly technologies in the future and enhancing the sustainable applications and demonstrating the commercial viability of membrane-based water purification technologies. Further research in the membrane-based separation technology is likely to boost solar-powered water treatment/desalination.

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DATA AVAILABILITY STATEMENT

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

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