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Review

A Review of Membrane-Based Desalination Systems Powered by Renewable Energy Sources

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Abstract: The rising demand for clean water and the environmental challenges associated with fossil fuels have encouraged the application of renewable and greener energy systems in desalination. Moreover, the small footprint and high productivity favored the membrane-based process in the water industry. In the past few decades, noticeable work has been performed on the development and applicability of membrane-based desalination processes powered by renewable energy sources such as solar, wind, tidal, and geothermal. Several integrated membrane desalination processes for producing clean water with sustainable and clean energy are introduced. This review details the source and performance efficiencies of existing renewable energy technologies and their application in membrane-based desalination processes, with a special focus on current advancements and challenges. This study reviews the interconnections between water, energy, and the environment and explores future energy-efficient desalination options for energy savings and environmental protection.

Keywords: renewable energy; membrane desalination; solar; photovoltaic; artificial intelligence

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Citation: Shahid, M.K.; Mainali, B.; Rout, P.R.; Lim, J.W.; Aslam, M.; Al-Rawajfeh, A.E.; Choi, Y. A Review of Membrane-Based Desalination Systems Powered by Renewable Energy Sources. *Water* **2023**, *15*, 534. https://doi.org/10.3390/w15030534

Academic Editor: Alexandre T. Paulino

Received: 2 January 2023
Revised: 20 January 2023
Accepted: 27 January 2023
Published: 29 January 2023

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1. Introduction

Water is the basis of life, and its availability and quality have always been major questions [1–3]. The water demand has increased rapidly due to development and industrialization [4]. On the other hand, a significant rise in wastewater discharge and depletion of fresh water sources pose major challenges [5,6]. Though most of the Earth is covered with water, the freshwater share is much lower, coming from groundwater, lakes, and rivers [7,8]. Freshwater makes up only 2.5% of all the water on Earth, with 68.7% of it in the form of ice and permanent snow cover, primarily in Antarctica and Greenland, 30.1% of freshwater is in the form of groundwater, and only 0.3% is in the form of surface water, such as lakes, rivers, and reservoirs [9,10]. It is worth noting that while the overall amount of freshwater on Earth may seem small, it is an incredibly important resource for life on our planet; however, it is not evenly distributed and many regions are facing water scarcity. Many developing countries have less access to freshwater resources, which can limit their economic and social development. The higher level of salinity in brackish water and seawater makes them unsuitable for domestic use, especially for drinking purposes [11,12]. Seawater has an average salinity of 35 ppt and brackish water has a salinity level between 0.5 and 30 ppt, varying depending on location [12,13].

Desalination is a widely applied technology that is used to remove the salinity from brackish water, seawater, or wastewater to make it usable for domestic and industrial use [14,15]. Desalination technologies are mainly categorized as conventional and advanced technologies, commonly known as thermal desalination and membrane-based desalination, respectively [16,17]. The thermal desalination process includes different methods such as multi-effect distillation (MED) [18], multistage flash distillation (MSF) [19], and vapor compression distillation (VCD) [20]. Similarly, the membrane-based desalination process includes methods such as electrodialysis/electrodialysis reversal (ED/EDR) [21], and reverse osmosis (RO) [22]. The integration of conventional and modern desalination technologies also created space for hybrid desalination technologies such as membrane distillation (MD), MED-RO, and MSF-RO [23]. The thermal desalination process involves using heat energy for the vaporization of permeate water. In contrast, the MD process utilizes high pressure from motor pumps for the separation of effluent from high-strength saline. Therefore, the MD process depends on electrical power, while both electrical and thermal energies are required for thermal desalination processes.

Water desalination requires an estimated 3.7 kWh/m^3 of energy for RO processes, 68 kWh/m^3 for multistage flash evaporation, and 650 kWh/m^3 for single-stage seawater evaporation [24]. According to an estimate, the desalination sector utilizes about 75.2 TWh of energy per year, which is around 0.4% of global energy consumption [16]. The recent advancements in membrane-based technologies highlight the potential of these processes to replace thermal processes in the desalination industry. Besides energy conservation, membrane-based processes also come with many other benefits, such as small footprints and high yields.

Renewable energy refers to energy sources that are replenished naturally and can be used indefinitely [25]. Conventional energy sources, such as fossil fuels are non-renewable and emit pollutants that contribute to air and water pollution and climate change [26,27]. Renewable energy has several benefits compared with conventional systems. For instance, it is sustainable and does not deplete natural resources; generates electricity with zero or very low greenhouse gas emissions; can reduce dependence on fossil fuels; can help stabilize energy prices; and can create jobs and economic opportunities in the growing clean energy industry [25,28]. Renewable energy can be used in several ways to power membrane-based desalination systems. Renewable energy sources such as solar and wind can be used to directly generate electricity to power the pumps and other equipment used in desalination systems [29]. Using renewable energy to power membrane-based desalination systems can help reduce the carbon footprint of these systems and make them more sustainable [30]. It can also help reduce the cost of desalination in the long run and decrease dependence on fossil fuels [31].

This review focuses on the current advancements, limitations, and future perspectives on the application of renewable energy in membrane-based desalination processes. The study is of great practical significance as it presents an in-depth analysis of the feasibility of a less deliberate, membrane-based desalination process operated by renewable energy sources.

2. Renewable Energies and Desalination

A variety of renewable energy sources are known and are being used in various parts of the world [27,32]. Solar, wind, geothermal, and tidal energy are the principal conventional sources of renewable energy for desalination processes [33–35]. It is noteworthy that the major contribution of renewable energy comes from wind and solar energy, and to a lesser extent, geothermal energy. Another emission-free energy source is nuclear energy, but because of safety concerns and waste disposal challenges it has not been broadly applied in desalination. In this section, an overview of different types of renewable energy is included.

2.1. Solar Energy

Solar energy is a widely available source of renewable energy throughout the world. It has been extensively studied in regions such as North America and the Middle East, as these areas often have limited freshwater resources and rely heavily on seawater and brackish water. Therefore, these regions are the perfect choice for using solar energy for desalination. Solar energy can be applied directly to heat highly saline water for desalination, or it can be converted into electrical energy for use in desalination processes. The direct application of solar energy in desalination includes methods such as solar chimneys [36], humidification–dehumidification process [37], and solar stills [38]. On the other hand, photoelectric technology is used to convert solar energy into electric power [39]. A recent study also reported a photovoltaic–membrane distillation process that can be used for both producing clean water and generating electric power [40]. The main merit of using solar energy in membrane desalination is that it is a renewable and sustainable source of energy, which reduces the dependence on fossil fuels and the associated environmental impacts. Additionally, solar energy is widely available and can be easily integrated into desalination systems, particularly in coastal and arid regions where sunlight is abundant. The main limitation of using solar energy in membrane-based desalination is that the process can be less efficient than traditional processes, particularly on cloudy or overcast days [41]. Additionally, the cost of solar-powered desalination systems can be high, particularly for larger-scale systems.

2.2. Wind Energy

Wind energy is a significant source of renewable energy in many regions worldwide. Desalination processes powered by wind energy are widely available in hilly areas, coastal regions, and islands. Wind resources are found in nearly every part of the world, and as a result the wind energy sector has seen significant growth in the past two decades. Wind turbines are widely used in several countries, and the power generated by these systems can be used mechanically or electrically in desalination units. The development and upgradation of existing wind power stations are limited by various factors such as visual effect, public acceptance, noise, land requirements, telecom interference, and potential effects on wildlife and natural habitat [42,43]. The air pollution caused by wind turbines is widely studied by researchers and is categorized as aerodynamic and mechanical noise. When the wind moves through the turbine blades, aerodynamic noise is generated. It increases in direct proportion to the rotor's speed and is affected by several other attributes, such as the direction and speed of the wind and atmospheric turbulence, which can produce a "whooshing" sound [44]. This type of noise can be decreased by altering the design of the turbine blades. Mechanical noise is generated by the moving components of the turbine, such as the bearings, generator, and gearbox. This type of wind turbine noise can be reduced by insulating the nacelle, applying vibration suppression, and using sound-absorbing materials [45]. Wind energy can be harnessed in coastal and offshore areas where wind speeds are high, making it well-suited for desalination systems located in these regions. The main limitation of applying wind energy in membrane-based desalination is that the system efficiency can be reduced in areas with low wind speeds. Another limitation is that wind energy is not constant and can be affected by weather conditions, which can cause fluctuations in the energy supply for the desalination process.

2.3. Wave Energy

Wave energy, also known as wave power, is a type of renewable energy that is captured from the wave motion in the sea and oceans. Several techniques or wave energy devices are known to capture the energy generated by the waves of the ocean. The estimated net theoretical ocean power potential is 29.5 PWh/yr [46]. If there are adequate waves along the coast, it is possible to directly apply wave power to pressurize seawater to yield fresh water. According to this concept, a number of desalination plants have been constructed, where the converter absorbs wave energy and then transfers it directly to the RO setups [47]. The transformation of wave energy is more efficient than the transformation of other kinds of renewable energy. Although wave energy is seldom used in comparison with wind and solar energies, the theoretical conversion efficiency for solar energy, for instance, does not cross 87% and is based on best arrangements. One limitation of using wave energy for membrane-based desalination is that it can be less reliable and consistent compared with other forms of renewable energy, such as solar or wind. The amount of energy that can be generated from waves can vary depending on weather conditions and the location of the system. Additionally, wave energy systems can be costly to install and maintain, and the technology is in the early stages of development.

2.4. Geothermal Energy

Geothermal energy is another renewable energy that is stored in the form of heat under the surface of the Earth. It is recognized as a high-potential energy source that can provide power and heat while emitting minimal greenhouse gases. The nature of geothermal resources varies by region, depending on factors such as basic rock composition, the efficacy of geothermal wells, the temperature of geothermal fluid, and the availability of geothermal fluid [48]. It is a sound approach for the production of heated water from underground reservoirs. The temperature of geothermal sources ranges from 70 to 80 °C, which makes them appropriate for low-temperature MED processes [49]. One limitation of applying geothermal energy for membrane-based desalination is that it is only available in certain geographic locations where there is suitable geothermal activity. Moreover, there may be environmental impacts associated with extracting geothermal fluids [50].

2.5. Nuclear Energy

Since the last 30 years, a significant rise has been observed in the production of electricity from nuclear energy, ranging from 14% of the net electricity production in 2009 to almost 19% in 2016 [51]. According to recent publications, the capacity of global nuclear power will increase to 511 GW(e) in 2030 from a capacity of about 370 GW(e) in 2009 [51]. Nuclear energy is mainly produced by the nuclear fission process. This process produces heat to generate steam that is used to power turbine generators for electricity production. It is also considered free of greenhouse gas emissions because it does not involve the burning of fossil fuels. However, this technology is conditioned by operational safety challenges and the appropriate disposal of radioactive waste. The utilization of nuclear energy in desalination processes introduced the term "nuclear desalination". Nuclear desalination is defined as the use of nuclear power plants' heat and electricity to remove minerals and salts from brackish water and seawater. A range of membrane-based desalination processes has been observed to be efficaciously integrated with various kinds of nuclear power plants to generate electricity and water at different levels [51].

2.6. Blue Energy

Blue energy, also known as salinity gradient energy, is also an emerging sustainable and renewable energy that originates from the salinity difference between seawater and freshwater. Where the river meets the sea, an irreversible and spontaneous mixing of seawater and freshwater happens, thus enhancing the entropy of a system. This change in entropy can be employed to convert a portion of the fluid's thermal energy into electrical energy [52]. The total global energy extraction potential from this resource is estimated at about 2.4–2.6 TW, close to the global utilization of electricity [53]. Pressure-retarded osmosis [54] and reverse electrodialysis [55] are two widely known membrane-based technologies for harvesting blue energy.

3. Membrane-Based Desalination Processes Coupled with Renewable Energy

Membrane-based desalination processes utilize a driving force and semipermeable membranes to separate minerals and salts from water. The driving force in these processes can be differential temperature, differential osmotic pressure, or differential voltage. Some studies categorize NF as a loose RO membrane that permits selective ions to cross; however, many consider NF a separate group. Generally, membranes are composed of synthetic or natural polymers [56]. The RO process relies heavily on applied hydrostatic pressure for water permeation through a semipermeable membrane. Owing to their selective permeation characteristics, RO membranes express higher rejection efficiencies for ions and solute particles other than water molecules [57]. RO-based desalination processes offer several benefits over thermal desalination processes. For instance, RO can be operated using ten times less energy than thermal desalination. Moreover, the small footprints, non-corrosive equipment, and comparatively safer process also favor large-scale applications of RO technology, thereby increasing the global share of RO in the desalination market. Currently, most of the thermal desalination plants are installed in regions rich in petroleum resources, such as the Middle East. Despite all the developments in the RO field, its energy demand is higher than the theoretical specific energy demand for desalination operations. Likewise, RO processes utilize high-grade energy generally obtained from carbon fuels. RO desalination of seawater released 4.05 g/m^3 and 1.78 kg/m^3 of NO_x and CO_2 emissions, respectively, when conventional fossil fuels were consumed [58]. In order to minimize the carbon footprint of desalination plants, RO can be a major point of focus.

3.1. RO-Based Desalination Systems Driven by Renewable Energy Sources

In the last few years, many studies have reported RO operations integrated with renewable energy sources. Several desalination RO plants coupled with renewable solar energy were installed in different regions of the world. Photovoltaic (PV) and solar thermal power technologies are the widely adopted methods to operate RO desalination units. A simple schematic of the RO desalination unit combined with PV technology is presented in Figure 1. A portion of the feed water flows through the PVT array to gain thermal energy and lower the array's PV cell temperature since the feed water source is sufficiently large to provide a consistent mass flow to the system. For sun tracking, the PVT array inclines. The feed water skips the PVT array at night or when the ambient temperature is too low to prevent heat loss to the atmosphere. To optimize the use of the received thermal energy, a set-volume thermal storage reservoir is used. Auxiliary heating is accessible if the temperature of the storage reservoir falls below a minimum threshold temperature. The RO receives a constant flow of the heated water that is kept in the tank, and due to the higher temperature and low viscosity of the heated water, the system's multiple pumps consume less electricity. The PVT array on the electrical side of the system supplies as much electrical power as necessary for pumping needs. The surplus electrical power produced throughout the day is retained in a battery and later utilized at night. The remaining electrical requirements, particularly in the early morning hours after the battery has been depleted, are satisfied by grid electricity [59].

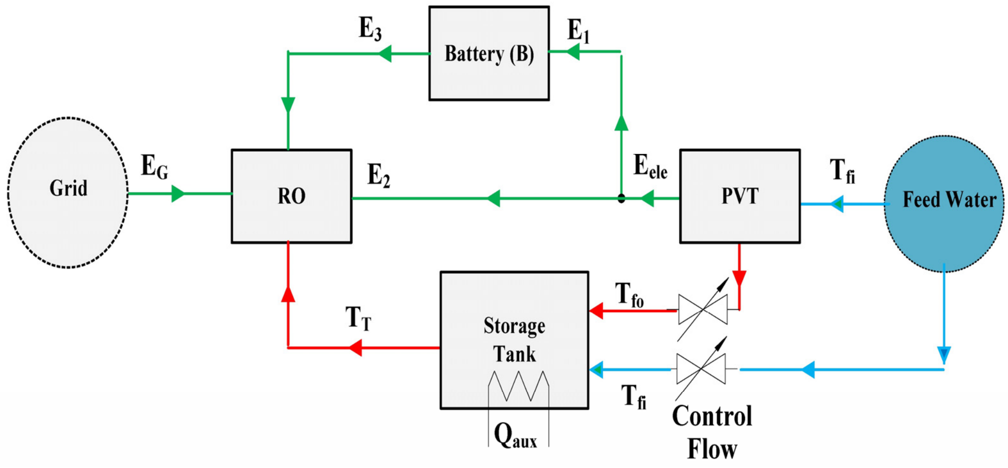

Figure 1. A scheme of PV thermal and RO-based operational setup for water desalination unit (T and E correspond to thermal and electrical energy, respectively) [59]. Image reused under the Creative Commons Attribution License.

A study introduced a low-capacity PV-driven RO desalination system with a 0.8–3 m^3/day production capacity for drinking water [60]. A PV system (4.8 kWp) with an additional 60 kWh of battery storage is connected to the plant. The specific energy consumption is found at 15 kWh/m^3 at 63 bar feed pressure. The plant was found effective for maintaining TDS values under 500 ppm, as recommended by the World Health Organization (WHO). Besides the successful operation, the cost associated with battery storage appears to be a major concern. Another study compared the operational and economic efficiency of battery-less PV-driven RO systems with battery-based units [61]. The battery-less system is coupled with an energy recovery device. The water production cost was found relatively less for battery-less systems. About 7.8 EUR/m^3 cost was estimated for the production of 0.35 m^3/d water with 4.6 kWh/m^3 specific energy consumption. Another study compared the efficiency of a PV-driven RO system with an organic solar Rankine RO system [62]. The heat generated in the solar collectors' field is converted to mechanical power by an organic Rankine cycle process. The shaft power obtained operates the high-pressure RO pumps, starting the desalination. The operational unit is constituted by a RO system with 0.3 m^3/h capacity, a 90 m^2 of vacuum tube solar collectors, and a 100 kW Rankine engine. The energy recovery unit of the RO system includes a couple of axial piston pumps, one of which functions reversely (as a turbine), using the hydraulic power of the brine fluid. The PV-RO and RO-solar Rankine units operated at a cost of 7.77 EUR/m^3 and 12.53 EUR/m^3, respectively.

Recently, a study reported the hybrid grid-coupled RO desalination unit containing PV, an energy storage system, and a pressure retarded osmosis (PRO) system [63]. An intelligent energy management system (IEMS) is designed for this integrated process. The objectives of IEMS were to enhance water production and percentage rejection and reduce the central grid energy simultaneously. The authors used three different algorithms for the process optimization, i.e., the grey wolf optimizer (GWO), the genetic algorithm (GA), and the particle swarm optimization (PSO) algorithm. Based on the results, it was observed that PSO outperforms these algorithms. The authors evaluated four different performance indices (PI), including PI_1 (total energy obtained from the main grid to produce 1 m^3 of water), PI_2 (energy efficiency for the RO-PRO unit), PI_3 (in-process battery consumption), and PI_4 (net solute rejection). In all cases, the simulation outcomes exhibited a substantial decrease in the PI_1 value when the IEMS was used. The authors reported a higher efficiency for the PSO algorithm compared with GWO and GA and recommended this algorithm for resolving the optimization issues of an integrated PV-RO-PRO unit.

Carta et al. applied wind power for a seawater RO desalination unit at variable energy consumption [64]. The authors suggested that the proposed operational methodology can be used in large-scale seawater RO desalination units. In their recent study, Carta et al.

employed a wind power-based RO process to meet the 1825 × 10^3 m^3 annual demand of freshwater, equivalent to the 5000 m^3/d water production capacity of a desalination plant [65]. Figure 2 shows the outline and images of the process steps. The power generation subsystem can be observed on the left side of Figure 2. The wind farm consists of one or more wind turbines. The electrical generation subsystem also includes the flywheel energy subsystem (FES) and an uninterrupted power system (UPS). The load's subsystem includes a desalination unit, which is composed of multiple single-stage SWRO module loads that are equipped with energy recovery devices (ERDs). Each module has the capability to produce freshwater at constant feed pressure and flow conditions. The transformer is used to protect against homopolar faults on the secondary side. In the event that one phase goes to Earth, the current passes through the neutral and protective measures are activated, causing the loads to shut off while the generation remains active. The operational efficiency and economics of a wind-powered RO process are subject to multiple factors. For instance, the application of a wind energy converter (WEC) for power distribution to the RO units can be more economically realistic in scenarios with promising yearly production rates or sites with appropriate wind speeds [66]. It is estimated that the unit price can significantly reduce to 20% at over 5 m/s regional wind mean velocities [66]. A study compared the several configurations of wind-powered RO desalination units with the same wind turbines and found that water production costs can be decreased by modifying their design and configuration [67].

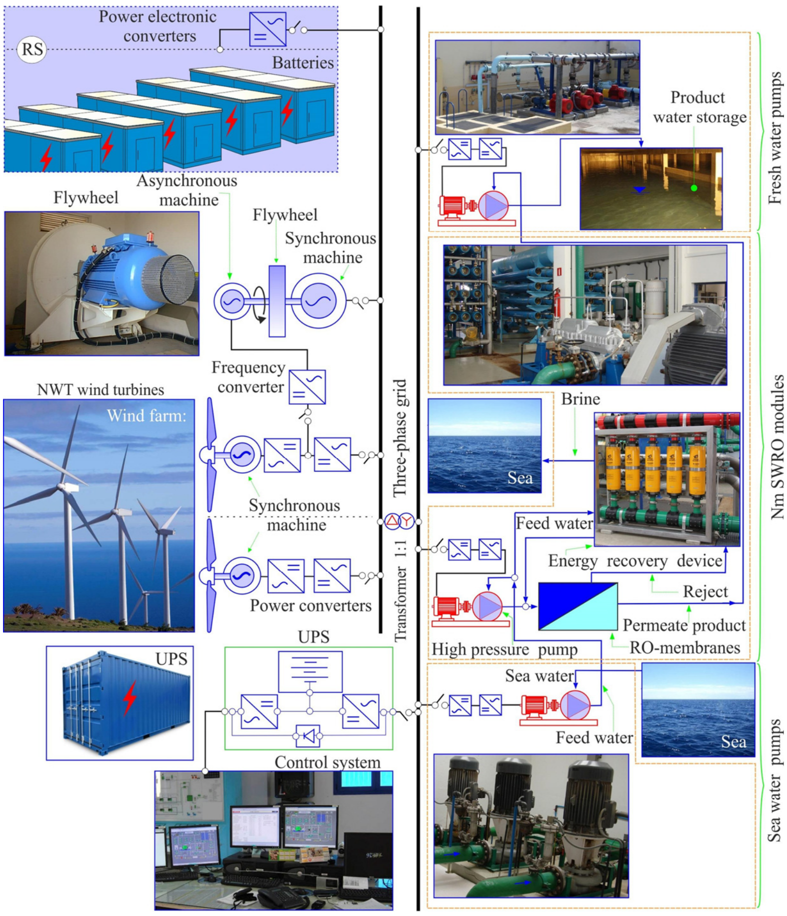

Figure 2. Illustration of the wind-powered seawater RO plant [65]. Image reused under the Creative Commons license.

3.2. MD-Based Desalination Systems Driven by Renewable Energy Sources

Several factors influence the RO desalination process in different ways. For instance, a higher amount of energy is required to maintain the high-pressure difference across the membranes [68], brine management associated with the rejected stream of the RO process [69], and the potential for fouling growth [70], especially biofouling on the RO membrane [71]. In this scenario, MD emerges as a feasible option due to its best performance under highly saline conditions. The MD process works based on temperature differences that can be easily obtained from solar collectors. Besides cleaning, solar collectors require no regular maintenance or repair due to their simple design and configuration. Wetting and fouling are two major limitations of MD processes [72]. Several studies have reported on the modification of MD membranes to improve their antifouling and anti-wetting properties [73,74].

Several types of configurations are known for MD processes, such as air gap MD (AGMD), direct contact MD (DCMD), sweeping gas MD (SGMD), liquid gap MD (LGMD), multi-effect MD (MEMD), material gap MD (MGMD), and vacuum MD (VMD) [75]. Each process has its advantages and limitations. For instance, the DCMD process involves the direct interaction of hot feed solution with the surfaces of hydrophobic membranes, while cold permeate solution interacts with the back side of the membrane. Consequently, evaporation occurs at the feed side of the membrane. Owing to the continuous interaction between the membrane, hot feed, and permeate cold side, DCMD exhibits a relatively higher loss in conductive heat, contrary to the other MD configurations [75]. The AGMD has a stagnant air space, known as an "air gap", between the membrane and distillate side. This air gap results in a higher temperature difference and reduces the loss of heat conduction. The vacuum pump in VMD creates suction on the cold permeate side. The hot solution composed of volatile molecules carries a higher saturation pressure than that of the applied vacuum pressure, aiming to contribute a driving force.

Several studies have reported on the performance of solar-driven MD processes. A study, for example, reported the DCMD process supported by flat-plate solar collectors [76]. The unit consisted of four key loops. The first loop was the solar power-collecting loop, to fulfill the plant's thermal energy need. This loop was composed of eight flat plate collectors with a 20 m^2 effective area. The solar collector loop and DCMD loop were linked through the 16 kW heat exchanger, located in a 300 L heat storage tank. This reserves the excess thermal energy generated from the collectors for the period of peak solar radiation intensity. The second loop was the solar power PV loop, which offered the desired electric power for the operational unit. It was composed of eight PV panels (1.48 kW_{peak} peak output), two electric batteries (24 volts, 100 Ah), and a DC/AC inverter. The third loop (desalination loop) was composed of three hollow fiber membranes having a total area of 3.39 m^2. The fourth loop was a controlled thermal sink (500 L capacity) used for the circulation of cooling water across the DCMD modules. Two heat exchangers are configured within the operational unit. The performance efficiency of DCMD was assessed with and without the heat recovery device under different operational conditions. The membrane permeability coefficient was assessed to be 3.27×10^{-7} L/m^2 s Pa. For arrangements with and without a heat recovery device, the distillate per module was 4.59 L/h and 3.31 L/h, respectively. The solar thermal energy coefficient was 31.3% higher when a heat recovery device was employed [76]. In a nutshell, this study obtained promising results through the integration of a solar power-driven DCMD pilot plant.

A recent study examined the performance and economics of solar-driven MD systems employing DCMD, AGMD, and VMD [77]. This study used Aspen Custom Molder® for dynamic and steady-state simulation of the solar-driven MD plants. The AGMD, DCMD, and VMD systems indicated a desire for the largest MD module, the largest heat exchanger, and the largest solar collector, respectively. The unit production costs of the optimum solar-based VMD, DCMD, and AGMD processes for desalination were estimated at USD 10.41/m^3, USD 5.38/m^3, and USD 2.71/m^3, respectively. Both the total annual costs and unit production costs of the solar-based AGMD unit were the lowest. The authors discovered no significant effect of membrane unit cost on water production costs or optimal system design. The unit production cost of solar-driven AGMD was decreased from

USD 2.71/m^2 to USD 2.04/m^2 by lowering the membrane unit cost from USD 90/m^2 to USD 36/m^2.

Another study on solar-driven DCMD reported a levelized water cost of USD 3.01/m^3 [78]. The levelized water cost is estimated based on capital and operational costs. The capital cost is determined based on direct (MD system, associated equipment, building, installation, and land acquisition) and indirect (administration and legal fees, insurance, labor, and contingencies) capital costs. The operational cost is assessed based on maintenance, membrane replacement, brine management, power consumption, and labor costs. The system description is presented in Figure 3a. The system includes a tank, a solar thermal collector, and a heat exchanger. Sunlight is converted to heat by the collector, which is absorbed by a fluid. The hot fluid then flows into the heat exchanger, where it transfers heat to a cold fluid (seawater) and increases its temperature. The heated seawater is stored in the tank and directed into the DCMD system, which includes channels for the feed (hot seawater) and permeate-side (freshwater) and a membrane that separates the fluids while allowing water vapor to pass through. The pressure difference created by the temperature difference across the membrane causes permeation and the water vapor that passes through the membrane (permeate flux) condenses on the permeate-side channel as it comes into contact with the cool fresh water. The change in temperature between the two fluids on either side of the membrane creates a pressure difference that leads to permeation, as shown in Figure 3b.

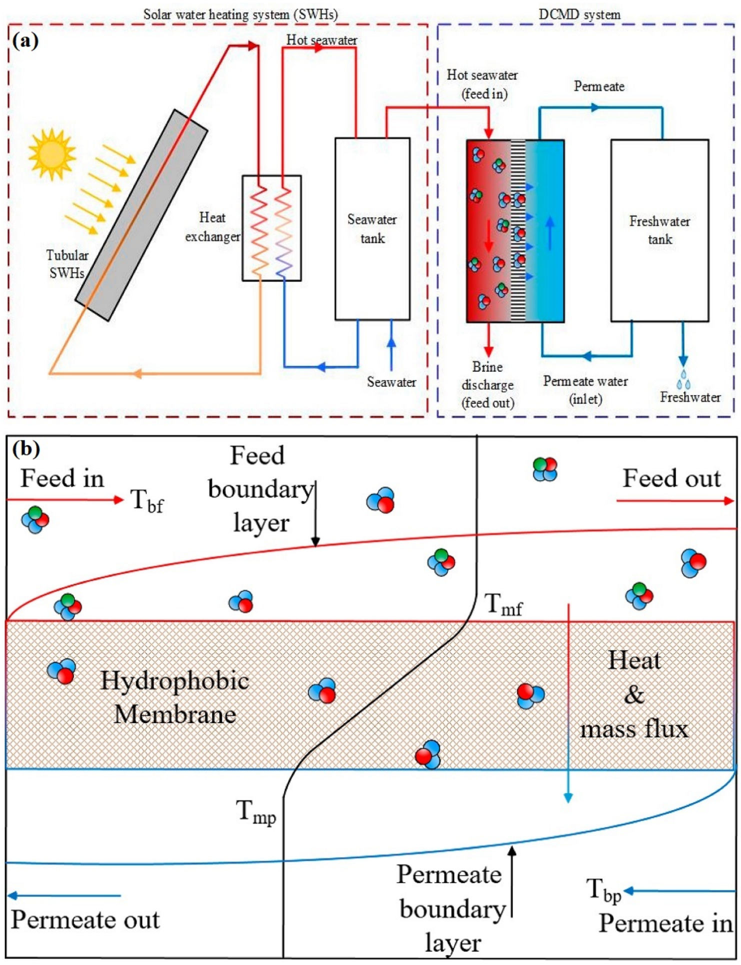

Figure 3. Operational scheme of solar power-driven DCMD system (**a**) and the representation of pressure gradient phenomena responsible for permeation (**b**) [78]. T_{bf}, T_{bp}, T_{mf}, and T_{mp} correspond to the temperature of bulk feed, bulk permeate, membrane feed, and membrane permeate, respectively. Image reused under the Creative Commons license.

Some studies have also reported the operation of MD plants using geothermal energy [79,80]. Figure 4 depicts a simple illustration of how geothermal resources can be used to generate both heat and electricity. The operational scheme is divided into three stages, where stage 1 represents the application of geothermal steam to produce electricity. In the next cycle (2), they can be utilized (after condensation) to produce electricity in the Kalina Cycle or the Organic Rankine Cycle, as the steam and water were separated in stage 1. Cycle 3 consumes the accumulated energy in geothermal waters (after electricity production) to produce heat. In such a synergetic process, it is likely to provide water desalination systems, which need both heat and electricity.

A recent study investigated the geothermal energy-driven hybrid desalination system for the production of freshwater and electricity and obtained 28.86% exergy efficiency from the system [81]. Another study used a cross-flow VMD module to investigate the use of geothermal power in water desalination [82]. The authors reported a 59% reduction in specific water costs when VMD operation is supported by geothermal energy. The membrane cost was discovered to have a significant impact on specific water costs. For example, a 40% reduction in membrane cost resulted in a 30% reduction in specific water costs. Another study examined the performance of the AGMD unit driven by the waste heat of a geothermal energy plant [83]. The outcomes of this study signified the potential of an AGMD process for geothermal water treatment, particularly with the consumption of waste heat from geothermal power plants and thereby decreasing operational costs. Geothermal energy can offer a reliable and suitable heat supply for MD, but the MD recovery ratio may not attain a high value utilizing only the sensible heat of geothermal wells. Further research is needed to determine the feasibility of combining other power technologies with MD and geothermal energy in order to increase the recovery fraction.

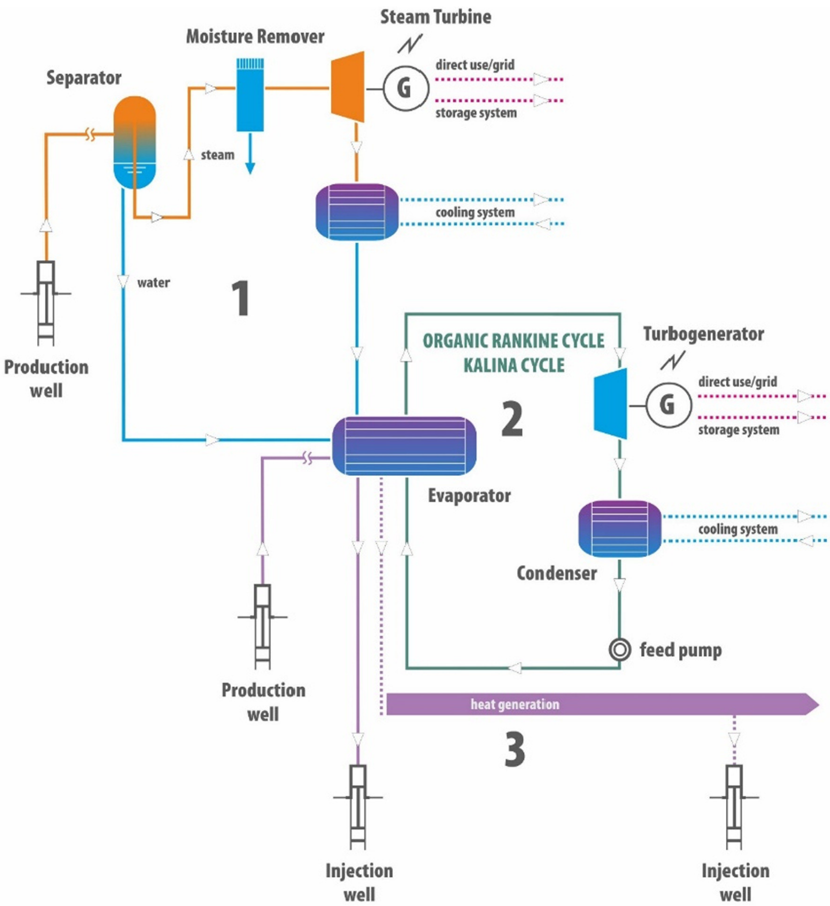

Figure 4. A simple illustration of using geothermal resources for the production of electricity and heat for MD processes [84]. Image reused under the Creative Commons license.

3.3. ED-Based Desalination Systems Driven by Renewable Energy Sources

ED systems have been used for the treatment of brackish and seawater [85,86]. The operation of ED is based on the transfer of cations and anions across cation exchange (CEM) and anion exchange (AEM) membranes, respectively, due to the difference in electrical potential. The electric field works as a driving force for the transfer of the species and can reduce or promote transfer, recovery, and removal. A general scheme of the PV solar-driven ED system and ED stack is presented in Figure 5a,b, respectively.

Several studies have reported on PV-powered ED processes. A study examined a small-scale ED unit with 24 cell pairs arranged in two electrical and four hydraulic stages [87]. The stack was operated by solar power converted into DC via PV with a 12 V nominal voltage and 33 W peak power. The permeate quality was considerably improved at a low permeate flowrate (150 gal./d), with 99% salt rejection for the saline solutions. Another study reported the PV solar-driven ED system for the treatment of brackish water [88]. This study explained the theoretical relationship between the PV generator and the ED system throughout the process. When 8 PV panels are used, the production capacity was approximately 0.29 m^3/h in 0.35 h. However, the desalination time is increased to 0.45 h and the water production capacity is decreased to 0.22 m^3/h when 4 PV panels were used. The presented system is proposed for small-scale applications in remote sites lacking an electric grid, with a daily water treatment capacity of 1–10 m^3. This study provides the basis for further investigation into the optimization and design of such systems, which depend on variables such as the arrangement of the photovoltaic generator and the number of panels, as well as the location and operating conditions.

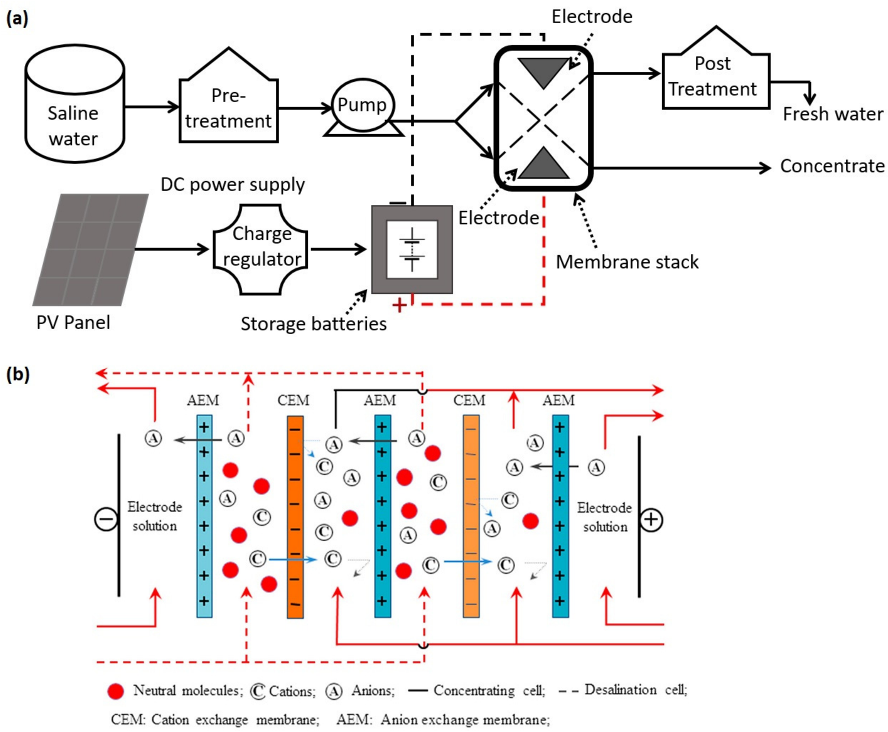

Figure 5. A schematic of a PV solar-driven ED system (**a**) and an electrodialysis stack (**b**). Sub-figure (**b**) is adopted from [89] and reused under the Creative Commons license.

A study reported the sustainability of PV energy-driven ED for brackish water desalination [90]. The application of a PV-powered ED system resulted in a substantial reduction in greenhouse gas emissions (0.02–0.03 kg CO_2/m^3). The ED system exhibited lower specific energy consumption values (0.49–0.91 kWh/m^3) than RO (1.5–2.5 kWh/m^3) for brackish water in its low range of salinity (i.e., <TDS 5000 mg/L^{-1}). Hence, PV-powered ED seemed a more sustainable alternative compared with a PV-powered RO system.

A study reported USD 3/m^3 water production cost for a 50 m^3/d capacity of a PV-driven ED plant [91]. The largest PV-driven ED plant is situated in Fukue, Japan, and has a 200 m^3/d average production capacity. The plant contains a 65 kWp PV unit with 1.2 Ah of storage capacity. The production capacity reached was 130–370 m^3/d utilizing kWh/m^3 of energy [91]. Another study reported a small-scale PV-driven ED system to meet the 6–15 m^3/day capacity for a village with a median population of about 2000–4999 people (3 L per capita per day) [92]. The results of this study justified the PV-ED system as an energy-efficient and cost-effective means of desalination. A cost comparison of different systems is presented in Table 1.

Table 1. Comparison of water production cost in membrane-based desalination processes powered by different renewable energies [16,93,94].

Desalination System	Capacity (m^3/d)	Water Cost (USD/m^3)
Wind-powered BWRO	50–2000	6.6–9
PV-powered SWRO	<100	11.7–15.6
PV-powered SWRO	250	3–4
Wind-powered RO	50–2000	2.0–5.2
Wave energy-powered RO	1000–3000	0.7–1.2
Solar-powered MD	0.15–10	10.4–19.5
PV-powered ED	<100	10.4–11.7

Veza et al. designed a wind-powered ED system for the desalination of brackish water [95]. The system was operated with a 3–8.5 m^3/h product flow rate and 4–19 kW energy consumption, whereas the conductivity of product water was 200–500 µS/cm. ED exhibited better flexibility, adapting easily to variable wind energy, even in cases of a sudden rise or drop. The standard design of the control unit is somewhat modified to manage sudden variations. The performance efficiencies of real operations and software-based prediction were found to be consistent.

3.4. FO-Based Desalination Systems Driven by Renewable Energy Sources

Forward osmosis (FO), another desalination technology, involves the movement of water molecules through the semipermeable membrane from a saline feed solution towards a highly concentrated draw solution. The natural osmotic pressure between the saline feed and draw solutions works as a driving force for FO. Aside from all other factors influencing FO operation, draw solutions play a key role in providing the desired driving force for FO desalination. It is a spontaneous phenomenon with no desire for external energy, for instance, hydraulic pressure in other membrane-based operations [96]. Thereby, lower energy needs, minimal fouling potential, and lower capital and operational costs are expected. The power consumption of FO energy can be as low as 0.25 kWh/m^3 for pumping a fluid [97]. Nonetheless, where draw solution recovery and regeneration are needed (for instance seawater desalination), the energetic efficiency of FO as an apparent energy-proficient desalination system is immensely questioned. The major reason is that the draw solution regeneration stage involves more than one operation, usually with some associated effects of increased power utilization compared with a standalone FO process. Figure 6 presents a schematic illustration of the FO desalination process. Rarely are studies reported on the integration of renewable energy sources and FO systems.

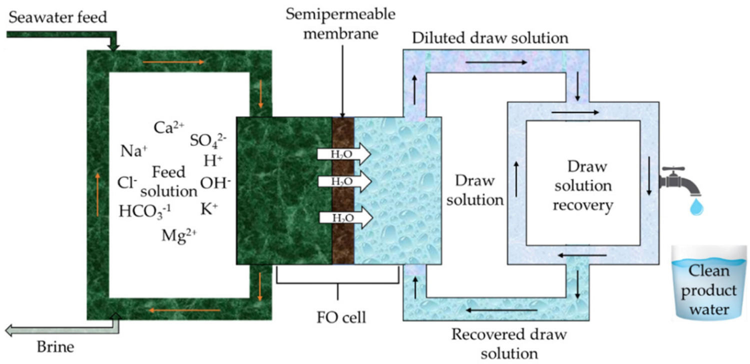

Figure 6. A schematic of the FO desalination process [98]. Image reused under the Creative Commons license.

Smart materials are known to adopt reversible changes in water absorption and dehydration owing to changes in neighboring stimuli (e.g., heat, pressure, and sunlight). Several stimuli-response hydrogels have been introduced as draw solutions for FO processes. An illustration of such a process is depicted in Figure 7. This new kind of hydrogel-driven FO system utilizing solar power for the draw solution regeneration has been gaining much attention. Particularly on exposure to sunlight, thermos-responsive or light hydrogels can discharge fresh water due to the shrinkage in their structures. For example, these hydrogels can absorb sufficient water at the maximum volume phase transition temperature and dewater at higher temperatures of volume phase transition [99,100].

Another study examined the incorporation of light-absorbing carbon materials into polymer hydrogels for FO desalination [101]. This resulted in improved heating and dewatering of the composites. These modifications also resulted in higher swelling rates of composite polymer hydrogels, and consequently, a higher water flux was obtained for the FO process. Likewise, with an increase in a load of light-absorbing carbon particles, water recovery is significantly improved.

A recent study reported a pilot-scale study on the optimization of solar thermal and PV-powered FO processes [102]. After fabrication, a commercial spiral-wound membrane module with a 0.35 m^2 effective area was employed. The maximum differential pressure and the maximum pressure of the draw solution were suggested to be <50 kPa and 70 kPa, respectively. The temperature of the feed water and permeate was maintained by employing a solar thermal collector. The circulation pumps for feed water and permeate were operated using PV-powered batteries. This study suggested the regeneration of draw solution using a solar-driven RO system. The energy consumption for the FO system is about 14.1% of the net energy required for the hybrid FO/RO process.

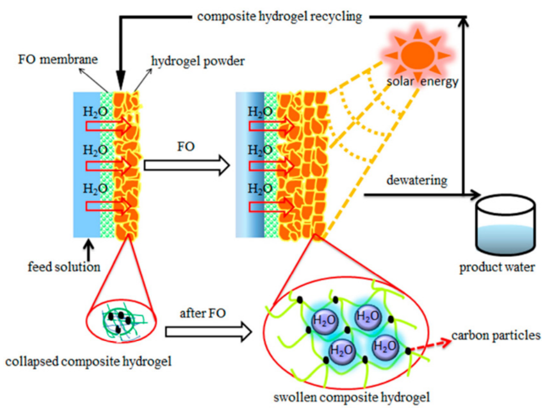

Figure 7. A description of employing solar energy for the recovery of thermos-responsive hydrogels draw solutions in the hydrogels-based FO system for desalination [103]. Image reused under the Creative Commons license.

4. Limitations and Future Perspectives

In the past few decades, renewable energy-based desalination technologies have attracted significant attention [104]. As highlighted in reported studies, advancement and growth in this field are heavily reliant on advances in energy harnessing processes, progress in system-centered procedures for the combination of renewable energy sources and desalination techniques, advancements in upgraded energy storage devices, the development of improved power regulators, and the availability of high-performance membranes [105,106]. Power generation has been the main objective behind most of the development in the solar power sector, resulting in substantially less focus being provided to the design and configuration of solar-driven desalination processes.

One of the major challenges in a large-scale application is energy loss during energy conversion processes. However, it is possible to reduce these losses by directly using this energy in desalination plants. More research is needed on the development of customized solar units for a variety of desalination applications. Another challenge is the exaggerated efficiency and cost-effectiveness of commercially available solar power devices and units. Additionally, the efficiency of solar energy systems is greatly affected by geographical conditions, so it is crucial to identify appropriate locations for desalination plants in order to make the most of solar power.

Countries with long coastlines have great potential for the production of wave energy. It is very important to perform a thorough feasibility analysis prior to installing a wave energy unit based on the spatial and temporal variability of the power source. The operation of desalination units with wave energy can significantly decrease CO_2 emissions.

The application of geothermal energy for desalination lacks commercial development, and hence there is much space for research and development in system design and configuration. Scale-up studies are needed on geothermal-powered desalination processes employing conventional and emergent technologies such as MD. Another major obstacle to the scale-up of renewable energy-based desalination plants is the intermittency of these energy sources, such as solar and wind. This issue also indicates the need for the development of efficacious power storage systems.

The humidification–dehumidification technology offers many striking features that are appropriate for wind energy, including simple design, modest technology, comparatively high efficiency compared with its counterparts, and primarily, the potential for integration with low-temperature renewable energy sources. Therefore, it is highly required to address the challenges of coupling the interface of the desalination unit with wind energy, design, configuration, optimization of process and structural constraints, and cost estimation schemes as well. The selection of an appropriate brine management approach essentially depends on the type of feed water and plant location. It is of high importance to develop regular monitoring plans, particularly for methods with potential for negative environmental impacts.

Well-organized engineering designs for combined FO-MD units can improve performance efficiency and operational economics. The cost of FO membrane is a major challenge in FO desalination, so it is needed to reduce costs for cost-effective integration operations. Substantial research work is needed to examine the scale-up application of integrated FO processes under factual conditions.

Artificial intelligence (AI), an emergent approach, is broadly found in the field of technology and engineering science. Owing to its great efficacy and precision, it is applied for optimization and process control in desalination processes. AI application in desalination is primarily categorized into four features: proficient decision-making, optimization, forecasting, and control through a sequence. Currently, the application of AI tools has not resulted in a complete framework and architecture for the design process of desalination. The algorithms lean toward diverse performance in predicting and optimizing, which would instigate the nonconformity of an ideal process. A framework should be set for the AI application in the whole desalination system and integrate the concepts of employing intelligent algorithms.

5. Conclusions

Renewable energy sources are receiving significant attention for their potential use in desalination plants. This increased attention is due to environmental challenges, freshwater scarcity, and the likelihood of a decrease in the use of fossil fuels in the future. Solar and wind energy are the most widely studied renewable energy sources for desalination processes, particularly for the reverse osmosis process. However, their intermittent nature can present challenges for their application in desalination. Further research is needed to ensure a consistent energy supply for desalination plants using renewable energy. Additionally, there is a large potential for further research and development in the less explored membrane processes that directly consume thermal energy, such as forward osmosis and membrane distillation. Small-scale implementation of these systems can greatly reduce the cost of the desalination process. The use of AI in desalination can also lead to high performance and cost-effective operation.

Author Contributions: Conceptualization and methodology, M.K.S.; writing—original draft preparation, M.K.S. and B.M.; writing—review and editing, P.R.R., J.W.L., M.A., A.E.A.-R. and Y.C.; data curation and visualization, M.A. and P.R.R.; funding acquisition, M.K.S. and Y.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by Brain Pool Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (Grant No.: 2019H1D3A1A02071191).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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