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Integration of Renewable Energy Systems in Desalination

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Abstract: Desalination plants, which provide drinking water for residents, rely on electricity generated by fossil fuels. However, the excessive use of fossil fuels leads to their rapid depletion and has detrimental effects on the environment. Thus, the use of renewable energy resources in water desalination has gained popularity. The current research investigates the integration of renewable energy systems with seawater and brackish water desalination technologies. In this regard, three primary renewable energy sources—wind, solar, and geothermal—are selected. Accordingly, a thorough investigation of the related research published and the trend of evolutions between 2013 and 2023 is carried out for Reverse Osmosis (RO), Multistage flash (MSF), and Multi-effect distillation (MED)-based water desalination facilities coupled with renewable energy sources. In our investigation, we particularly focus on performance indicators, energy efficiency, economic factors, and environmental effects. Also, the associated challenges of these hybrid systems, such as technological complexity, unpredictability, and intermittency, are addressed. Prospects for the future that address these issues and the prospects of using renewable energy in water desalination technologies are also covered.

Keywords: water desalination; solar energy; wind energy; geothermal energy; hybrid systems; performance metrics

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1. Introduction

The involvement of renewable energy sources in the water desalination industry signals a significant change toward sustainability by matching economic efficiency with respect for the environment. There are many advantages to employing renewable energy sources for water desalination, such as hydropower, wind, and solar energy. First, it diminishes the carbon footprint left by old-fashioned energy sources, assisting in the worldwide fight against climate change [1]. In this respect, solar panels can use sunshine to generate electricity to power treatment technologies, making the energy input clean and renewable [2]. Moreover, water desalination facilities can become more power-independent as a result of the discrete character of many renewable energy sources, which upsurges resilience and drops susceptibility to centralized power grids. These resolutions have equally strong economic rewards in addition to helping to preserve the environment.

Potential long-term savings are revealed by a life cycle cost analysis, as renewable energy sources become more trustworthy and affordable. Nonetheless, there are also a number of concerns, such as the unbalanced operation of some renewable energy sources, which makes effective energy storage solutions compulsory to ensure things run constantly [3]. Financial impediments may also arise from the initial expenditure of renewable infrastructure; however, these concerns are gradually being addressed by lessening prices and government encouragements [4]. In summary, the combination of renewable energy sources and the water desalination industry signifies a substantial advancement towards sustainable practices and endorses the opportunity for significant economic and environmental advances with careful planning and analysis [5].

Several review studies can be found in the public publication domain that are encountered when analyzing renewable energy sources powered water desalination methods. For instance, Eltawil et al. [6] presented a review study to highlight the efforts made in integrated renewable energy sources and seawater desalination technologies up to 2009. This included a comparative study to signify the technological development and economic aspects of these hybrid systems. It has been said that wind energy technology is the most affordable and widely applied approach globally. Reverse osmosis is also becoming the preferred method as efforts to lessen the cost of drinking water and overall energy usage continue. Unfortunately, there is not a solid foundation for examining the economic feasibility of the different desalination technologies in the economic evaluations that have been conducted up to this point. The system component, system energy source, system capacity, and water source have all been considered when conveying economical findings, while focusing on the freshwater production cost. As a result, with such discrepancies, appraising the economic performance of an approved technology and comparing it with other technologies is thought-provoking, if not unattainable.

According to Ghaffour et al. [7], there has been a lot of work conducted in evaluating solar, wind, and geothermal energy integration in water production using various water desalination techniques in the Kingdom of Saudi Arabia. According to some, the most cutting-edge and effective water desalination methods applicable to the regional conditions in the Kingdom of Saudi Arabia are membrane distillation and adsorption desalination. Furthermore, these technologies increase the efficiency of both standalone and hybrid systems that use geothermal and solar energy. In particular, these technologies consume less energy and chemicals, which reduces greenhouse gas emissions and future climate change. Thus far, the most efficient and reliable way to run these systems is by employing integrated cycle solar and geothermal energy sources to supply latent heat. However, the operational carbon footprint is reduced when renewable energy sources are used exclusively.

Esmaeilion [8] focused on demonstrating thermal and membrane desalination methods (RO, nanofiltration, electrodialysis/reverse electrodialysis, multi-stage flash and multi-effect distillation, and vapor compression) powered by renewable energy systems of nuclear energy, solar energy, wind energy, geothermal energy, and wave energy. In this regard, the authors discussed the performance indicators and energy consumption of thermal and membrane desalination techniques along with evaluating their economic aspects and environmental effects. Considering the published studies up to 2020, the exergy and energy analysis and the exergoeconomic analysis of these hybrid systems (desalination methods and renewable energy systems) were all addressed. According to Esmaeilion [8], the Persian Gulf has a large supply of cheap and readily available fossil fuels, making it a good location for the majority of desalination facilities. They concluded that the supreme prevalent desalination procedures are RO and multi-effect distillation, and significant research is undertaken to improve these two processes' productivities and lower their capital costs. Furthermore, solar and wind energy were used by most desalination plants worldwide (in the renewable sector). Using a system powered by a single renewable resource also has a significant financial and performance risk. A hybrid system, which is an actual arrangement that combines two or more energy systems with specific resources, is a reliable choice that would be appropriate. Esmaeilion [8] indicated that desalination procedures are highly costly and have a low energy efficiency. Therefore, it would be more cost-effective and inexpensive to recommend creative ways that lower expenses. Although wind energy performs better, solar energy is still an essential component of hybrid systems. It has been discovered that geothermal energy contributes relatively little to the desalination process. However, compared to other renewable energy sources, the energy from this source is steadier because of the consistent temperature at a certain depth.

To minimize the environmental effect caused by the generation of freshwater and lower specific energy consumption through combinations with solar energy, Gude and Fthenakis [9] emphasized current key advancements and discussed potential avenues for additional growth in the desalination energy group. Possibilities for increasing energy efficacy and energy recovery in thermal and membrane water desalination methods were discussed after a description of existing desalination technologies and how much energy they need was given. After that, different configurations of desalination facilities driven by renewable energy sources were inspected, with a focus on more recent progress in solar-energy-driven thermal, membrane, and hybrid desalination technologies. The presentation covered the technological level of preparedness for innovative desalination techniques, their anticipated influences, and anticipated near-term advancements in combined desalination systems utilizing renewable energy. Lastly, the possibility of solar-powered desalination as an affordable substitute for freshwater supply was examined. Even though solar-powered desalination facilities can be appealing in the majority of water-scarce areas, other renewable energy sources, such as wind, geothermal, and wave power, must be taken into account when they are technically and economically viable. New process designs should be created to improve energy and water recovery in order to increase energy savings. This calls for the creation of robust, more effective membrane materials and procedures. Lastly, whenever possible, waste-heat-driven operations must be taken into account for concentrating management in both zero liquid discharge and desalination systems.

The implication of alternative renewable energy sources in water desalination was detailed by Bundschuh et al. [10]. The aforementioned encompasses the presentation of the experience pertaining to the application of solar thermal units, such as solar collectors and concentrated solar power systems using solar electricity, such as photovoltaic, hydroelectric, wind, biomass, and geothermal energy. For a variety of desalination technology procedures, the energy and production costs associated with desalinated water were examined. The primary options for the advancement of the examined renewable energy units were assessed, together with an evaluation of their benefits and drawbacks. Such an extensive analysis revealed that numerous techno-economic barriers continue to impede the growth of the efficient utilization of renewable energy sources. The primary issues addressed in the article were the requirement to optimize energy units, particularly by developing more economically and energy-effective solutions, energy recovery, energy storage, and the growth of off-grid systems. The consequence of the investigation was that, notwithstanding certain drawbacks, more thorough study and demonstrated units are required to guarantee the long-term performance of mixing renewable energy with desalination procedures. There is still an urgent requirement for regulations to create desalination systems that use less energy.

After providing a brief summary of the review investigations that have been conducted on integrated renewable energy sources and water desalination techniques (discussed above), it is reasonable to say that no attempt has been made to thoroughly review integrated renewable energy sources and water desalination methods, particularly for the last ten years between 2013 and 2023. Thus, with a focus on technologies and performance metrics, this paper intends to provide a concise overview of the major advancements made globally over the past ten years in the arena of seawater and brackish water desalination techniques integrated with renewable energy sources, as well as the state of the art. This includes a comparison of several water treatment systems connected to renewable energy technologies with a focus on performance metrics, energy, and economic aspects. Examining the research that was conducted during this time frame (2013 and 2023) is essential to determining whether or not these integrated systems are economically feasible. Policymakers can learn a great deal about the long-term advantages and cost-effectiveness of implementing renewable-energy-driven water desalination technologies by closely examining economic factors. Comprehending the recent advances in this domain enables a clear summary of technological advances, enhanced productivity, and possible obstacles. It is reasonable to say that the conclusions of the current review would enable comprehending the association between renewable energy and water desalination, and aid in developing strategies for reliable and sustainable water infrastructure. The associated results of the current review can also support decision makers to decide the proper renewable energy sources for building new water desalination plants.

2. Renewable Energy Systems

In the present global scenario, the growth of various types of energy use is regulated by the rising use of electricity. Fossil fuels offer an easy option to fulfill the world's energy requirements. We have to locate a replacement for fossil fuels in order to produce energy because they have a detrimental impact on the planet. To reduce pollution and provide an eco-friendlier atmosphere, this alternative form of energy needs to be harmless to the environment. Resources for renewable energy are those that meet the aforementioned requirements. Technologies based on renewable energy can be applied to enhance living circumstances. Since renewable energy can lower carbon emissions and air pollutants, it generally has several benefits over fossil fuels. Researchers want to see these technologies progress from pilot projects to commercial applications and play a significant role in global electricity supply in the future. The subsequent sections discuss the conceptual designs of common renewable energy systems.

2.1. Solar Energy Systems

The latest and greatest non-conventional energy source is solar energy, also known as a photovoltaic (PV) system, which can continuously meet a considerable part of the world's energy requirements in the present and future. It is also a clean, ecologically friendly energy source that is available in practically every corner of the globe. PV technology is characterized by directly converting sunlight into electrical energy. Due to the lack of moving parts (specifically for a fixed PV panel), it operates in an environmentally friendly manner and is a good source for distant applications that require little to no maintenance [11]. These are just a few of its many benefits. PV systems have proven their efficacy and dependability in numerous small- to medium-sized standalone applications and MW grid-connected power plants [12]. The primary barrier to the adoption of multi-MW solar systems is their extremely high module start-up cost [13]. Depending on their many uses, solar PV systems can be operated in multiple modes, including standalone, hybrid, and grid-connected. A freestanding system can have a storage battery or not. The solar resource at the location, the load parameters, and the system setup are the only factors that affect the system's performance [14,15]. The incident solar radiation, which is reliant on the location, day of the week, and time of day, as well as the angle at which the sun is received and other pertinent environmental factors, is the input energy for solar PV systems [16]. The temperature at which the solar cells operate, which is influenced by the surrounding air temperature, also affects the output of the solar PV array. Hourly, daily, monthly, and annual changes are still occurring in these parameters.

Description of a Solar Energy System

Despite the solar energy system potentially varying based on specific configurations and user needs, the solar panels, inverter, battery, charge controller, mounting system, and grid connection are the main components of an actual solar energy system, as represented in Figure 1. Solar panels or PV cells made of silicon are the main parts of a solar energy system that capture sunlight and convert it into electricity. These solar panels can be designed as a number of arrays and mounted on a mounting system to secure them in place (rooftop or ground). The second part of a solar energy system is the inverter. This is responsible for converting the direct current (DC) of photovoltaic cells into an alternating current (AC). The produced AC electricity can be used in most households and industrial applications. The third part is the energy storage system (battery). This is specifically included to restore the excess electricity generated in summer periods. Therefore, during the night and during overcast conditions, when the solar cells are not actively producing electricity, this excess electricity can be used to ensure a steady supply of electricity. The amount of electricity generated by a solar energy system can be measured by a solar power meter. To deliver the best possible charge in this case, a charge controller can be utilized for managing the charging and discharging of the batteries. Excess electricity generated by a solar energy system can be fed back into the grid and, therefore, the solar energy system can be optionally connected to the grid.

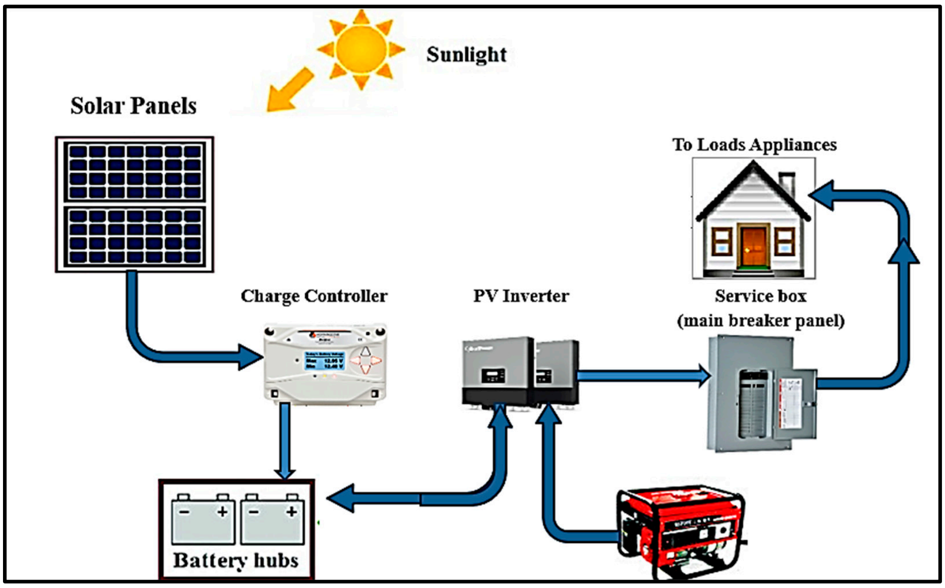

Figure 1. A representation of a solar energy system.

2.2. Wind Energy Systems

Wind energy is an environmentally friendly source of renewable energy that has been obtaining noteworthy attention in current years. Wind turbines are employed to transform the kinetic energy of wind movement into mechanical and subsequently electrical energy. Although wind turbines are classically enormous in size, it is feasible to capture wind energy in urban areas by installing microturbines on rooftops. Figure 2 depicts a diagram of a standard wind-powered desalination plant [17].

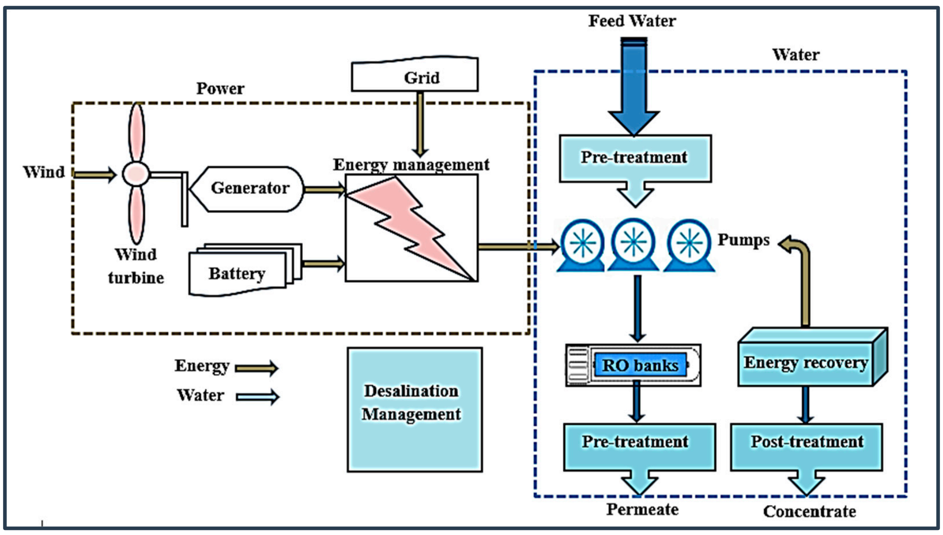

Figure 2. A representation of a typical wind driven desalination plant (adapted from Abdelkareem et al. [17]).

A classic wind energy standalone system (Figure 3) contains one or more wind converter, a suitable energy storage device, a rectifier, a charge controller, an uninterruptible power supply to assure a high-quality alternating current (AC), and a direct current (DC)/AC inverter. The rated power of the nominated wind turbine is subject to the system's electricity requests, the existing wind potential, and the operative features of the device [18].

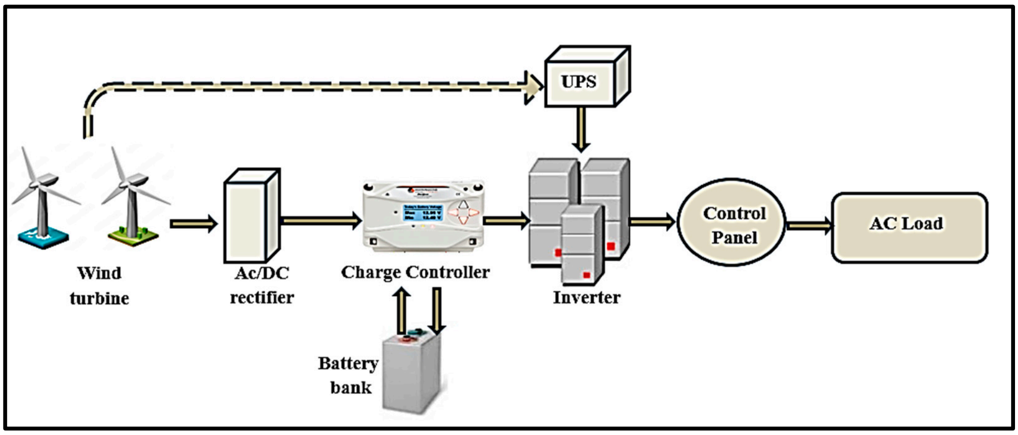

Figure 3. A representation of a typical wind energy system (adapted from Kaldellis [18]).

The output power of a wind system is dependent upon the velocity of the wind. The wind passes through the wind turbines, causing them to rotate. This rotation converts mechanical energy into electrical energy through the use of turbines. Specifically, the rotation of the wind turbines would drive a generator to produce electricity. Due to the unpredictable wind speed, the energy generation is unsteady, resulting in a variable AC. Rectifiers are employed to convert fluctuating AC into stable DC. However, to power the rectifier, a converter is utilized to transform the stable DC into stable AC. The control system of this system operates on the same fundamental premise as a solar system. A charge controller is employed to control the process of charging and discharging a battery, hence enhancing its lifespan. Excess electricity generated by the system is utilized to charge the batteries. If the system does not meet the load requirement, the battery power is utilized as a backup security measure [19].

2.3. Geothermal Energy Systems

Using nearly all of the retrieved latent heat, the emergence of geothermal energy aims to generate electric energy and desalinate water as efficiently as possible [20]. To optimize overall heat conservation, the generation of electric energy and desalination must be linked. When compared to renewable energy sources that may generate electricity for a portion of a 24 h day, geothermal energy harvesting offers a significant advantage when used to power water desalination appliances. If appropriately engineered, a geothermal energy system can supply "base-load" electricity continuously and for a prolonged amount of time. The most effective utilization of this resource can be obtained by combining the production of electricity and desalination with a geothermal energy source (Figure 4).

Missimer et al. [21] suggested the combination of a geothermal energy system with solar power for seawater desalination. This permits geothermal heat source regeneration and excludes the necessity of having thermal storage for the night-time use of a solar-powered desalination system. In particular, the recommended system is run on geothermal energy at night and on overcast days, and solar energy during the day. Drilling shallower and less costly collection wells is made possible by the integrated cycle operation, which enables the geothermal heat source to be regenerated.

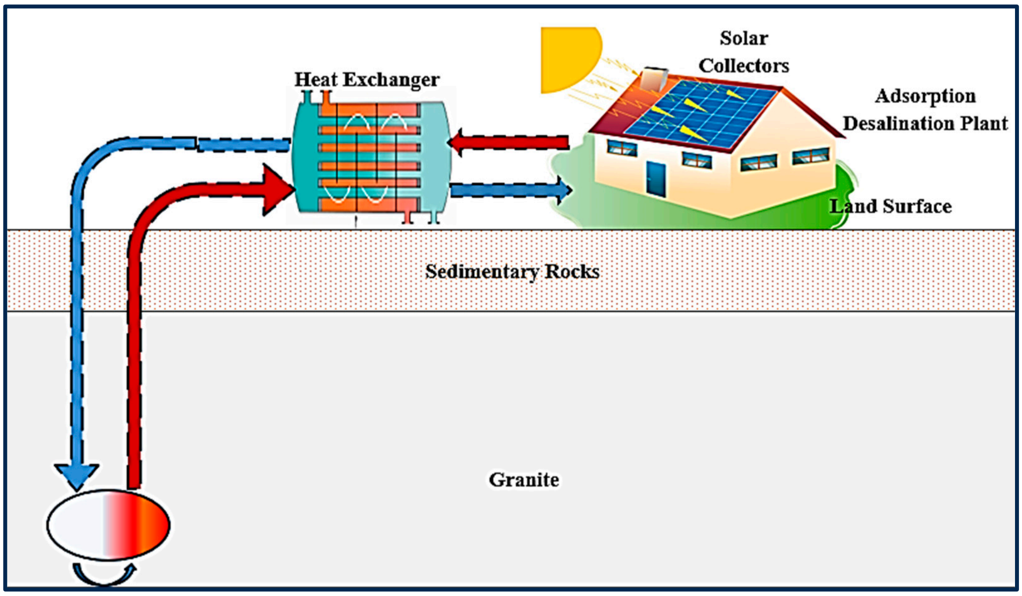

Figure 4. A representation of proposed integrated system of geothermal and solar powered water desalination (adapted from Missimer et al. [21]).

There are three primary classifications for geothermal energy systems. Initially, accessible heat from dug wells or naturally occurring water flow springs is used by the natural dry steam. Cooled water is pumped into the groundwater in this system, just like in heat pump technology, to allow for warming and its return to the system [22]. Second, to generate superheated water under pressure in regions with active volcanic activity, a natural dry steam system is recommended. This, in turn, would enable employing the superheated steam in a number of turbines to generate electricity. Third, in a hot dry rock (HDR) geothermal system, heat is obtained by constructing a synthetic system of interconnected both injection and extraction wells, where the superheated fluid is retrieved and heat is extracted [23]. Geothermal oil may be the fluid utilized, and energy can be recovered at the surface of the earth using a number of heat exchangers.

Geothermal energy can be utilized with desalination processes in a variety of ways. Using geothermal fluid, seawater in a desalination system can be heated directly in the first method. This approach lowers energy consumption and operating expenses, despite eliminating the requirement for extra heating components [24]. The second type would include first producing electricity from geothermal energy and then operating a standalone RO desalination plant. Utilizing geothermal energy to power a hybrid water desalination system, such as one that combines RO and MED units, is the third type. In this sense, electrical energy for an RO unit can be produced using the flashed steam from a dry steam reservoir. In addition, the released steam from the turbines can be applied to heat the feed water that is supplied to the MED unit. With this technology, high-salinity seawater can be excellently treated while still making an operative deployment of the acquired geothermal heat [8,17].

3. MSF Desalination and Renewable Energies

Thermal desalination technology is considered to be the most vigorous and reliable procedure in seawater desalination. In fact, it is the best option for desalting water with a salinity greater than 36,000 ppm [25]. The most distinguished thermal desalination processes are the multi-stage flash desalination process (MSF) and multiple evaporating distillation process (MED).

The MSF is a process where the seawater is heated in a sequence of many stages by absorbing the latent heat of the condensation of produced vapor from flashing brine. The preheated seawater enters a brine heater where the temperature of the seawater is raised to the preferred top brine temperature (TBT), which ranges between 90 °C and 110 °C. The hot brine leaving the brine heater is then fed into a pool of flashing chambers, where the brine starts to flash, producing a vapor. This process is repetitive in successive stages as the pressure continues to drop to maintain the saturation temperature at a low pressure. A representative diagram of the MSF process is depicted in Figure 5.

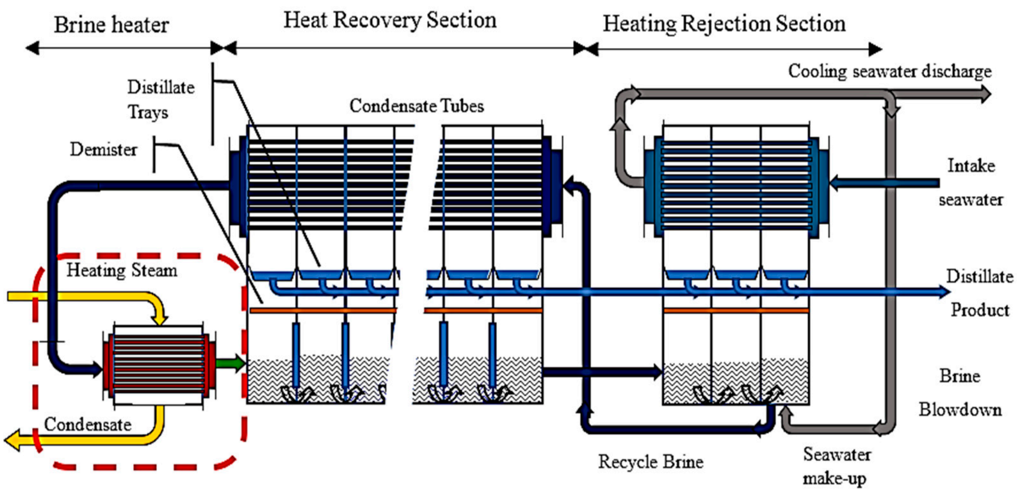

Figure 5. A representation of the MSF desalination system (adapted from Hasan et al. [26]).

The MSF desalination technique is known as an energy-intensive process compared to membrane technologies. Besides the required electric energy to power the pumps and other equipment, immense thermal energy is needed for the MSF process to heat the preheated seawater to the desired temperature. The brine heater in the MSF, which receives the thermal heat, is highlighted in the dashed box in Figure 5. The key source of energy in thermal desalination processes is saturated steam, which is supplied by auxiliary boilers using fossil fuel. The performance of the MSF process is measured by a parameter called gained output ratio (GOR), which is the amount of distillate water per kg of steam.

Thermal desalination technologies are very sensitive to increases in the price of the fuel, hence, they are confronting several problems to cut their costs. Due to their high cost, the dominant market position of thermal desalination technologies has decreased significantly from 84% of the global desalination size in the 1980s to around 25% in 2019, with 18% tied to MSF and 7% to MED [27]. However, in the Middle East and North African countries, where the cost of fossil fuels is low, thermal desalination technologies such as MED and MSF are still favored techniques over other technologies. Along with the high costs of fossil fuels, greenhouse emission gases (GHG) are the foremost global concern. Due to the use of fossil fuels, 76 million tons of CO_2 per year are produced from installed desalination plants, and this number is estimated to increase to 218 million tons per annum by 2040 [28].

Eltawil et al. [6] showed conceivable integrations between renewable energy sources and different methods of water desalination. Technically, as depicted in Figure 6, an MSF system can only be powered by solar and geothermal energies because of their direct supply of energy as a form of heat. However, using a wind turbine to drive MSF requires the conversion of electricity into thermal energy before running the MSF unit.

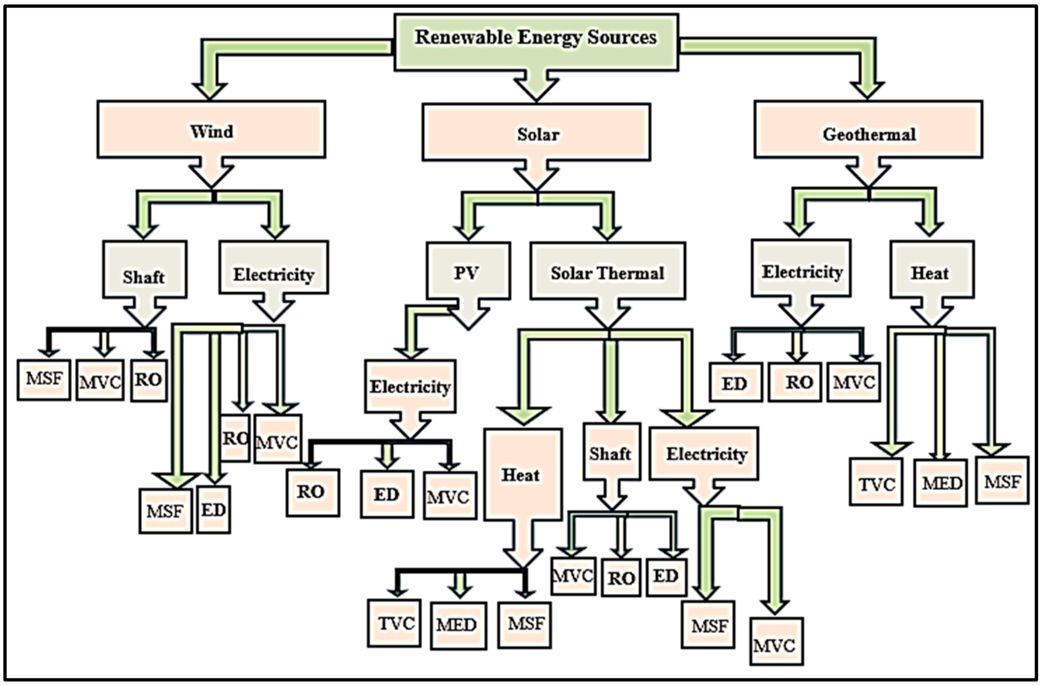

Figure 6. The most common combinations between renewable energy sources and desalination types (adapted from Eltawil et al. [6]). Reprinted/adapted with permission from Ref. (Eltawil et al. [6]) 2024, Elsevier.

3.1. Solar Energy—MSF

While solar-powered desalination systems are currently costly, they may be the most viable option for small-scale desalination (up to 10 cubic meters per day) in remote areas lacking access to fuel, electricity, and technical support, as they provide a clean and sustainable source of drinking water [29]. Arid regions that experience the most freshwater scarcity are, interestingly, also those with the greatest solar source abundance [30]. Solar energy is considered as the most abundant source of renewable energy, presenting 60 terawatts of technologically feasible potential energy, which is much higher than that of all other renewable energy sources [31]. Despite the installation of a number of MSF desalination plants driven by solar energy in the last century, the maximum production capacity has reached around 100 m^3/day [32]. In the Middle East, the share of renewable energy in seawater desalination was only 1% in 2016, however, this figure is predicted to upsurge meaningfully by the end of 2040 [33]. Nevertheless, the reduction in the cost of water in large-scale solar plants indicates that this kind of energy source will become a potentially viable option in the future [34].

Solar energy sources can be combined with the MSF desalination process either directly, where distillate water is produced using a solar collector, or indirectly, where the MSF desalination plant is combined with the solar collector to generate heat in the brine heater via a medium. Direct solar, in comparison with indirect solar, requires a large footprint and has a low production rate [35]. Thus, the direct solar technique suits small production systems such as a solar stills, while indirect solar technology can be integrated into large desalination systems such as MED and MSF [36].

Four kinds of solar collectors are most commonly used in desalination systems, namely, salinity gradient solar ponds (SPs), evacuated tube collectors (ETCs), flat-plate collectors (FPCs), and parabolic trough collectors (PTCs) [35]. Among several installed desalination plants, salinity gradient SPs and PTCs are the common types of solar collectors [37].

In contrast to other kinds of renewable energy such as wind and geothermal energy, solar energy is considered as the most attractive source that can be combined with MSF plants. Despite there being several published studies in the available literature that focus on powering the MSF process by solar energy, the intention of this paper to evaluate the published studies between 2013 and 2023.

Hassabou et al. [38] conducted a simulation study to economically estimate a large MSF plant with 5000 m^3/day of capacity powered by a concentrated solar thermal system. Using a wide range of operative conditions and based on data from the Arabian Gulf region, it was established that the cost of freshwater generated by MSF driven by concentrated solar power was almost three times more than the cost of water generated by conventional MSF. However, this situation may be different worldwide. Hassabou et al. [38] concluded that RO-based solar power could be suitable for the North African region, while MSF-based solar power suits the countries in the Gulf Region.

Eldean and Fath [39] conducted a thermo-economic analysis to evaluate MSF driven by parabolic trough concentrator solar power. Two techniques were considered; the first was a standalone desalination process and the second was a dual-purpose power generation unit and desalination unit. The tested desalination plant contained 40 stages and had a capacity of 5000 m^3/day and a performance ratio of 12. The thermos-economic data that were obtained showed that the first approach, the standalone desalination unit, used less specific power (4.09 kWh/m^3) than the second technique of MSF driven by parabolic trough concentrator solar power (5 kWh/m^3). Furthermore, the solar field needed 61,680 m^2 of land for the first technique (the desalination unit), whereas 92,050 m^2 of land (the power-generating unit and desalination) was needed for the solar field in the second technique—nearly 49% more.

Abdunnabi and Ramadan [40] studied and evaluated a small MSF process with a 5 m^3/day capacity powered by vacuum tube solar collectors. The TRNSYS software (a transient simulation program version 17.00.0019) was used to evaluate different configurations and arrangements of solar thermal collectors and thermal storage tanks. Six configurations were considered, and the results showed that the configuration of 90 collectors and two tanks, each at 500 L, connected to 9 × 5 collectors provided 77% of the required thermal energy and a temperature of 70 °C. This significant fraction of thermal energy was obtained for 8 operational hours per a day. However, the solar fraction could be reduced by 25% if the plant ran for 24 h. With increasing fossil fuel prices and decreasing costs of parabolic trough collectors, solar-powered MSF desalination plants could become more cost-effective than conventional MSF desalination in the future, especially if they utilize a higher proportion of solar energy.

In regard to utilizing solar systems on multi-building complexes to provide electricity, heat, freshwater, and hydrogen, Ozlu and Dincer [41] established a thermodynamic model to conduct a thermodynamic analysis this system. For freshwater production, Ozlu and Dincer [41] applied an MSF unit consisting of 15 stages powered by solar collectors to produce around 3.45 m^3/day of freshwater.

To minimize the required area of the solar collectors, Alsehli et al. [42] advanced a new design for a solar system powered an MSF desalination unit. The proposed design used concentrated solar collectors and two thermal storage tanks arranged in such a way that one tank received the pre-heated seawater, which was circulated through the solar collectors and then delivered to the second tank. The second tank supplied the MSF with brine that was enough for one day. To overcome the availability of daily solar energy, the brine flow rate was modified in such a way to maintain the TBT at a desirable value. The developed system used 42,552 m^2 of the solar-collecting area to generate 2230 m^3/day of freshwater with 6.8 of GOR at a minimum cost of USD 2.72 per cubic meter.

Al-Othman et al. [43] combined solar ponds and parabolic trough collectors to supply a proposed MSF desalination unit with the required energy to generate 1880 m^3/day of drinking water. The theoretical developed design was simulated using HYSYS V8.8 and the estimated results revealed that the parabolic trough collectors, with a total area of 3160 m^2, were capable of producing 76% of the required MSF energy. The remaining fraction of the energy was expected to be supplied by solar ponds with a total surface area of 0.53 km^2. However, to overcome the shortage of energy in the absence of sunlight, the system was supplied with a fire tube heater. Garg et al. [44] established a numerical model for an MSF unit supplied by a heat source through nano-fluid absorbing its heat directly from solar collectors. Interestingly, the authors obtained a high TBT and a very high performance ratio ranging between 11 and 14, depending on the height and length of the solar collectors and other operating conditions. Moreover, the developed system was also compered to parabolic trough collectors, and it was found that the direct absorption solar collector had a performance ratio around 11% higher.

Shaaban [45] used an optimization technique for an integrated solar combined cycle to power an MSF desalination unit. The outcomes revealed that the output power rose by 3.3–6.8% using a 50 MW solar field and, accordingly, the heat rate decreased by 1.9–3.5%.

Darawsheh et al. [46] conducted an experimental investigation to cut the costs of producing freshwater using an MSF desalination unit by integrating flat-plate solar collectors with the desalination unit. The designed MSF unit contained two flashing stages, and the results showed that, by decreasing the pressure by 20%, the performance ratio could be improved by 53% and the energy consumption decreased by 35%. The freshwater generated per unit area of solar collectors could reach 0.3 L/h. Also, increases in the brine flowrate from 0.5 L/min to 0.75 L/min and 1 L/min led to decreases in the distillation rate by 29% and 51%, respectively.

Méndez and Bicer [47] employed a combined system for electricity and water production to be powered by a solar chimney method. To overcome the intermission of the electricity and drinking water demand, a hydro-storage system was combined with a water turbine. The incorporated MSF could generate around 8.3 kg/s of freshwater with a GOR of about 8.91.

Similarly to Darawsheh et al. [46], Babaeebazaz et al. [48] integrated a small-scale two-stage MSF unit with a solar parabolic dish to examine the viability of utilizing solar energy as the main heating source. During six days of experiments, the outcomes exhibited that an increase in the feed flowrate from 0.7 L/min to 1.3 L/min resulted in a 76.4% drop in the water production rate. However, running the experiment at 10 kPa of vacuum pressure could enhance the production of the MSF unit by 34% at a feed flowrate of 0.7 L/min and by 82.98% at a feed flowrate of 1 L/min.

A dual-purpose system, where a desalination unit and steam turbine are combined to produce electricity and water, is one of the preferred methods for minimizing the production costs of drinking water and electricity [49,50] carried out an economic and environmental study into utilizing parabolic solar collectors to power dual-purpose MSF desalination plants. Their results revealed that it was possible to generate 310 MW of electricity during the year, and the MSF unit produced 115.4 kg/s of freshwater at 9.62 of the GOR. Also, the results indicated a reduction of around 41% in the total cost compared to the base steam power plant without solar power. Interestingly, the cost of freshwater was appraised to be around USD 0.21/m^3 of freshwater.

Dabwan et al. [32] studied the feasibility of integrated gas turbine tri-generation with parabolic trough collectors to drive an MSF desalination unit to produce freshwater, electricity, and chilled water. The results showed the possibility to produce 45,461 m^3/day of freshwater, 230 MWe of electricity, and 2300 kg/s of chilled water. Despite a minor increase observed in levelized electricity costs (11.8–22.6%) compared to conventional techniques, the results indicated a decrease of 30.2% in annual CO_2 emissions.

Ziyaei et al. [51] conducted theoretical study using the TRNSYS software to simulate an MSF desalination unit powered by solar parabolic trough collectors. The study was applied to seven different cities with various climate conditions and solar radiations. By applying the life cycle method, their results depicted that using solar energy with natural gas as the heat source was more economic than using natural gas only (Figure 7). Moreover, the findings indicated a variation in the cost of desalted water between USD 2.21/m^3 and USD 4.32/m^3, depending on the location of the cities.

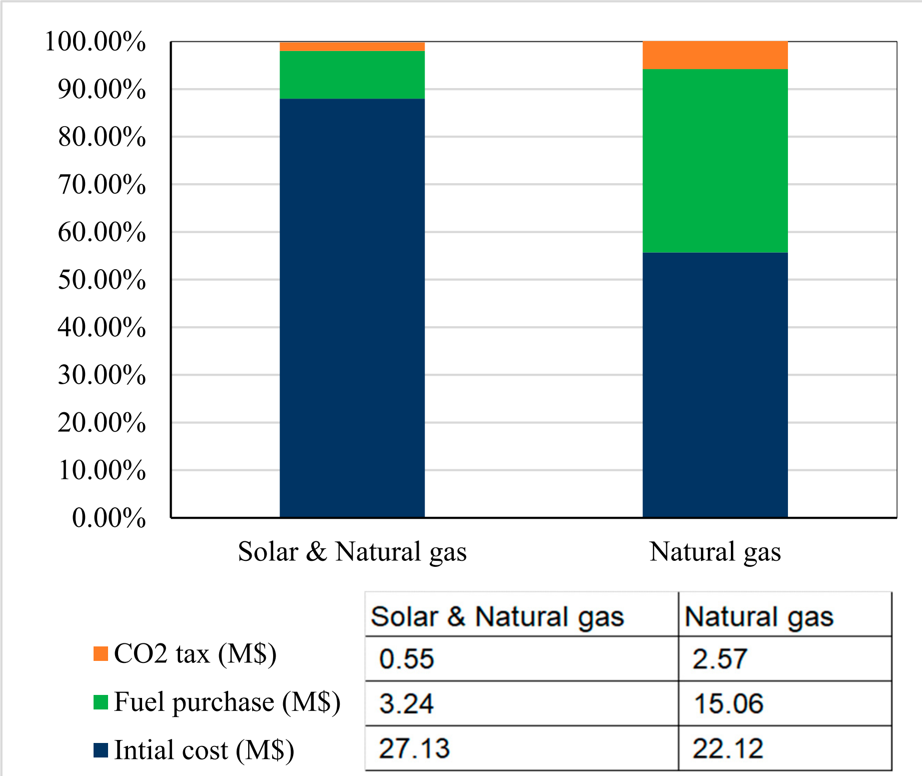

Figure 7. Life cycle cost of MSF system powered by solar and natural gas (adapted from Ziyaei et al. [51]). Reprinted/adapted with permission from Ref. (Ziyaei et al. [51]) 2024, Elsevier.

Al bkoor Alrawashdeh et al. [52] developed a numerical model to assess the feasibility of powering an MSF plant using a poly PV array solar energy type. The solar power unit was made of 72 poly-Si panels with 34 strings each to drive the MSF unit, consisting of 24 flashing stages. Their results showed that the solar unit produced around 30 MW, 15 MW of which was used to produce a superheated steam of 6.52 kg/s to be applied in the MSF unit. A TBT of around 110 °C was achieved, and the freshwater productivity was 63.314 kg/s.

Recently, Yadav et al. [53] designed an MSF process powered by solar energy to desalinate geothermal water. To achieve the required MSF temperature, evacuated tube collectors were used. Python programming (https://www.python.org/about/gettingstarted/: Access Date: 14 February 2024) was used to design the solar and MSF systems, while the thermodynamic properties were estimated using the CoolProp properties (http://coolprop.org/fluid_properties/index.html; Access Date: 14 February 2024). Satisfactory results were obtained, and the cost of the freshwater productivity was expected to be USD 0.1034/m^3.

The aforementioned studies over the last ten years depicted an increasing interest in powering MSF desalination techniques by solar energy. However, despite the numerous number of studies on utilizing solar energy in MSF desalination, its implementation is confronting a few problems. The main barriers are the low solar cell efficiencies and the availability of solar energy throughout the whole day, along with its high upfront costs [54].

3.2. Wind Energy—MSF

Currently, wind energy is considered as the second-most well-known form of renewable energy source for desalination after solar energy [33]. The most appropriate desalination techniques to be combined with wind energy are RO, mechanical vapor compression (MVC), and electro-dialysis (ED) desalination systems [55], However, solar energy is best-suited for MSF and MED desalination systems. In their study on using renewable energy on arid islands, Mentis et al. [56] recommended wind turbines for large islands, while on small islands, solar photovoltaics are more preferred over wind turbines.

Although there are many wind energy farms operating worldwide and more undergoing development, there is no evidence in the literature of combining them with MSF desalination plants. The most common form of energy produced by wind turbines is electricity, and this electricity is then applied to power pumps and heaters to produce thermal energy for MSF desalination systems. In an attempt to produce distillate water directly from wind turbines, Nakatake and Tanaka [57] proposed a maritime lifesaving distiller completely and without electricity driven by wind. The wind power was converted into frictional thermal energy in a thin layer of liquid between the rotating shaft connected directly to the windmill. The developed device was estimated to produce between 1.6 and 2.2 kg/day of freshwater at wind speeds of 3 and 6 m/s, respectively. Furthermore, Cheboxarov and Cheboxarov [58] developed a wind energy marine unit to empower an MSF unit. However, no results related to the cost of water nor the production rate were presented.

3.3. Geothermal Energy—MSF

Geothermal energy is harnessed from the core of the earth as a hot fluid known as geo-fluid. This geo-fluid can be applied directly to heat seawater or indirectly by heating water to steam, which can be utilized to heat seawater in MSF brine heaters or drive turbines for electricity use. Noorollahi et al. [59] pointed out that the direct use of geothermal energy is more cost-effective than generating electricity. As mentioned in Figure 8, geothermal energy sources, unlike wind sources, are the most appropriate renewable sources to be combined with thermal desalination techniques such as MSF. One of the greatest advantages of geothermal energy is its invariance and stability. Unlike wind or solar energy, geothermal energy sources are not affected by seasonal variations and weather conditions [60]. Hence, there is no need for thermal storage tanks or battery storage to save energy, making this source a preferred option over wind or solar energy sources [61]. Compared to solar sources, providing heat to desalination systems from geothermal energy is considered to be more economic [10]. Karagiannis and Soldatos [62] pointed out that the cost of producing water from brackish water resources using geothermal energy is cheaper than the use of photovoltaic solar energy. Nevertheless, the high initial cost of exploration and well drilling [60] and the length of the payback period [63] are the main problems that prevent the full utilization of geothermal energy sources. For example, to achieve the desired temperature for MSF, which ranges between 90 and 110 °C, the depth of the extracted geo-fluid well should be in the range between 2 and 3 km (Figure 4) [64,65]. This requires the costs of drilling, pipes, and powerful pumps to overcome the high pressure underneath the surface. For desalination systems running at lower temperatures such as MED, where its operating temperature is less than 70 °C, it is possible to achieve the necessary temperature at a lower depth. For lower costs, Noorollahi et al. [59] suggested the utilization of abandoned useless oil and gas wells to provide geothermal heat due to zero drill costs. However, in volcanic reigns, the required temperature can be achieved at a lower depth and close to the surface. In fact, a temperature of 300–323 °C has been identified by the public power Co of Greece at depths between 800 and 1400 m below the sea level of Milos Island [66].

Geothermal energy remains an unknown source compared to the dominant competitive types of renewable sources such as solar and wind energy. Nevertheless, Ali et al. [67] estimated an increase in the interest in applying geothermal energy for desalination units in the near future, and it might become the most preferred option in some arid areas. For the period between 2013 and 2023, there are a few investigations in the literature that examined the feasibility of integrating geothermal energy sources into MSF desalination units, as discussed below. Table 1 summarizes the previous investigations published between 2013 and 2023 on MSF systems driven by renewable energy sources.

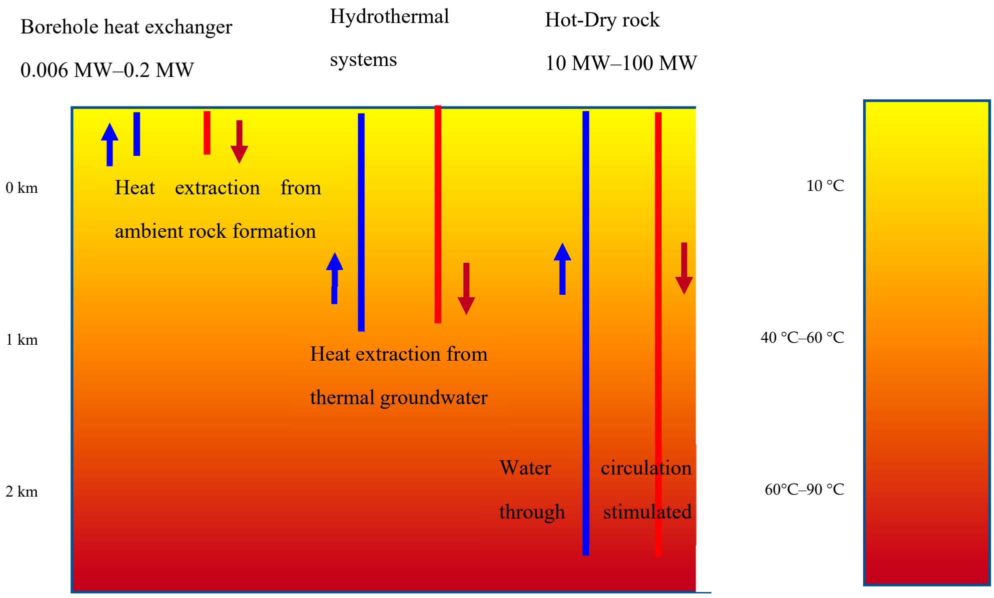

Figure 8. Temperature gradient against depth of the wells (adapted from Missimer et al. [64]).

Table 1. A summary of the conducted investigations on MSF powered by renewable energy sources.

Authors and Year	MSF Design	Renewable Energy Process Design	Aim of the Research	Operating Conditions	Highlights
Hassabou et al. [38]	Unknown number of stages	Concentrated solar	To conduct a numerical analysis and techno economic evaluation of a concentrated solar thermal system to power a large MSF desalination plant	Seawater temp. of 25 °C -Seawater salinity of 35,000 ppm -TBT of 112 °C	-Productivity of 5000 m^3/day
Eldean and Fath [39]	40 flashing stages MSF unit	Parabolic trough concentrator solar	To carry out exergic and thermo-economic analyses for large MSF desalination process powered by solar thermal energy	-Seawater temp. of 28 °C -Salinity of 47,300 ppm -TBT of 90 °C	-Productivity of 5000 m^3/day -GOR of 12
Abdunnabi and Ramadan [40]	14 flashing stages MSF unit	Vacuum tubes solar collectors	To investigate the finest use of solar thermal collectors to run the MSF desalination unit using TRNSYS software	-Seawater temp. of 20 °C -Seawater salinity of 35,000 ppm -TBT of 80 °C	-Productivity of 5 m^3/day
Ozlu and Dincer [41]	15 flashing stages MSF unit	Parabolic solar collector	To carry out a thermodynamic analysis of a new multi-generation system powered by solar energy and to generate electricity, heat, freshwater, and hydrogen	-Seawater temp. of 18 °C -Seawater salinity of 35,000 ppm	-Productivity around 3.45 m^3/day
Alsehli et al. [42]	20 flashing stages MSF unit	Concentrating solar collectors	To develop a new design of a solar desalination approach with smaller solar collectors area	-Seawater temp. of 25 °C -TBT of 90 °C	-Productivity of 2230 m^3/day -GOR of 6.8 -Fresh water production cost of USD 2.72 /m^3
Al-Othman et al. [43]	4 flashing stages MSF unit	Parabolic trough collectors and solar pond	To investigate the utilization of parabolic tough collectors and solar ponds driven an MSF plant using ASPEN HYSYS V8.8	-Seawater temp. of 25 °C -TBT of 96 °C	-Product 1880 m^3/day -Fresh water production cost of USD 2.23/m^3
Garg et al. [44]	20 flashing stages MSF unit	Direct absorption solar collector	To measure the thermal performance of an MSF system via a mathematical model of an MSF system integrated with a nano-fluid-based direct absorption solar collector	-Seawater temp. of 25 °C -Seawater salinity of 42,000 ppm -TBT of 90 °C	-GOR between 11 and 14

Table 1. *Cont.*

Authors and Year	MSF Design	Renewable Energy Process Design	Aim of the Research	Operating Conditions	Highlights
Shaaban [45]	24 flashing stages MSF unit	Integrated solar combined cycle	To enhance the power output and reduce the MSF size via an optimization of a combined solar cycle that is used to power an MSF desalination process	-Seawater temp. of 25 °C -Seawater salinity of 42,000 ppm -TBT of 105 °C	-Productivity of 16,364.2 m^3/day
Darawsheh et al. [46]	Two flashing stages MSF unit	Plate solar collectors	To optimize the process performance and cost effectiveness of the MSF desalination process by integrating flat-plate solar collectors with multi-stage flash (MSF)	-Feed flow rate of 0.5 L/min -Pressure 20 kPa	-Productivity of 0.3 L/h/m^2
Méndez and Bicer [47]	16 flashing stages MSF unit	Solar chimney	To conduct a thermal assessment of the feasibility of integrating a solar chimney with MSF for workable water production	-Seawater temp. of 25 °C -Seawater salinity of 35,000 ppm -TBT of 96.55 °C	-Productivity of 8.3 kg/s -GOR of 8.91
Babaeebazaz et al. [48]	Small-scale two flashing stages MSF unit	Solar parabolic dish collector	To examine the feasibility of using solar parabolic collectors as the main heating source for a small-scale two-stage MSF system	-Feed flow rate 0.7 L/min -Pressure 10 kPa -TBT between 94.25 °C	-Productivity of 0.644 L/h
Kabiri et al. [50]	22 flashing stages MSF unit	Parabolic trough collectors	To examine the thermodynamics of the MSF process to be powered with a solar energy source based on environmental friendliness and economic benefit	-Seawater salinity of 45,000 ppm -TBT of 110.6 °C	-Productivity of 115.4 kg/s -GOR of 9.62. -Fresh water production cost of USD 0.21/m^3
Dabwan et al. [32]	--	Parabolic trough collectors	To examine the probable adjustments of a gas turbine tri-generation plant via combining it with a parabolic trough collector for producing electricity, chilled water, and freshwater	--	-Productivity of 45,461 m^3/day -Fresh water production cost of 0.8 USD/m^3
Ziyaei et al. [51]	24 flashing stages MSF unit	Parabolic trough collectors	To develop a dynamic simulation and carry out a life cycle cost analysis for an MSF plant powered by solar parabolic trough collectors using TRNSYS software	-Seawater temp. of 25 °C -Seawater salinity of 42,000 ppm -TBT of 106 °C	-GOR of 7.18 -Fresh water production cost varies between USD 2.21/m^3 and USD 4.32/m^3
Al bkoor Alrawashdeh et al. [52]	24 flashing stages MSF unit	Poly PV array	To develop a model to examine the performance ratio of MSF powered by a solar energy source utilizing a poly PV array type	-Seawater temp. of 25 °C -Seawater salinity of 42,000 ppm -TBT of 110 °C	-Productivity of 63.3 kg/s -GOR of 10.3
Yadav et al. [53]	3 flashing stages MSF unit	Solar evacuated tubes	To design an MSF system to desalt geothermal water and produce potable fresh drinking water using solar evacuated tubes as the main heating source	-Geothermal temp. of 40 °C -Water salinity of 4205 ppm -TBT of 143.5 °C	-Productivity of 0.66 kg/s -Fresh water production cost of 0.1034 USD/m^3

4. RO Desalination and Renewable Energy

Reverse osmosis (RO) is a prominent membrane-based technology for water desalination, wastewater treatment [68], and the food and beverage industry [69]. As a unique method for excluding organic and non-organic micro-pollutants and delivering drinking water of the upmost quality, semi-permeable membranes are used in the RO process. Despite RO offering several advantages, it faces fouling issues as its major challenge [70]. Fouling can happen as a result of accumulating dissolved particles on the membrane surface, which decreases the water permeation rate. In turn, this would increase the power consumption, with a greater maintenance cost [71] and reduced water production rate.

A practical and forward-thinking method for tackling global water scarcity and energy sustainability is the integration of the RO process with renewable energy systems. The water desalination process is environmentally friendly and useful when it works in combination with renewable energy sources. Photovoltaic systems, which capture solar energy, deliver a plentiful and pure power supply for RO plants, especially in areas with high solar radiation. Specifically, geothermal energy delivers a dependable power source in areas with suitable geological characteristics. Similarly, wind energy aids in constructing water desalination plants, especially in coastal areas. The increased application of these integrated systems is a feasible option for accomplishing global energy and water security, helping sustainable growth and lessening the influences of climate change [72]. Li et al. [73] emphasized that these combined systems are most cost-effective and can overcome the issue of the intermittence of solar energy. Li et al. [73] estimated that solar desalination combined with another renewable energy could be a good option for future desalination facilities due to the cost discount of ground-breaking solar technologies.

The next sections deliberate on the combined systems of RO-based water desalination and renewable energy sources of solar energy, wind energy, and geothermal energy.

4.1. Solar Energy—RO

A small-scale 2 kWp PV system and two-stage arrangement of a brackish water RO desalination system were manufactured by Alghoul et al. [74], as signified in Figure 9. This study intended to measure how climatic design and operational parameters affect the performance and longevity of a PV–brackish water RO desalination system. Different membranes such as SW30HRLE4040 and SW30XLE400i were utilized in this round of analyses to realize which one used the minimum amount of electricity and generated identical levels of product water flowrate. In this respect, the desalination system contained a photovoltaic (PV) power system and a brackish water RO unit. The PV system contained multi-crystalline PV modules, a charge controller, batteries, a converter, and communication modules. The brackish water RO system contained a pressure vessel, membrane module, a high-pressure pump, filtration unit, and an anti-scalant dosing unit. Furthermore, a number of sensors were used to measure the temperature, irradiance, total dissolved solids (TDSs), pH, pressure, and flowrate. Alghoul et al. [74] stated that 5.1 m^3 of freshwater could be produced from the RO system over 10 operation hours with 50 ppm of product water salinity, which required 1.1 kWh/m^3 of specific energy consumption. However, the operational parameters were the pump pressure of 8.3 bar and brackish water salinity of 5000 ppm.

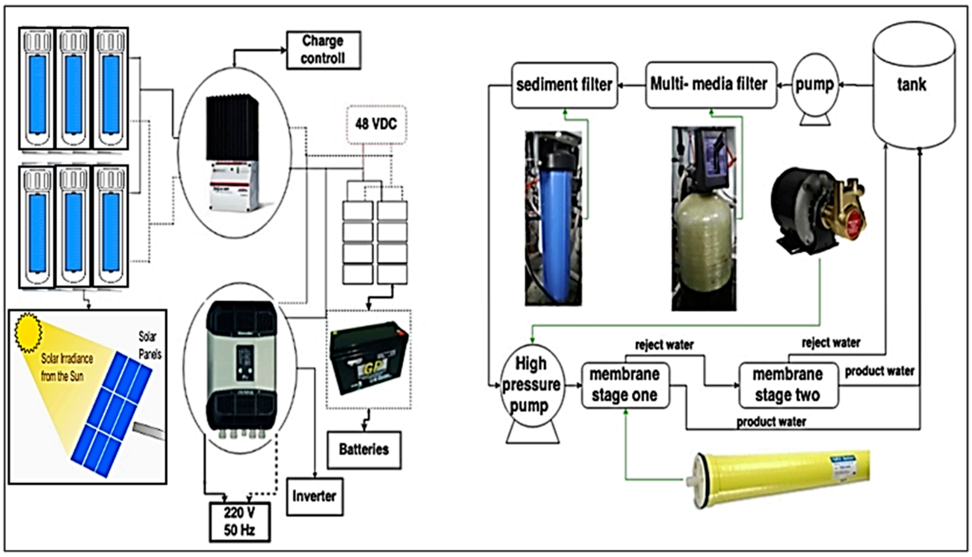

Figure 9. A representation of PV-RO systems (adapted from Alghoul et al. [74]). Reprinted/adapted with permission from Ref. (Alghoul et al. [74]) 2024, Elsevier.

A simultaneous evaluation was carried out by Mostafaeipour et al. [75] to measure the consistency of electricity and costs in an off-grid photovoltaic unit integrated into an RO water desalination plant in nine districts of Bushehr Province in Iran. The outcomes showed that the PV units were economically and technically viable. They found that the fuzzy time functions improved the off-grid PV system's reliability over that of basic methods. Figure 10 shows the PV-RO system, including 12 RO units, a motor, a high-pressure pump, energy storage batteries, and PV panels. Two kinds of RO units were designed, with and without an energy recovery device (ERD). The RO unit with ERD was the most effective combination.

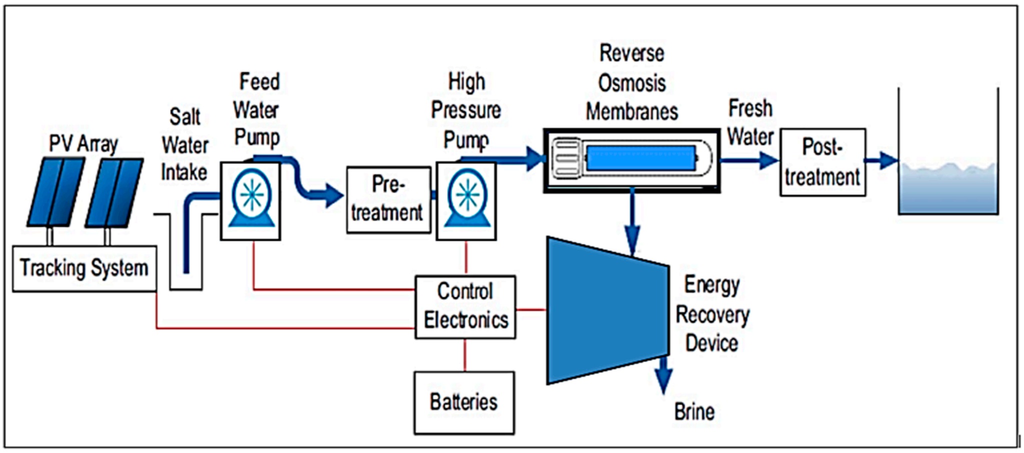

Figure 10. A representation of PV-RO desalination system with an ERD (adapted from Mostafaeipour et al. [75]). Reprinted/adapted with permission from Ref. (Mostafaeipour et al. [75]) 2024, Elsevier.

Karavas et al. [76] considered a standalone small-scale seawater RO desalination system, powered by PV for installation on a typical island in the Cyclades complex, with a productivity of 20 m^3/month. The intention of this investigation was to determine the most-efficient economic and technical configuration of system components for its independent operation. As shown in Figure 1, a small-scale seawater RO desalination system contains a feed water pump, filtration unit, ERD, and membrane powered by a PV system. Five scenarios were chosen to determine the most efficient system. The PV–seawater RO desalination unit needed energy storage in the first two scenarios. The desalination system operated at a minor load in the first scenario and variable load by following PV power in the second scenario. The PV–seawater RO desalination unit had a battery bank in the next three scenarios. The most efficient system was the one designed in the fifth scenario, as it had the lowest cost and the lowest power losses compared to the other reverse osmosis (RO) plant scenarios.

Abdelgaied et al. [77] conducted a mathematical study on the effects of a pre-heating approach on the energy consumption of an RO system. Abdelgaied et al. [77] focused on reducing the energy consumption in RO units equipped with ERDs. Additionally, the study intended to develop a standalone desalination system driven by renewable energy for isolated areas. The suggested system (Figure 11) comprised solar PV panels with a thermal recovery system, a solar dish concentrator with a solar thermal receiver, and an RO unit with an ERD. Four PV panels (350 W each) connected in parallel generated electricity for the RO unit. Flat-plate thermal collectors positioned beneath the solar PV panels cooled the panels to enhance electricity generation and preheat the feed water before it entered the solar thermal receiver of the solar dish concentrator. The solar dish condenser employed aluminum reflectors (reflectivity 0.83), while a hollow copper spiral coil in a truncated conical shape served as the solar thermal receiver at the focal point of the solar dish condenser. This two-stage solar preheating system raised the feed water temperature before it entered the RO unit, resulting in increased permeate water production and reduced electrical power consumption. The study of Abdelgaied et al. [77] demonstrated that the power consumption of the RO desalination system decreased by 18.69% to 22.87% when treating seawater and by 24.33% to 35.79% when treating brackish water, compared to a conservative RO unit without preheating.

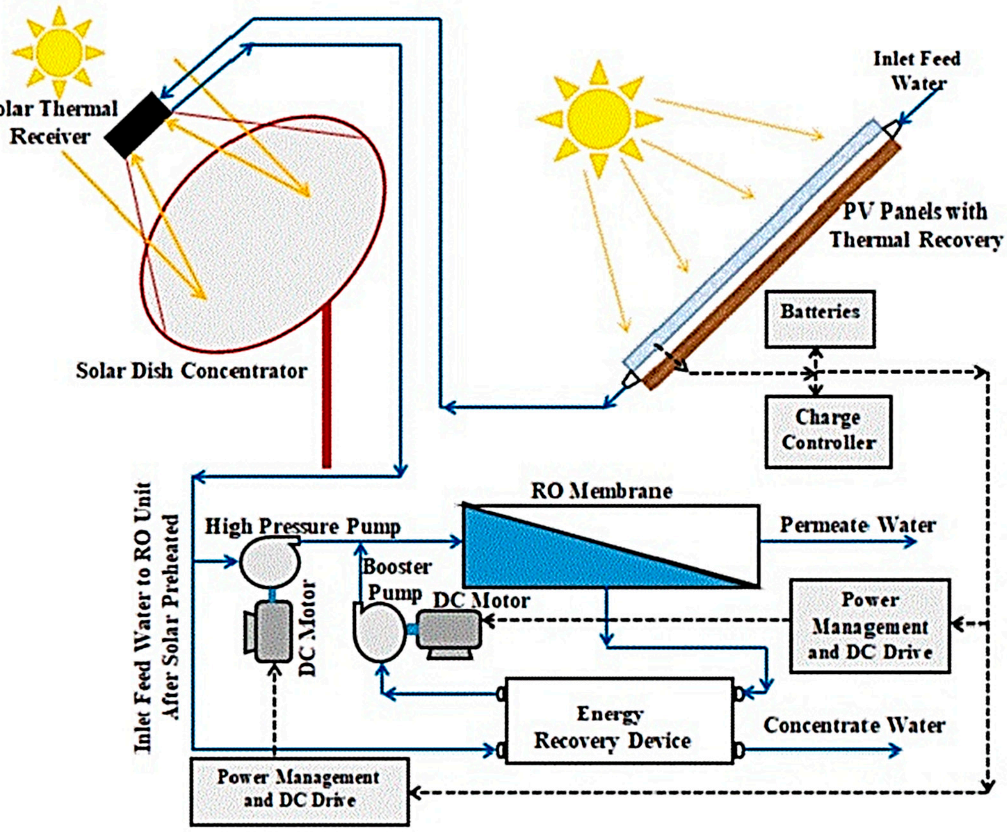

Figure 11. A representation of hybrid PV-driven RO desalination unit (adapted from Abdelgaied et al. [77]).

4.2. Wind Energy—RO

Wind energy is a mature renewable energy source for power production, with commercial turbines available for a variety of nominal power. Wind turbines can supply electrical power for desalination plants [78].

Wind-powered desalination systems are one of the most common renewable desalination plants in seaside areas with substantial wind energy [79]. Desalination employing wind energy has the lowest environmental impact of all other renewable energy sources [80].

Several investigations in the available literature examined the efficiency of wind turbines in a hybrid system combining wind turbines and RO-technology-based water desalination. Overall, wind-powered RO plants seem to be a highly promising option for desalination employing renewable energy. This is attributed to RO having the lowest energy demands among desalination processes [68,81,82].

Carta et al. [83] examined the efficiency of an RO system driven by wind energy and determined the impact of fluctuations in wind conditions. They noted that variations in the supplied electrical power, caused by alterations in wind, resulted in fluctuations in the pressure of feed water. However, these fluctuations could be reduced by employing a pressure stabilizer or wind turbine de-rating. Moreover, they suggested an alternative approach to lessening the variability caused by the alternating nature of wind. They confirmed that various control systems can be implemented in RO units utilizing stabilizers and driven by wind turbines.

Alsarayreh et al. [84] studied the feasibility of an integrated wind turbine and RO desalination system of APC (Arab Potash Company) (Figure 12). They verified the feasibility of this hybrid system, as a single wind turbine was capable of affording the necessary electricity for the RO system. Nonetheless, a group of fifty-one wind turbines was required to power the RO plant during occasions with a low wind speed.

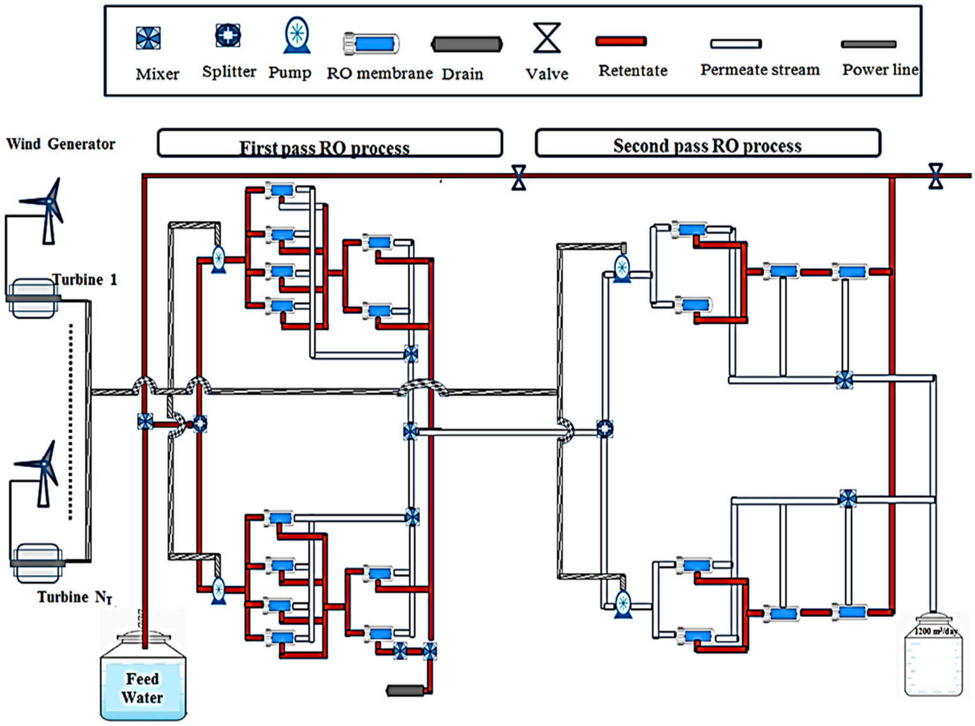

Figure 12. A representation of brackish water RO plant of APC driven by wind turbine system (adapted from Alsarayreh et al. [84]).

4.3. Geothermal Energy—RO

Geothermal energy is a promising renewable energy source that can be harnessed to produce electricity for desalination plants. Notwithstanding its imperfect commercial adoption, geothermal energy delivers several benefits for addressing water scarcity and decreasing fossil fuel consumption. Geothermal energy is environmentally friendly, as it does not emit air toxins or greenhouse gases. It offers a stable and reliable heat source, making it the best option for thermal desalination and RO processes. By utilizing geothermal energy, fossil fuels can be well-preserved for other demands. Also, geothermal energy is well-organized and cost-effective, making it a useful choice for sustainable desalination [85]. On top of this, it is fair to clarify that solar and wind energy are not continuous, which means that they demand complex collection mechanisms and expensive energy storage devices. Furthermore, these storage devices are inhibited in terms of their size, making it challenging to enlarge them for large-scale facilities. All of these unwelcome influences have not been detected in geothermal energy systems [86].

Assad et al. [87] presented a dry steam geothermal power plant used to power an RO seawater desalination system. Specifically, the dry steam system was used to drive the pumps of the RO unit. The single-stage single-pass configuration of RO links to a pressure exchanger was used to desalinate feed seawater of 48,787 ppm salinity at a total energy consumption of 3.3 kWh/m^3, total productivity of 450 m^3/day, and 335.58 ppm product water salinity. In this regard, the geothermal energy system was designed for 350,400 kWh/year of electricity. The optimization yielded a mean electrical output of 40 kW and auto-size backup generator rating of 98 kW. Accordingly, the dry steam geothermal energy system was able to satisfy the electrical requirements of RO units.

4.4. Solar Energy and Wind Energy—RO

Mokheimer et al. [88] modelled, simulated, and optimized a solar–wind hybrid RO desalination plant. The proposed integrated plant was tested in Saudi Arabia while considering the weather data of a typical year. The simulation introduced the optimum system for powering a 1 kW RO system for 12 h/day and 24 h/day at the lowest average costs of energy. Specifically, the optimal design consisted of two wind turbines, forty solar panels, and six batteries, with an average levelized cost of energy of 0.624 USD/kW h. Also, the optimum design for a demand of 1 kW for 24 h/day consisted of 66 PVs modules, 6 wind turbines, and 16 batteries with 0.672 USD/kW h as the lowest levelized cost of energy. The desalination process required between 8 and 20 kWh/m^3 of energy referring to the raw water salinity.

Sigarchian et al. [89] designed a small-scale unit of a hybrid PV/wind/engine energy scheme to deliver electricity and clean water for one thousand people. The emphasis of this research was to design a moveable container as an alternative module to deliver freshwater and electricity for catastrophe circumstances. The hybrid PV/wind/engine-energy-powered RO desalination unit contained the following constituents: a wind turbine with a rated power of 1 kW, 22 solar PV modules with a rated power of 5 kW, a diesel generator with a rated power of 1.5 kW, 6 batteries (12 V, 200 Ah), and 200 RO units, as depicted in Figure 13. The system was modelled using TRNSYS, analyzing its performance throughout one operational cycle while considering two geographical locations of comparatively high-solar insolation. The simulation results demonstrated that solar energy contributes 63% and 80% of power generation in Nairobi in Kenya and Nyala in Sudan, respectively. However, wind power is responsible for 27% and 12% of power generation in these two cities. To guarantee the dependability and accessibility of power supply, a control algorithm was implemented.

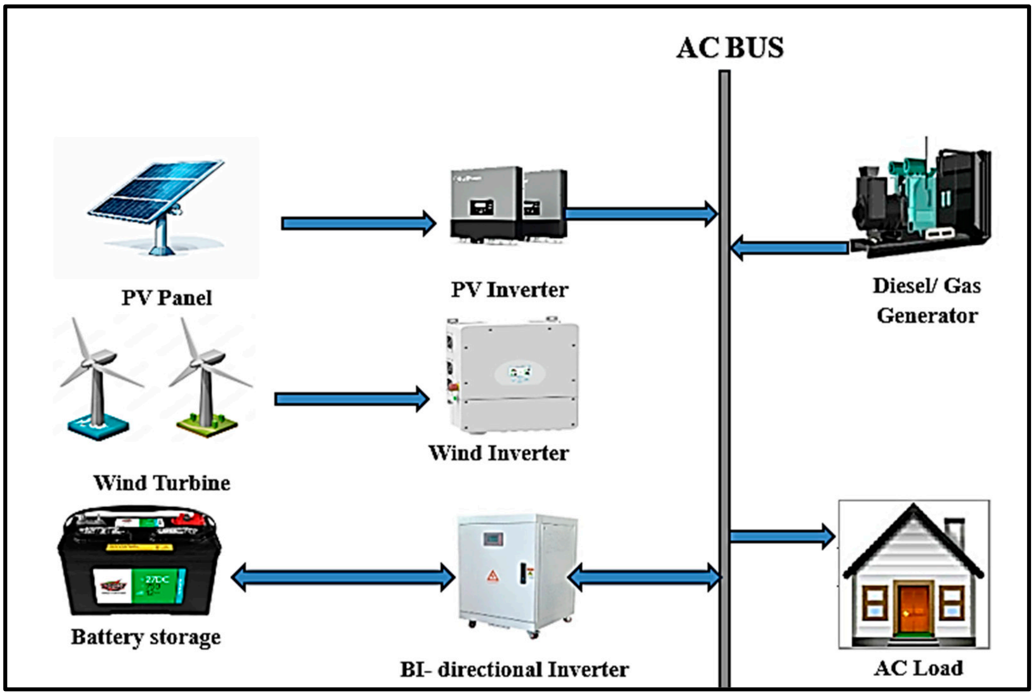

Figure 13. A representation of the hybrid PV/wind/engine energy scheme (adapted from Sigarchian et al. [89]).

Gökçek [90] assessed the operations of seven different (off-grid) power systems that contained PV–wind turbine–diesel generator batteries and a converter utilized to meet the electrical energy request of an RO unit with 24 m^3/day of daily productivity. Figure 14 displays a schematic diagram of the overall RO desalination system. The researchers used HOMER software (HOMER energy, (n.d.). https://homerenergy.com/index.html; Accessed Date: 14 February 2024) to find the best combination of power systems that ensured the energy request of the RO system. The findings assured the economic feasibility of the presented hybrid power system. According to the simulation results, the optimum hybrid power system for operating the RO system was found to be the PV–wind–diesel hybrid system with a storage battery. This particular configuration consisted of one wind turbine, PV panels of 20 kW with a rated power of 10 kW, a 8.90 kW diesel generator, a 7.35 kW converter, and a 120 kWh LA battery.

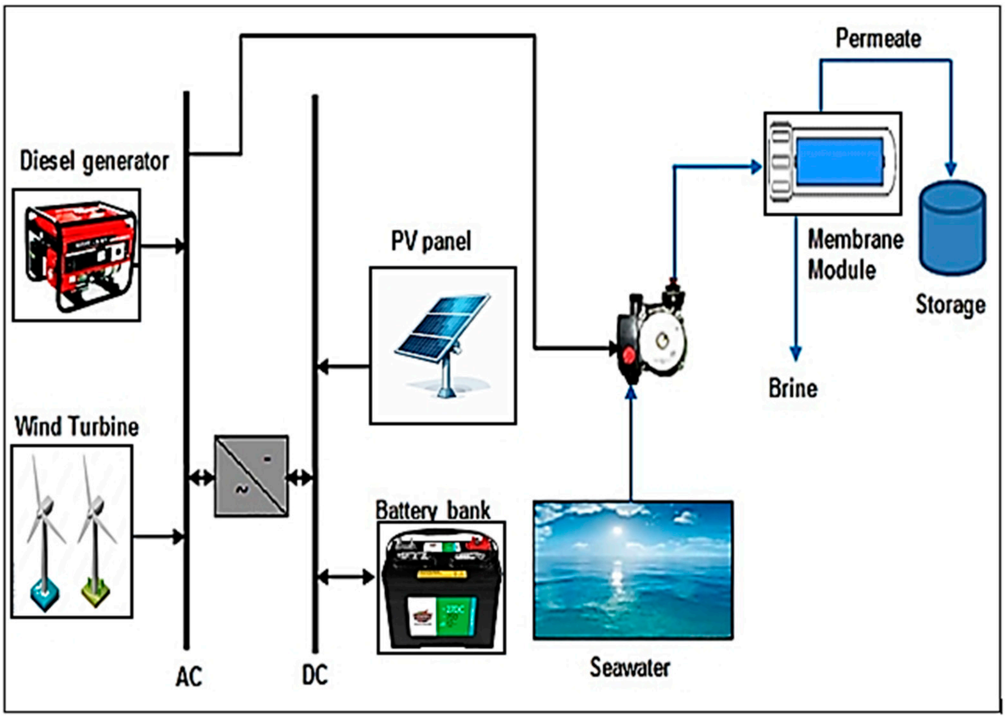

Figure 14. A representation of PV–wind–diesel–battery RO system (adapted from Gökçek [90]). Reprinted/adapted with permission from Ref. (Gökçek [90]) 2024, Elsevier.

Mito et al. [91] designed, modeled, and optimized an integrated solar–wind renewable system to produce electrical energy and fresh water for isolated islands. Mito et al. [91] considered various desalination techniques, including RO, with a critical evaluation to invent the optimal technique in terms of cost and technical characteristics. The model-based simulation results showed that the hybrid electric and water supply system, integrating RO desalination, was the most cost-effective decision. Additionally, the system that depended on RO desalination had the supreme proportion of renewable energy integration and the lowest levelized cost of energy. Mito et al. [91] also planned to govern the optimal arrangement of the components. In the case of an emergency, a diesel generator operated as a backup. The simulation indicated that the optimum total of 20 installed capacities for the RO-based desalination were 500 kW, PV panels of 100 kW, and wind turbines of 3000 kW.

Leijon et al. [92] experimentally analyzed an RO desalination system driven by a hybrid system, including wave and solar power. The results demonstrated that an increase in the quantity of wave energy converters would increase the production of both energy and freshwater. However, this would cause an increase in the total system costs along with an increase in power surplus production. Thus, it was concluded that wave energy integrated with PV panels can be considered as a desalination power source, with or without a battery storage.

Ali et al. [93] introduced a mathematical model that implemented an energy management system for an RO desalination unit. The RO unit was driven by a combination of PV and wind turbine sources. The model was designed for off-grid communities that are lacking a source of fresh water. Pump sizing and water/power management were shown to be strongly related. The simulation findings indicated that the energy management system could be used by increasing the brackish water storage tank capacity and enhancing the system energy efficacy. Figure 15 presents a representation of the hybrid system. The system was powered by a direct current (DC) bus with variable power generation (Pdc) based on wind speed and solar irradiation conditions, without the use of battery storage.

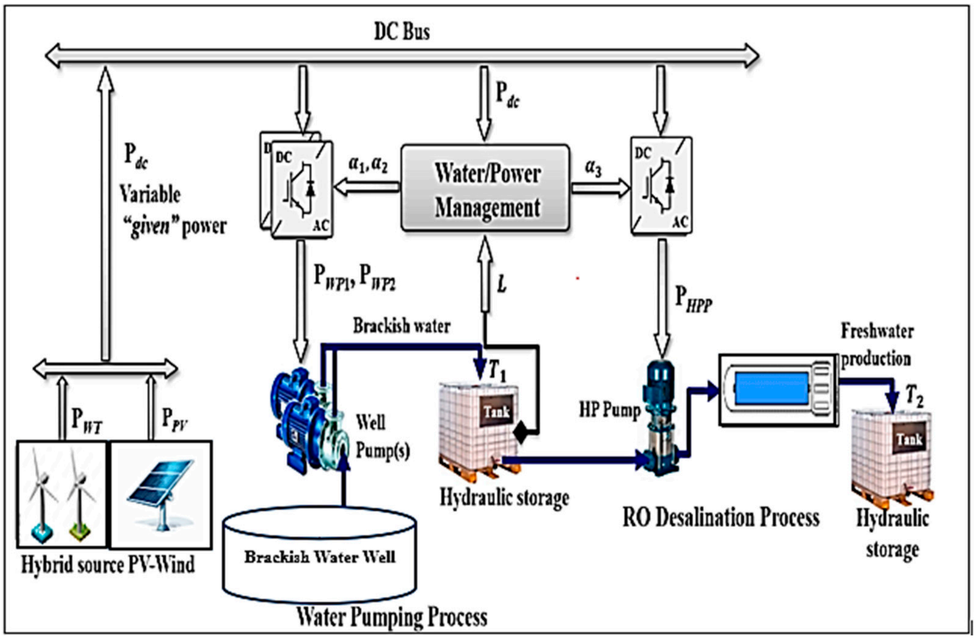

Figure 15. A representation of brackish water RO desalination system (adapted from Ali et al. [93]). Reprinted/adapted with permission from Ref. (Ali et al. [93]) 2024, Elsevier.

Ghaithan et al. [94] used a multi-objective optimization model to allocate the optimal size of a wind–PV grid-connected system. This system was designed to fulfil the energy needs of an RO unit. The first objective function of the optimization was to minimize the total life cycle cost. The second objective function was to mitigate the emissions of greenhouse gases from the presented system. Figure 16 presents a diagram of the hybrid power system integrated with the RO units. It should be noted that the grid was hosted as an auxiliary source of energy to substitute any shortages in the produced energy of renewable energy systems. The findings showed that the overall capacity of the integrated system was 800 m^3/day within 3 kWh/m^3 of specific energy consumption.

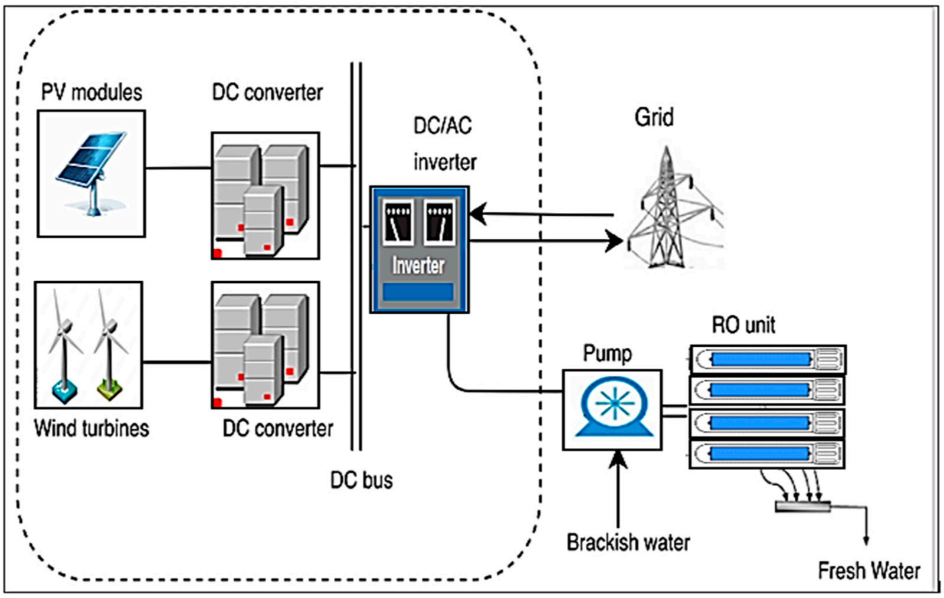

Figure 16. A representation of the PV–wind system coupled with an RO unit (Adapted from Ghaithan et al. [94]).

Ba-Alawi et al. [95] developed a new coordinated sizing model for a solar/wind-powered RO desalination plant and optimized the overall design using a follower–leader optimization framework with and without the attention of demand-side water management (DSWM). As shown in Figure 17, the system consisted of wind turbines and PV panels for electricity generation, a battery bank for excess electricity storage, an RO unit for seawater desalination and freshwater production, and storage tanks for freshwater. Notably, a hydrogen storage system was incorporated to store surplus electricity at the end of each day as a long-term storage solution. The PVs and WTs primarily powered the RO system, with any excess electricity being stored in an integrated battery–hydrogen storage (B-HS) system.

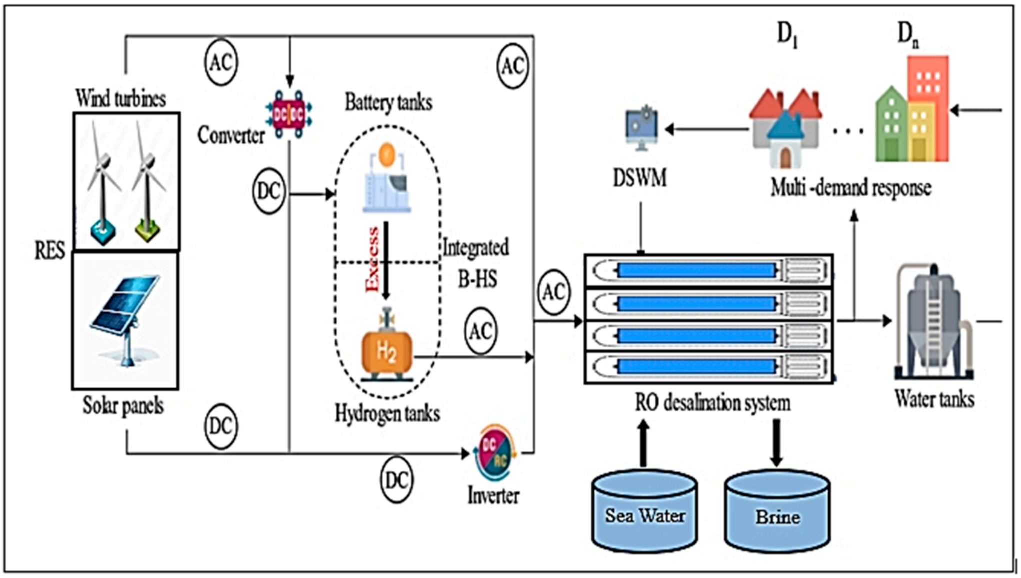

Figure 17. A representation of the renewable-energy-powered RO configuration (adapted from Ba-Alawi et al. [95]). Reprinted/adapted with permission from Ref. (Ba-Alawi et al. [95]) 2024, Elsevier.

Using a multi-objective genetic optimization algorithm, the established coordinated sizing approach supported by DSWM can assist in optimizing the size of the renewable energy–RO system, causing a noteworthy cost decrease, flexible request fulfilment, reduced emissions, and greater sustainability. The optimization results indicated that the scenario with DSWM integration required a smaller quantity of PVs (18 WTs and 30 PVs) in comparison to the scenario without DSWM incorporation (18 WTs and 30 PVs). The integration of DSWM in the case study resulted in a reduced size of the key parameters related to the RO unit, including the power capacity, inlet feed water flowrate, vessels, and elements. This reduction indicated an improved efficiency and decreased costs in comparison to the scenario where DSWM was not integrated.

4.5. Solar Energy and Geothermal Energy—RO

Shalaby et al. [96] considered the efficiency of an RO desalination unit driven by a combination of PV/geothermal energy. The RO unit was assessed at various salinities of brackish water while implementing the pre-heating practice of the geothermal unit. The PV integrated with the geothermal system was linked to a DC motor-powered pump to power the RO desalination unit (Figure 18). The system contained three matching PV panels of a rated power of 0.25 kW, 37 V, and 9 A and a length and width 1.6 and 1.00 m, respectively. Each panel was bordered by an aluminum frame of 3 cm thickness. The capacity of the RO unit was 600 gallons per day of drinking water. The RO unit contained four stages. The researchers installed and tested two cooling methods fixed on the back surfaces of two PV panels of 0.25 kW. This was an attempt to improve the efficacy of the PV panels to power the RO system. The findings indicated that the presented PV–geothermal RO desalination plant could produce 366 L per a day if the supplied brackish water had 3000 ppm of salinity.

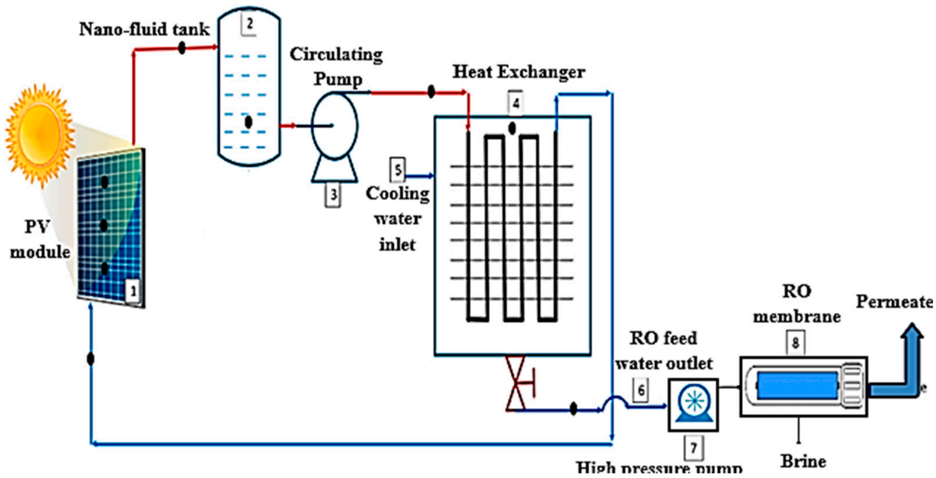

Figure 18. A representation of the PV integrated with the geothermal system and RO unit (adapted from Shalaby et al. [96]). Reprinted/adapted with permission from Ref. (Shalaby et al. [96]) 2024, Elsevier.

Bacha et al. [97] proposed an RO desalination system prepared with an ERD, PV/thermal panels, and a geothermal energy extraction unit (Figure 19). The researchers planned to evaluate the effectiveness of the system by inspecting three combined units. The feed water was initially pre-heated in the thermal recovery device of the PV/thermal panels, as well as by two cooled PV panels, to augment the electricity generation performance. Afterward, the feed water was further heated using geothermal energy to raise its temperature before being pumped into the RO desalination system, which used a pressure exchanger (PX) as an ERD. The experimental results proved that the suggested integration boosted the water productivity and decreased the specific energy consumption. Statistically, the average reduction in energy consumption attained was 29.1% for seawater and 40.75% for brackish water. Also, the economic examination specified that the cost savings in freshwater production could extend up to 39.6%.

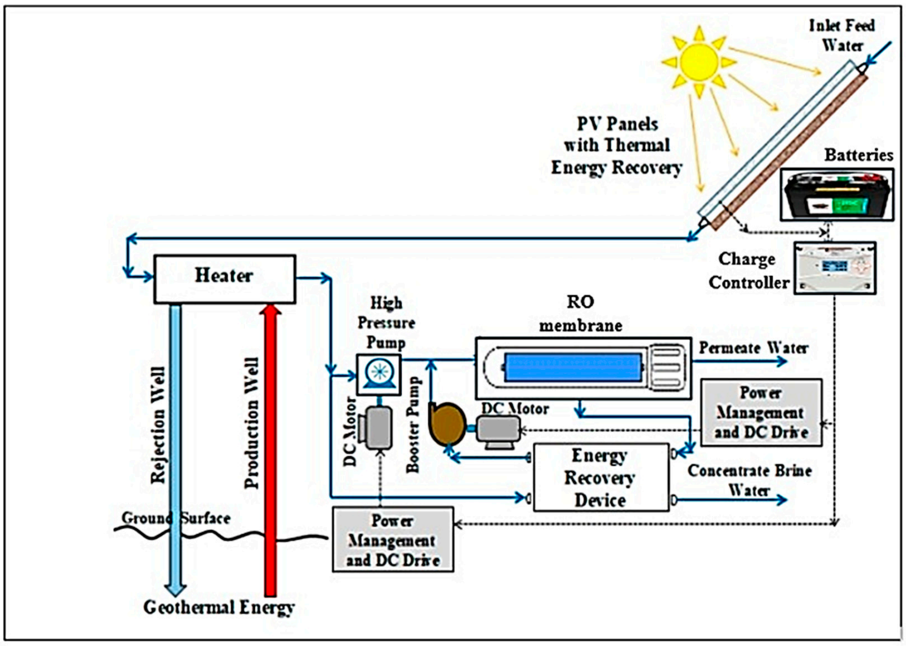

Figure 19. A representation of the proposed RO desalination cycle (adapted from Bacha et al. [97]).

Table 2 presents a summary of the directed studies of seawater and brackish water RO desalination processes powered by renewable energy systems.

Table 2. A summary of conducted investigations on hybrid RO desalination and renewable energy systems.

Authors (Year)	RO Process Design	Renewable Energy Process Design	Operating Conditions	Results	Advantages	Disadvantages
Alghoul et al. [74]	A small-scale BWRO unit	2 kWp PV system	-Water salinity of up to 2000 ppm -Feed pressure of 8.3 bar	-5.1 m^3 of fresh water for 10 h a day -Specific energy consumption of 1.1 kWh/m^3 -Permeate salinity of less than 50 ppm -The initial investment cost of the PV–brackish water RO system is around USD 30,000	PV–RO-systems-based brackish water can be assumed as a favorable desalination option in isolated areas	-It was established that there are numerous hours when the PV module operates at high temperatures (above 45 °C) and in the battery room (above 35 °C), both of which have the potential to have a detrimental impact on power production and battery autonomy
Mostafaeipour et al. [75]	RO desalination system in districts of Bushehr, Iran	PV unit	-Seawater salinity of 39,600 ppm -Feed flow rate of 8.33 m^3/h	-Maximum and minimum productivity of 228 m^3/day and 148 m^3/day, respectively, for Daylam Port -Specific energy consumption of 0.83 kWh/m^3 -The cost of production per cubic meter of fresh water is approximately USD 2.43 -The freshwater production cost of PV–RO desalination systems in different areas ranges between 1.96 and 3.02 USD/m^3.	-PV cells are much cheaper than diesel generators in spite of the higher initial investment costs -The system reduces CO_2 emissions and the dependability on the import of fossil energy sources	---
Karavas et al. [76]	A small-scale seawater RO, island in Cyclades, Aegean sea, Greece	PV system	-Feed pressure of 42 bar -Feed flow rate of 3.333 m^3/h	-Productivity of 20 $m^3/month$ -The freshwater production cost can be up to 2.18 EUR/m^3	The PV–RO system presents a promising solution for water scarcity, offering both economic viability and environmental sustainability	
Abdelgaied et al. [77]	A standalone RO desalination system in remote areas with an ERD	PV–geothermal energy	-Feed pressure of 150 kpa -Brackish water salinity of 2000 ppm -Seawater salinity of 40,000 ppm -Water temperature of 30 °C -Feed flow rate of 1.4 m^3/h	-Specific energy consumption of 0.475 kWh/m^3 -The freshwater production cost of the hybrid system of PVT-driven RO desalination unit integrated with a solar dish concentrator is calculated to be 1.07 USD/m^3 -The economic analysis depicts that the utilization of solar dish concentrators as preheating units reduced the freshwater cost by 33.1% compared to other desalination plants	Incorporating solar pre-heating units significantly reduces the specific power consumption of the desalination system. This reduction ranges from 24.33% to 35.79% for brackish water treatment and 18.69% to 22.87% for seawater treatment	The salt concentration permeation rate is significantly higher (between 490 and 510 ppm) when using geothermal pre-heating units, compared to only 170 ppm without pre-heating

Table 2. *Cont.*

Authors (Year)	RO Process Design	Renewable Energy Process Design	Operating Conditions	Results	Advantages	Disadvantages
Assad et al. [87]	A single-stage single pass RO system integrated with a dry steam geothermal energy system	A dry steam geothermal energy system	-Seawater salinity of 48,787 ppm -Feed flowrate of 31 m^3/day -Feed pressure of 74.96 bar	-Specific energy consumption of 3.33 kWh/m^3 -Product salinity of 335.85 ppm -Productivity of 450 m^3/day	-The existence of a pressure exchanger reduces the specific energy consumption from 6.51 kWh/m^3 to 3.33 kWh/m^3.	The study has not provided detailed information for utilizing the dry steam of geothermal energy system
Mokheimer et al. [88]	A standalone RO desalination plant in Saudi Arabia	-Hybrid wind/solar-powered RO desalination plant -1 to 10 wind turbines with rated power of 1 kW each -1 to 400 of PV modules with rated power of 50 W each	-Seawater temperature of 25 °C. -Solar radiation: 1000 W/m^2	-Max. power output for PV module of 50 W -The freshwater production cost of the hybrid wind/solar system ranges between USD 3.693/m^3 and USD 3.812/m^3	The optimized design of the proposed hybrid wind/solar system significantly reduces the cost of freshwater production	-Solar energy can be effectively utilized for water desalination, but it requires backup systems to ensure continuous operation -The intermittent nature of solar energy generation poses challenges, necessitating quick-start backup units to compensate for shortfalls or absorb excess energy production
Sigarchian et al. [89]	A small-scale RO system in Sudan	-Hybrid PV/wind/engine energy-powered RO desalination system that is designed in a parallel configuration with AC coupling -22 solar PV modules with a rated power of 5 kW -A wind turbine with a rated power of 1 kW -A diesel generator with a rated power of 1.5 kW		-Provide electricity and drinkable water for 1000 individuals in disaster situations	The hybrid system addresses environmental concerns compared to relying solely on diesel engines, a common solution in disaster scenarios	-Parallel configurations offer advantages over series configurations but requires a well-designed energy management system and a more complex control system

Table 2. *Cont.*

Authors (Year)	RO Process Design	Renewable Energy Process Design	Operating Conditions	Results	Advantages	Disadvantages
Gökçek [90]	Small-scale RO system in Turkey	Wind/PV of the various off-grid power systems	-Seawater salinity of 37,864.4 ppm -Wind speed has a range of 4.78–7.35 m/s -Solar radiation varies between 1.56 $kWh/m^2/day$ and 7.80 $kWh/m^2/day$, and its annual average value is 4.62 $kWh/m^2/day$	-A capacity of 24 m^3/day -The freshwater production cost is estimated to be USD 2.20/m^3.	The study demonstrated that utilizing a hybrid power system instead of a diesel generator resulted in a substantial 90% reduction in annual carbon dioxide (CO_2) emissions	-This study focused on assessing the operational emissions of the hybrid power system, excluding the emissions related to the manufacturing of the equipment used
Mito et al. [91]	RO system	Hybrid solar-wind renewable system		-The plant capacity: 4800 m^3/day -Optimum total 20 installed capacities for RO-based desalination are 500 kw, PV panels of 100 kW, and wind turbines of 3000 kW	-A hybrid power and water supply system with RO desalination is the most cost-effective option -The RO desalination system has the greatest renewable energy penetration and lowermost energy cost. This will reduce environmental consequences and improve cost affordability	-While it is mathematically feasible to eliminate or minimize capacity shortages, this approach would result in a substantial increase in project expenses
Leijon et al. [92]	Brackish water RO system in Kenya	A hybrid solar and wave desalination system	-Seawater salinity of 4000 ppm Minimum and maximum feed pressure of 8.4 bar and 16.2 bar, respectively -Water temperature of 20 °C	-Capacity of 24 m^3/day -Maximum power output of 7 kW -Product water salinity of 433.93 ppm. -Specific energy consumption of 4.38 kWh/m^3	Increasing the quantity of wave energy converters increased the production of freshwater. However, this results in a higher total system cost and an increase in the power surplus production	Wave power is still in a pre-commercial state
Ghaithan et al. [94]	Brackish water RO desalination plant in Saudi Arabia.	A hybrid solar–wind energy and grid-connected system of 100 photovoltaic modules and 94 wind turbines	-Seawater temperature varies between 10 °C and 42 °C -Standard solar radiation of 1000 W/m^2	-Productivity of 800 m^3/day -Specific energy consumption of 3 kWh/m^3 -The freshwater production cost is USD 1.572/m^3, USD 1.911/m^3 and USD 1.639/m^3 for the first, second, and third plant, respectively	The energy shortfall of the RO system is met by the utility grid and, to some extent, by the wind turbine system	Significant energy shortages occur during April, May, August, and October due to either limited renewable energy resources or high energy consumption

Table 2. *Cont.*

Authors (Year)	RO Process Design	Renewable Energy Process Design	Operating Conditions	Results	Advantages	Disadvantages
Ba-Alawi et al. [95]	RO system	A hybrid system of PV–wind	Feed flow rate of 9.537 m^3/h	-The integration of distributed seawater membrane (DSWM) technology has led to significant improvements in various aspects of the system's performance -Compared to the scenario without DSWM, the total annual cost, total environmental cost, scheduling profit, and potential loss of power supply probability are enhanced by 5.37%, 32.4438%, 57.9311%, and 23.78%, respectively	-The integrated sizing model that takes into account DSWM can aid in optimizing the sizing of renewable energy–RO systems, ensuing in noteworthy cost savings, adaptive demand satisfaction, lower emissions, and a higher level of sustainability	To address the constraints of short-term battery storage in power storage systems, long-term energy storage is necessary to enable flexible electricity loading
Shalaby et al. [96]	RO desalination system in Egypt	PV–geothermal energy	-Productivity of 600 gallons /day of freshwater -Feed Temp.: 30 °C -PV cells of 0.25 kW	-Salt rejection of 97% -Product water flow rate of 300 L/day -The freshwater production cost is reported to be in the range of 0.74–1.12 USD/m^3	The benefits of the geothermal pre-heating of the feed water are particularly evident when the salinity of the water is high. Additionally, the proposed PV–RO desalination system has a high potential for commercialization due to its ability to produce fresh water at a very low cost	Geothermal water is not available in all locations with the existence pf a number of influential parameters. In turn, this would limit the viability of integrating RO systems with geothermal energy systems in some districts
Bacha et al. [97]	RO desalination unit with an energy recovery device	A hybrid system of PV–geothermal	-Feed water flow rate of 1.4 m^3/h -Feed water temperature of 25 °C	-Reducing the energy consumption rates by 29.1% for seawater treatment and 40.75% for brackish water -The freshwater production cost was found to be 0.966 USD/m^3.	-An improvement of the water productivity of RO plants, in addition to dropping their specific energy consumption compared to traditional technologies	High exploration costs, high investment risk, and high installation costs are the most highlighted disadvantages

5. MED Desalination and Renewable Energy

Multi-effect distillation (MED) uses low-temperature heat and pressure for water distillation [40]. To sustainably meet the increasing demands for drinking water, it is essential to integrate MED systems with renewable energy sources, including solar, wind, and geothermal energy. Using renewable energy sources to run MED systems will expressively lessen the dependence on fossil fuels and decrease the environmental impact of old-fashioned desalination technologies. Solar energy is predominantly advantageous for powering MED systems in areas with abundant sunshine, since it delivers consistent, readily available power [98]. Coastal districts where desalination services are regularly situated benefit greatly from wind energy, which assists as a complementary source of energy [99]. Furthermore, geothermal energy, which comes from the Earth's interior heat, offers MED systems with a steady and dependable energy supply, principally in areas where geothermal resources are abundant [100]. Merging renewable energy units with MED systems supports reducing the impact of greenhouse gas emissions and lessening the dependence on finite fossil fuels. This not only recovers energy utilization and depresses running costs, but it also advances the protection of the environment. In general, integrated MED and renewable energy unit systems are imperative, since they can offer economical and sustainable custom content requirements for drinking water in a world that is becoming more and more water-stressed.

5.1. Solar Energy—MED

Iaquaniello et al. [101] suggested a combination of ten aspects of MED and an RO seawater desalination scheme powered by solar energy to lower the overall costs accompanying water production. A concentrating solar power (CSP) system, MED unit, RO unit, and backup gas turbine-based system made up the recommended integrated desalination procedure. A block diagram of the proposed hybrid system is shown in Figure 20. The MED used thermal energy from the CSP system to generate fresh water. The electricity produced from the CSP system and gas turbine drove the RO unit. During times of low solar radiation, the backup system made sure the desalination plant ran continuously. To systematically conduct this study and to assess how well the suggested hybrid desalination technique performed, a thorough model was created. The model explored how different operating factors affected the water production efficiency and the cost. It was ascertained that the operating conditions, including the quantity of solar energy, the system temperature, and the feed water salinity, impacted the suggested technique's performance. The simulation results indicated that the production cost of freshwater amounted to EUR 0.97/m^3. The annual freshwater productivity of the suggested hybrid desalination plant was 6,864,000 m^3. In this regard, the RO unit produced 807 m^3/h of desalinated water, compared to 51 m^3/h from the MED unit. The estimated specific energy consumption of the proposed system was 2.52 kWe/m^3 with a specific CO_2 emission of 1.53 kg CO_2/m^3 of desalinated water. The desalination plant could keep operating, even during periods of low solar radiation, because a thermal storage system was installed.

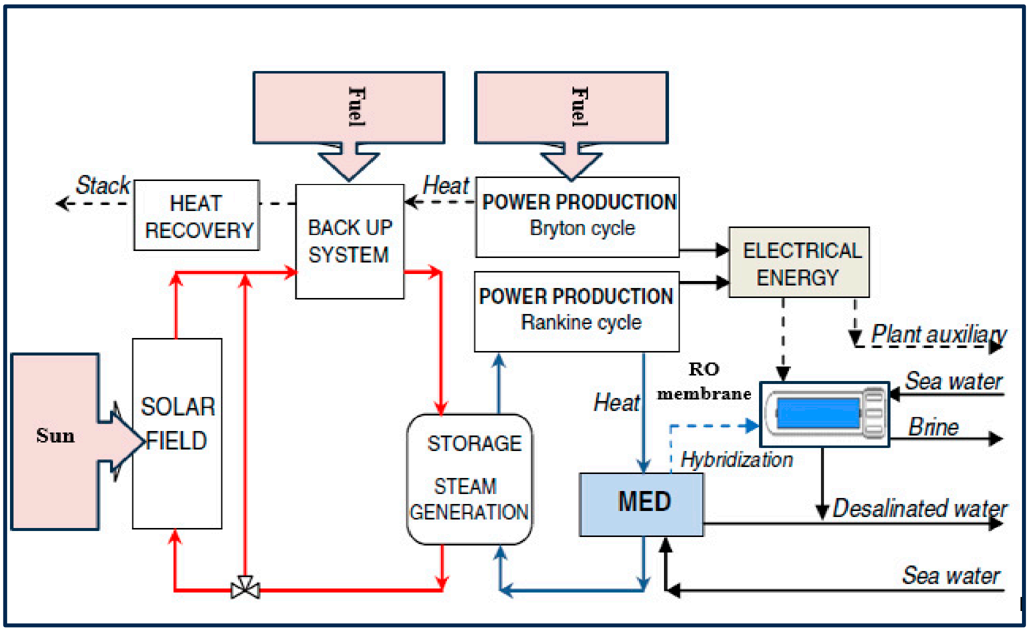

Figure 20. A representation of the integrated MED-RO and CSP (adapted from Iaquaniello et al. [101]). Reprinted/adapted with permission from Ref. (Iaquaniello et al. [101]) 2024, Elsevier.

Weiner et al. [102] developed and analyzed a solar-powered hybrid RO–MED desalination process for the treatment of agricultural wastewater in California. A CSP plant, RO unit, and MED unit made up the hybrid RO-MED system. The MED linked to a thermal vapor-compressor (TVC) unit received thermal energy generated by the CSP plant, while RO and MED auxiliaries received electricity. A specific recovery ratio was reached by desalinating the feed water with the RO unit, and permeate was produced by further desalinating the RO brine with the MED unit. A thermodynamic and economic model of the hybrid system was constructed with the help of the Engineering Equation Solver (EES). The influences of the MED effect number and RO operating flux on the levelized cost of produced water were inspected using a parametric analysis. A grid-powered RO unit and a stand-alone MED were compared to the hybrid system. The simulation results indicated that the levelized water production cost of the hybrid RO-MED could be decreased as the working flux of the RO increased. Therefore, the RO unit could be smaller and cheaper due to a larger RO flowrate. Nonetheless, the specific energy consumption of the RO system increased with the RO flux, interpreting a rise in the levelized water production cost. Also, the levelized water production cost of the hybrid RO-MED system dropped as a result of increasing the number of MED effects. This can be ascribed to generating the required volume of fresh water with less thermal energy if more MED effects were used. In this context, the levelized cost of water increased as a response to increasing the number of MED effects, which required a larger capital cost.

According to the findings, the water production cost with the hybrid RO-MED system was 41% less than that of producing water with a standalone MED system, with a levelized cost of USD 0.45/m^3. Furthermore, it was concluded that the ideal number of MED was five effects, and 18.2 LMH was the ideal RO operating flux.

Askari and Ameri [103] examined the use of a Linear Fresnel (LF) solar field to serve as the heat source for a Solar Rankine Cycle (SRC) coupled to an MED system with parallel feed (Figure 21). The objective was to determine the optimal LF solar field dimensions for two distinct thermal storage durations—six and twelve hours. Along with determining the cost involved in producing water, the study again sought to ascertain the cost of producing electricity in the SRC/MED plant, under several MED unit Gain Output Ratio (GOR) scenarios (9.8 and 12) and for two thermal storage capacities. The SRC/MED plant consisted of two low-pressure and high-pressure turbines, two pumps, a feed water heater (FWH), two LF solar fields, and a condenser that was replaced with a low-temperature MED unit. The SRC ran at 11,000 kPa of pressure and 395 °C of intake temperature during the day and 380 °C at night. The MED unit's GOR was operating from 9.8 to 12. The MATLAB computer tool (https://uk.mathworks.com/support/learn-with-matlab-tutorials.html?gclid=Cj0KCQjwq86wBhDiARIsAJhuphkUQGfTSq2VCm_NG0ljSEEmpqdZWNjkbNMwaYAk0R4WHQfcJuu1QU0aAgSlEALw_wcB&ef_id=Cj0KCQjwq86wBhDiARIsAJhuphkUQGfTSq2VCm_NG0ljSEEmpqdZWNjkbNMwaYAk0R4WHQfcJuu1QU0aAgSlEALw_wcB:G:s&s_kwcid=AL!8664!3!547141034323!b!!g!!mathworks%20tutorials&s_eid=ppc_105516610291&q=mathworks+tutorials&gad_source=1, Accessed Date: 14 February 2024) was used to calculate the hourly output thermal power of the LF solar field. The program computed the hourly defocused fraction, NGB share, fuel usage, Levelized Cost of Water (LCOW), and Levelized Cost of Electricity (LCOE) for the SRC/MED plant. The results showed that the smallest LCOE was found at the identical solar multiple and solar share for both GOR levels (9.8 and 12). On the other hand, the solar field loop numbers of the setup with a GOR of 9.8 were larger than those of the setup with a GOR of 12. In particular, the GOR of 12 (1.91 USD/m^3) for the SRC/MED plant was over 5.5% lower than the GOR of 9.8 (2.01 USD/m^3) for the other plant. This finding suggests that increasing the MED unit GOR from 9.8 to 12 would reduce the number of loops in the solar field by 24%. Also, increasing the TES capacity from 6 to 12 h resulted in roughly 45% and 5% growth in solar share and LCOE, respectively. The plant's LCOW for both GORs was 1.25 USD/m^3 and 1.27 USD/m^3 with 6 h and 12 h of thermal storage, respectively; these values were calculated by discounting the thermal energy costs of water production. The cost of producing water through the SRC/MED plant was 1.98 USD/m^3 for both GORs, approximately 3.66% more than its LCOW. The LCOW estimated assuming the SRC/Ref plant's condenser temperature was 46 °C.

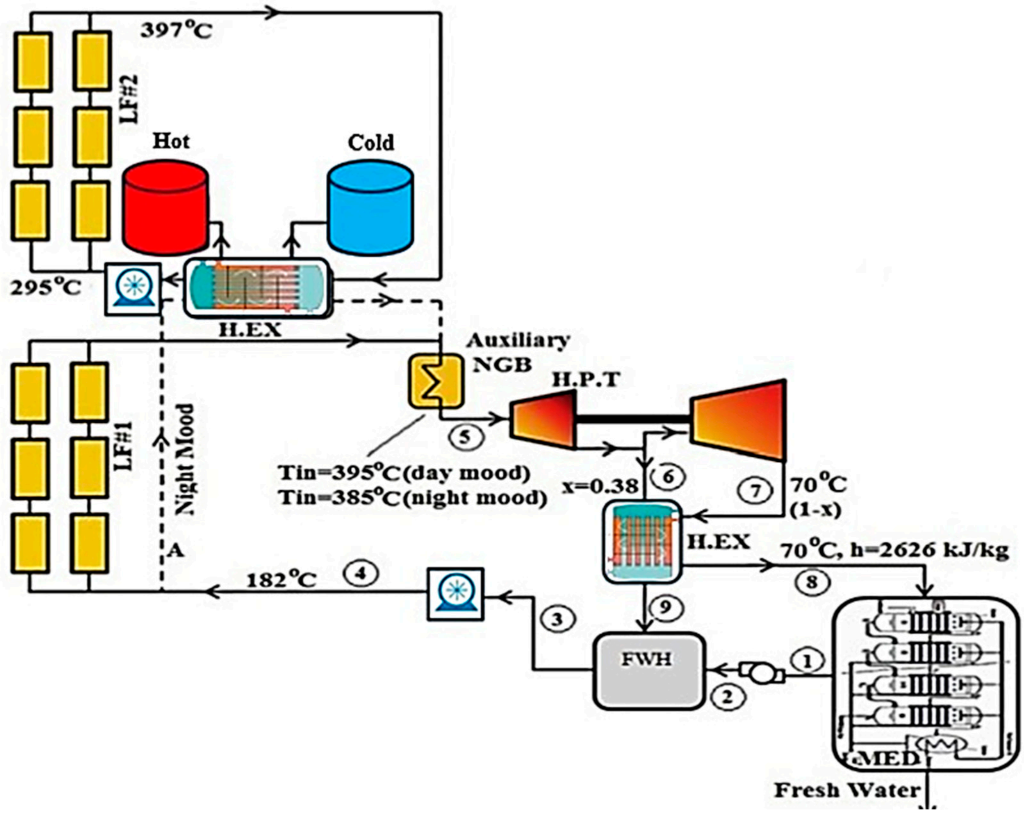

Figure 21. A representation of SRC-MED and solar energy system (adapted from Askari and Ameri [103]). Reprinted/adapted with permission from Ref. (Askari and Ameri [103]) 2024, Elsevier.

Saldivia et al. [2] introduced an integration system of a forward-feed MED unit (prior to entering the first effect, seawater underwent preheating) and parabolic trough collector (PTC) for seawater desalination (Figure 22). Each MED plant effect was composed of a preheater, a flashing box, and an evaporator. A thermal storage tank, a steam generator, and a field of PTCs made up the solar steam generation facility. The solar steam production plant generated saturated steam, which powered the MED unit. The MED plant produced freshwater via a series of seawater evaporators and vapor condensers. A complete numerical model was established for the MED plant, which introduced the mass, energy, and heat transfer equations for the combined MED and solar steam generation plants. Using a solar field size of 500 collectors, the simulation results showed that the MED unit could generate an average of 3000 m^3 of drinking water per a day. However, the MED unit should be in operation for over 90% of the year to comply with an average annual freshwater production of 2000 m^3/d. Saldivia et al. [2] also deduced that the maximum allowable concentration of rejected brine and external steam temperature are two key factors that influence the operation of an MED plant.

Alhaj et al. [30] demonstrated an appraisal of the life cycle of an optimal integrated solar-driven MED plant (Figure 23). The researchers assessed the consequence of choosing various solar collectors, including the linear Fresnel collector (LFC) and parabolic trough collector (PTC), on the environment while comparing the environmental associations of the integrated system with those of a single MED plant. A low-pressure MED chamber and a solar LFC that delivered saturated steam to the MED evaporators made up the solar-powered MED plant. The traditional MED plant is a cogeneration facility that applies a combined power cycle (natural gas combined cycle, or NGCC) to generate electricity and drinking water. The outcomes indicated that, with the exception of ozone depletion and human toxicity, the solar-driven MED plant had a minor consequence on the environment compared to the old-fashioned MED plant in every impact category. Precisely, the solar-driven MED plant lessened the effects of climate change by 10 kg of CO_2 corresponding to every 1 m^3 of freshwater generated compared to a classic MED plant. Ozone depletion is mostly caused by the implication of anti-foaming chemicals used during the pre-treatment process of treated water. In every respect, including metal depletion and land area, the LFC has a greater life cycle assessment rating compared to the PTC.

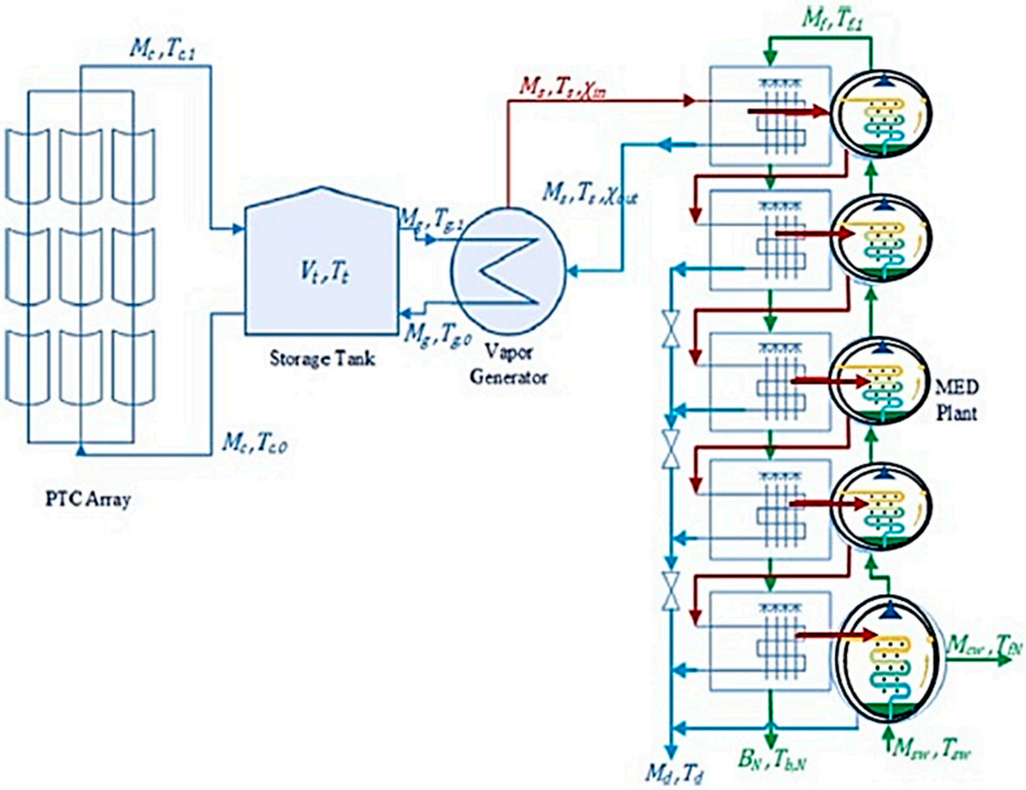

Figure 22. A representation of integrated MED-PTC (adapted from Saldivia et al. [2]). Reprinted/adapted with permission from Ref. (Saldivia et al. [2]) 2024, Elsevier.

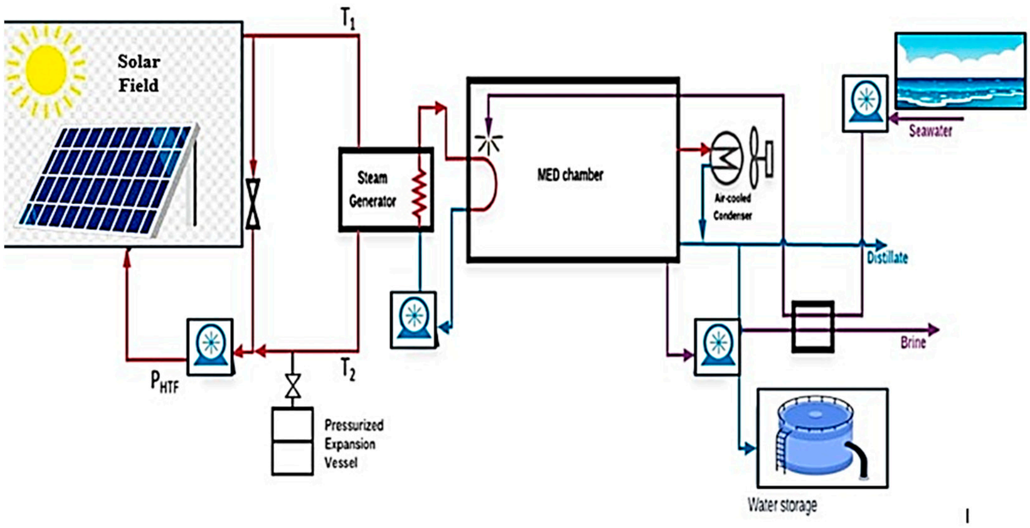

Figure 23. A representation of integrated solar energy and MED (adapted from Alhaj et al. [30]).

5.2. Wind Energy—MED

In distant and coastal places that have little access to freshwater, Khalilzadeh and Nezhad [35] examined the viability of utilizing waste heat produced by a high-capacity wind turbine to power an MED desalination plant. The system operated in the following manner: the wind turbine with a high capacity harnessed the kinetic energy of the wind and transformed it into electrical energy. The process of steam creation involved the utilization of residual heat that was produced by the generator of a wind turbine. The MED desalination machine used steam generated from waste heat to fuel its operations of evaporation and condensation, turning seawater into drinkable water. The wind turbine produced electricity, which powered the pumps and other additional machinery needed for the desalination process. Figure 24 shows a representation of the proposed integrated system. Khalilzadeh and Nezhad [35] modeled the combined system of a high-capacity wind turbine and an MED unit. To evaluate the efficacy of the combined system and pinpoint areas in need of development, the study conducted in-depth assessments of the associated energy, exergy, and thermo-economic factors. A sensitivity examination was completed by Khalilzadeh and Nezhad [35] to appraise the outcomes of many features such as the wind speed on the overall performance. It was revealed that the high-capacity wind turbine could generate a remarkable amount of waste heat, which ranged between 122 kW at 8 m/s and 269.9 kW at 12 m/s wind speed. Using the waste heat from the wind turbine as a power source, the MED unit could produce freshwater at a rate of 23.81 m^3/day while using 8 m/s of wind speed. Also, it was concluded that the energy efficiency of the combined system could be increased as a result of increasing the wind speed, reaching 46.52% at 12 m/s from 69.14% at 8 m/s. Moreover, the exergy efficiency of the combined system could be increased by increasing the wind speed, rising from 7.34% at 8 m/s to 13.30% at 12 m/s. The projected price of producing potable water with the integrated system was 16.676 USD/m^3, conferring to the thermo-economic study.

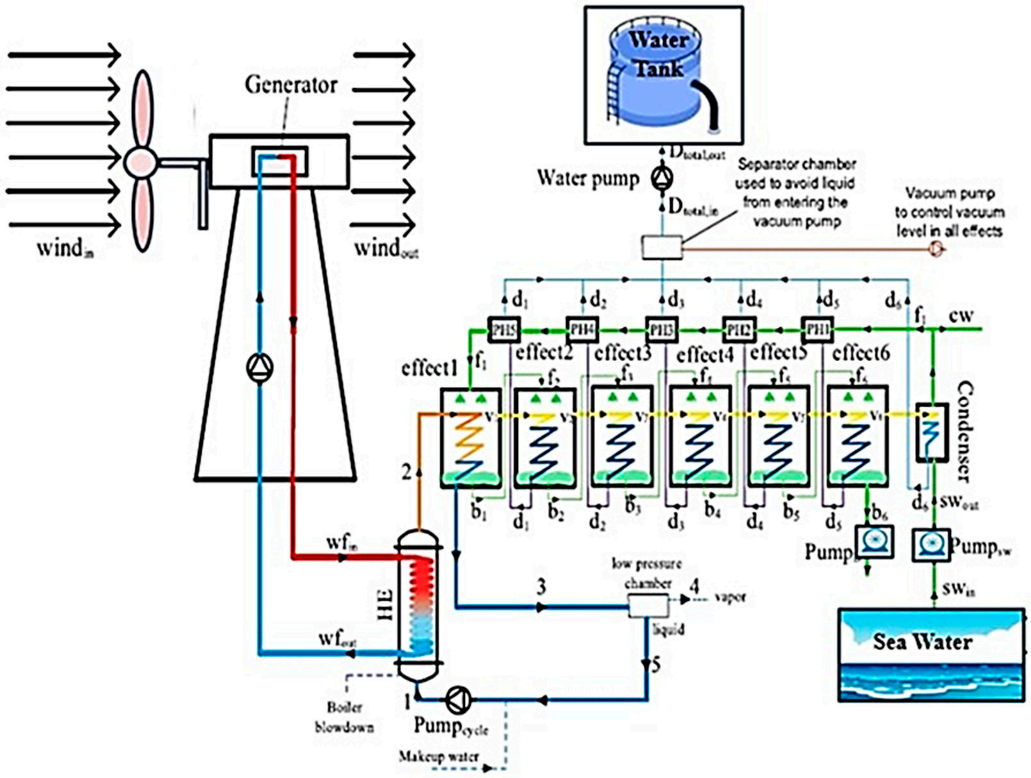

Figure 24. A representation of integrated wind energy and MED (adapted from Khalilzadeh and Nezhad [35]). Reprinted/adapted with permission from Ref. (Khalilzadeh and Nezhad [35]) 2024, Elsevier.

5.3. Geothermal Energy—MED

The geographic viability of producing drinking water from brackish aquifers in Texas through a geothermal MED plant was considered by Birney et al. [104]. Water was purified using a sequence of evaporators with reduced pressure in the MED unit. Geothermal water served as the primary source of heat, which entered the first effect. The geothermal water was then cycled back into the groundwater source by an injection well after leaving the first effect while keeping the loop closed. Figure 25 demonstrates the binary cycle, which contained a turbine, condenser, pump, preheater, and evaporator linked to the MED unit. Thermodynamic data from an extant brackish well and regionally defined geothermal gradient information in Texas were combined with a binary-cycle MED plant model. Instead of assessing the production potential at a particular location, the model was utilized to estimate it for the entire state of Texas. The associated results assured that it is possible to construct a geothermal-powered MED plant in southeast Texas' geopressured Frio and Wilcox fairways that would function independently of the grid's electricity. Freshwater from wells in these fairways could provide 232–2133 persons with a daily production of 121–1132 m^3/day. In every other part of Texas, a geothermal-energy-driven micro-engineering system would need to buy extra electricity from the grid or be constructed in combination with a supplementary renewable energy source, like solar or wind power.

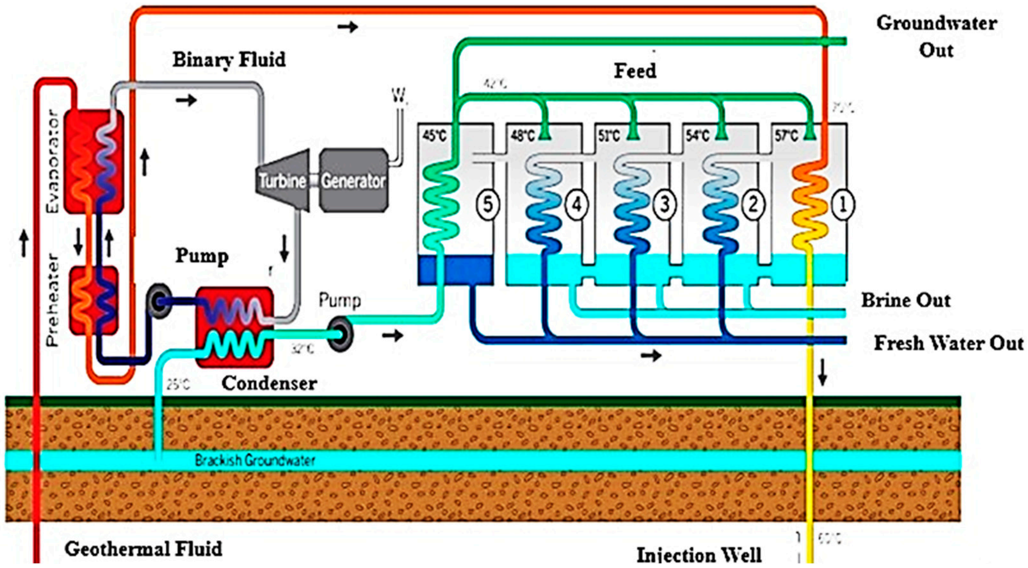

Figure 25. A representation of the binary cycle of geothermal energy connected to MED system for brackish water desalination (adapted from Birney et al. [104]).

Farsi and Rosen [105] designed and examined a geothermal-electricity–freshwater hybrid system that combined a MED desalination unit with an Organic Rankine cycle (ORC) (Figure 26). The MED desalination unit and ORC made up the geothermal combination system. Geothermal hot water powered the ORC by creating steam, which grew in a turbine in order to generate energy. In the MED desalination unit, which created freshwater through a sequence of evaporation and condensation processes, the seawater was additionally heated by the geothermal hot water. To conduct this study, mass, energy, entropy, and energy rate balances were created for every component of the system. Also, equations for energy and energy efficiency were obtained for every subsystem. Furthermore, an examination of sustainability was carried out, linking the ideas of energy and environmental impact. The integrated system's overall energy effectiveness was determined to be 38%, greater than the joint exergy efficiency of the ORC and MED subsystems working independently. The boiler was linked to the highest rates of exergy degradation, mostly because of heat transmission over wide temperature changes. Out of all the MED effects, the first effect had the highest rate of exergy destruction, since it was the only one that exchanged thermal energy with the high-temperature steam. Based on statistical analysis, it was determined that 6% of the overall exergy destruction rate of the MED desalination system was determined to be connected with the temperature disequilibrium of the freshwater and 14% of it was linked to the temperature and chemical disequilibrium of the brine, respectively.

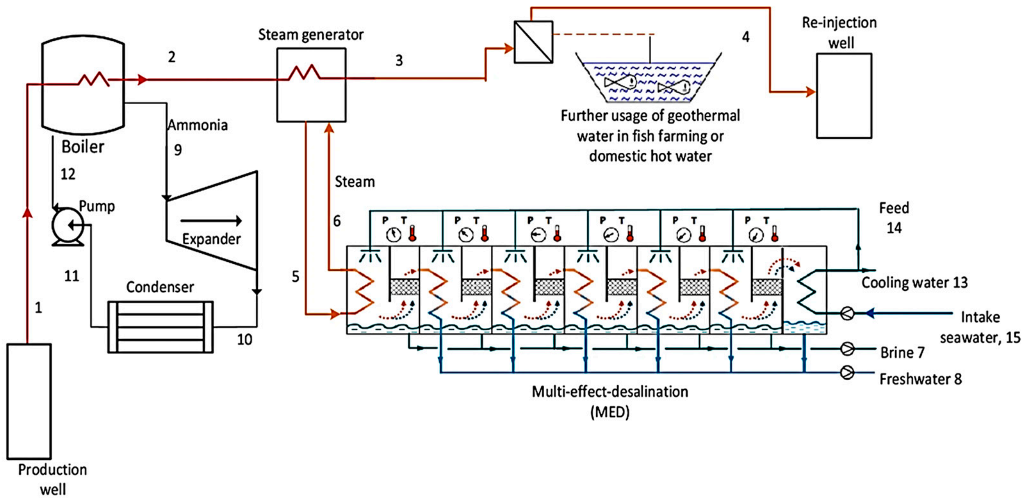

Figure 26. A representation of integrated ORC and MED powered by geothermal energy (adapted from Farsi and Rosen [105]).

Table 3 depicts a summary of the studies conducted between 2013 and 2023 regarding the use of renewable energy sources to power MED water desalination systems.

Note, further to what has been discussed above, heat pumps can be utilized as a heat source or the exhaust heat of the desalination process can be used to operate an absorption heat pump. By coupling heat pumps, this enhances the performance of saline evaporation-based desalination systems. This involves equipping single and multi-effect evaporation with heat pumps, either of the compression or absorption type, to recover exhaust heat and increase the overall cycle efficiency.

Table 3. Technological trends of hybrid MED desalination and renewable energy systems.

Authors (Year)	MED Process Design	Renewable Energy Process Design	Operating Conditions	Results	Advantages	Disadvantages
Saldivia et al. [2]	Forward-feed MED Steam temperature of less than 70.8 °C Feed flow rate of 8 m^3/h	Parabolic trough collector (PTC)	-Feed flow rate of 8 m^3/h	-Productivity of 3000 m^3 of fresh water each day	-The study offers a thorough numerical model for a solar-powered MED plant that can be applied to planning, enhancing, and evaluating the system -The study offers insightful information about the technological viability of solar-powered MED plants in Chile	-Because the study is focused on a particular MED plant design and location, it is possible that the findings will not apply to other MED plants or places -The economics of solar MED plants, which are crucial for determining their commercial feasibility, are not taken into account in this study -Due to an absence of thorough experimental data, the study encountered difficulties when predicting the heat transfer coefficients for the preheaters and evaporators

Table 3. *Cont.*

Authors (Year)	MED Process Design	Renewable Energy Process Design	Operating Conditions	Results	Advantages	Disadvantages
Iaquaniello et al. [101]	10 effects of MED at 70 °C of top brine temperature	To extend the operating time beyond the direct heat irradiation period, the CSP system uses molten salts as its thermal medium, which is fitted with a thermal storage unit. A continuous operating mode is made possible by a backup system that functions as a heat recovery device on flue gas supplied by a gas turbine (GT)	Seawater salinity of 35,000 ppm, temperature of 25 °C, heating steam temperature of 69 °C	-Freshwater production cost is USD 0.97/m^3 -The annual productivity is 6,864,000 m^3 -The specific energy consumption is 2.52 kWe/m^3 -CO_2 emission of 1.53 kg/m^3 of freshwater	-The price of natural gas and the plant's lifespan have an impact on the cost of producing water -The suggested method has the potential to drastically lower greenhouse gas emissions when compared to traditional desalination facilities	-A significant obstacle to the proposed scheme's deployment is the CSP system's high capital cost -Because solar radiation is irregular, the desalination plant needs a dependable backup system to keep running continuously
Weiner et al. [102]	Five MED effects at 70 °C of top brine temperature. To raise the temperature and pressure of the resultant mixture to the levels needed by the first effect, some of the vapor from the final effect is fed into a TVC, where high-pressure motive steam is introduced	-In order to heat a circulating heat transfer fluid, solar radiation is collected and concentrated using trough collectors	Brackish water salinity of 15,000 ppm	-At a levelized cost of USD 0.45/m^3, the hybrid RO–MED system may generate water at a 41% cheaper cost than a standalone MED system -The product salinity of 500 ppm	-In California, the hybrid RO–MED system is a viable technological solution for purifying agricultural drainage water -The optimal number of MED effects is five, and the ideal RO working flux is 18.2 LMH -The number of effects used in the MED system has the greatest impact on the hybrid RO-MED system	-Because of the high capital cost of the CSP plant, the hybrid RO-MED system implementation is hindered -Solar radiation availability affects the system as well -Fouling and scaling of the RO and MED membranes may lead to reduced system performance
Askari and Ameri [103]	14 effects of MED Top brine temperature of 70.8 °C	In order to improve the charging and discharging procedure and enhance the thermal energy storage capacity of the Thermal Storage System (TES), two Linear Fresnel (LF) solar fields were employed	Seawater temperature between 35 and 66 °C	-Specific heat consumptions are 66 and 54 kWht/m^3 for 9.8 and 12 of DOR, respectively	-The study concluded that a viable substitute for producing both water and electricity is to use an LF solar field as the thermal source of an SRC/MED plant -The research additionally discovered that the LCOW of the SRC/MED plant and the number of loops in the solar field are reduced with an increase in the MED unit GOR -The study also discovered that the solar share and LCOE of the SRC/MED plant rise with an increased TES capacity	-The impact of the solar field orientations on the solar share and LCOE of the SRC/MED plant was not taken into account in the analysis -Additionally, the impact of the MED unit design on the LCOW of the SRC/MED plant was not taken into account in this study -It is possible that the study overestimated the mass flow rate in the LF1 solar field

Table 3. *Cont.*

Authors (Year)	MED Process Design	Renewable Energy Process Design	Operating Conditions	Results	Advantages	Disadvantages
Alhaj et al. [30]	10 effects of MED at 70 °C of top brine temperature	Solar collectors (parabolic trough collector (PTC) and linear Fresnel collector (LFC)	Seawater salinity of 48,000 ppm, temperature of 30 °C	-Specific energy consumption of 4.2 kWh/m^3	For each m^3 of freshwater generated, the solar-driven MED plant offsets the impact of climate change by 10 kg of CO_2 equivalent. This is in contrast to the regular MED plant	-The absence of thorough data on the effects of desalination procedures on the environment is the primary obstacle to doing LCA studies on desalination plants -Comparing the findings of several studies can be challenging since the assumptions and methodologies employed in LCA research can have a significant impact on the findings -The social and economic advantages of desalination, such as the supply of clean drinking water and the generation of jobs, are sometimes overlooked in LCA studies
Khalilzadeh and Nezhad [35]	Six effects MED unit	Wind turbine of 7580 kW Enercon-E126 model	Seawater salinity and temperature of 42,000 ppm and 25 °C	-When steam is created at 100 °C and 101.3 kPa, 45.069 m^3/day of drinkable water may be produced -An estimated 16.676 USD/m^3 is the cost of fresh water	The study proved that it is feasible to run MED desalination machines with waste heat from high-capacity wind turbines, providing a cost-effective and environmentally friendly option for freshwater production in isolated and coastal places	The short-term nature of wind energy makes it difficult for the desalination system to run continuously. The combined system's expensive initial investment cost could prevent it from being widely adopted, especially in lower-income nations
Birney et al. [104]	Top brine temperature of 70 °C	Geothermal temperature 90–150 °C and geothermal gradient of 36 °C/km	Brackish water salinity between 1000 and 10,000 ppm	-Freshwater from wells in these fairways may provide 232–2133 persons with a daily yield of 121–1132 m^3/day	-It is possible to construct a geothermal-powered MED plant in southeast Texas' geopressured Frio and Wilcox fairways that would function independently of the grid's electricity -In every other part of Texas, a geothermal-energy-driven micro-engineering system would need to buy extra electricity from the grid or be constructed in combination with another renewable energy source, like solar or wind power	-It takes a lot of energy to pump water out of deep sea; hence, the binary-MED system struggles to become energy independent on its own -The environmental issues associated with brine disposal and the financial aspects of constructing a geothermal MED plant are not covered in the paper

Table 3. *Cont.*

Authors (Year)	MED Process Design	Renewable Energy Process Design	Operating Conditions	Results	Advantages	Disadvantages
Farsi and Rosen [105]	Six effects of MED and Organic Rankine cycle (ORC) Top brine temperature of MED of 63 °C Steam flowrate of MED of 9.02 kg/s	Geothermal energy of 180 °C of water temperature	Seawater salinity and temperature of 42,000 ppm and 20 °C, respectively	-Freshwater production rate of 32.7 kg/s -Fresh water salinity of 0.0 ppm -Overall exergy efficiency of 38% -ORC exergy efficiency of 34% -MED exergy efficiency of 20.5%	-Geothermal energy-powered ORC and MED combination may boost energy effectiveness, lower energy destruction, and lessen environmental effects	-The geothermal-based combination system's economics were not taken into account in the research. -The study made the assumption that saltwater and geothermal hot water were easily accessible in appropriate amounts and temperatures -The study did not take into account the greenhouse gas emissions from the geothermal-based combination system or its effects on the environment

MED desalination with a heat pump could produce up to 15,000 cubic meters of clean water per day at a cost rate of only USD 0.11 per second, making it highly cost-effective [106]. Baccioli et al. [107] explored the potential of waste heat from an ORC to power an MED unit, which could reduce investment costs. However, the payback time may be longer. Datsgerdi and Chua [37] investigated the economic viability of three multi-effect distillation (MED) based processes against the traditional MED coupled with low-grade waste heat. They evaluated Boosted MED (BMED), Flash Boosted MED (FBMED), and Distributed Boosted MED (DBMED) processes in terms of waste heat performance ratio and economics. All three new configurations outperformed the traditional MED.

6. Challenges and Conceptual Ideas of Improvement of Utilization of Renewable Energy Seawater Treatment Systems

Despite the fact that the deployment of renewable energy to power wastewater treatment facilities is of high importance to mitigate their operating costs and reduce their environmental impact along with improving the sustainability of their operations, there are still a number of challenges facing their complete utilization. The most important obstacles that need to be overcome are listed below:

- Renewable energy sources are irregular, which means that they do not always exist when needed. Examples of irregular energy sources are solar and wind power. Because water desalination and wastewater treatment systems run around the clock, seven days a week, it may be challenging to rely solely on renewable energy to power them.
- Due to the discontinuous nature of solar and wind energy, efficient energy storage and management systems are necessary to maintain a steady and dependable power supply and meet the fluctuating energy demands of desalination operations. In this regard, finding economical and practical energy storage options for wastewater treatment plants is still a problem, especially for large-scale applications [108].
- Weather conditions can have a substantial influence on the affordability of renewable energy sources. This might make it thought-provoking for desalination facilities to bring a steady and dependable source of electricity.
- Intensive amounts of heat or power are required to run water desalination facilities, predominantly thermal desalination technologies, which require a high-energy procedure. Although renewable energy sources are environmentally friendly substitutes

for fossil fuels, they do not always have the high-energy demand wanted for properly operating desalination technologies.

- Common industrial desalination plants are constructed to be large-scale operations necessitating considerable energy consumption. Regrettably, the majority of renewable energy technologies are still in the early phases of development and require additional investigation.
- The manufacture of renewable energy systems such as solar energy and wind energy is associated with large initial expenditures [109].
- Geographical location and environmental features affect the availability of proper renewable energy equipment, such as wind and direct sunlight. The handiness of local resources must be wisely considered in order to distinguish and assess the practicability of renewable energy choices for specific seawater desalination plants.
- For the time being, the freshwater production cost of seawater desalination technologies powered by renewable energy systems is typically greater than the freshwater production cost of seawater desalination systems powered by fossil fuels. Due to the intermittent nature of renewable energy, seawater desalination systems powered by renewable energy systems need more backup power than seawater desalination systems powered by fossil fuels. Table 4 illustrates a comparison of freshwater production costs for these systems for desalting seawater. Realizing the fact that fossil fuels are suspected to be depleted, using renewable energy systems is still a suitable option to drive desalination technologies, as well as enabling reductions in the harmful effects on the ecosystem.

Table 4. Freshwater production cost of conventional seawater desalination systems and renewable energy integrated seawater desalination systems (adapted from Nassrullah et al. [3]).

Energy Type	Productivity (m^3/day)	Freshwater Production Cost (USD$/$m^3$)
Fossil fuel		0.46–3.5
Photovoltaic	Less than 100	11.7–15.6
Wind energy		1.3–6.5
Solar collectors		4.55–10.40
Solar still	Less than 0.1	1.3–6.5
Solar/CSP + MED	More than 5000	2.3–2.8
Solar + MED	1–100	2.6–6.5
Solar + MSF	1	1.0–5.0
PV + RO	Less than 100	11.7–15.6
Geothermal + MED	80	2.0–2.8
Wind + RO	50–2000	Small capacity: 6.6–9.0 High capacity: 1.95–5.2
Wind + Mechanical Vapor Compression (MVC)	Less than 100	5.2–7.8

To systematically enhance the feasibility of integrated renewable energy technologies for water desalination plants, the following directions need to be considered in future research.

- The intermittent nature and instability of single renewable energy sources can be reduced by combining numerous sources, such as solar, wind, and geothermal energy, into hybrid systems. This results in a more dependable and constant source of electricity for water desalination processes. Moreover, hybrid systems have synergistic advantages like an improved utilization of energy in both energy capture and consumption.

- Further studies are required to improve water desalination technologies to make them more compatible with renewable energy technologies. Advancing efficient energy desalination technologies would undoubtedly mitigate the overall energy consumption and enhance the reliability of their integration into renewable energy sources.
- The development of sophisticated energy storage technologies allows for excess renewable energy to be stored for use at a later time of low energy availability. Examples of these devices include batteries, thermal storage, and pumped hydro storage.
- Further techno-economic simulation and optimization studies are required to identify the most effective renewable energy sources to be integrated into water desalination systems, besides evaluating their life cycle cost.

7. Conclusions

This research examined the potential use of renewable energy sources in water desalination technologies, including RO, MSF, and MED. The performance and economic viability of these methods in conjunction with renewable energy sources—solar energy, wind energy, and geothermal energy, in particular—were methodically examined in this study. The review elucidated the possible advantages and difficulties of incorporating renewable energy sources into water desalination procedures by the means of an inclusive analysis of the literature. The following conclusions can be made:

- Due to the unstable nature of a single renewable energy source, the systematic incorporation of different renewable energy sources such as solar, wind, and geothermal energy into water desalination facilities would introduce a fixed source of electricity along with acquiring the lowest energy consumption and greenhouse gas emissions.
- The PV–RO system can unquestionably secure an economically practicable and environmentally friendly solution to water scarcity.
- The freshwater production cost of using MSF powered by concentrated solar power is about three times higher than that of using traditional MSF.
- Thermo-economic data revealed that the employment of MSF powered by parabolic trough concentrator solar power would consume more specific power of 5 kWh/m^3, compared to a standalone desalination unit of 4.09 kWh/m^3.
- Geothermal energy is unaffected by weather or seasonal changes, unlike solar or wind energy. Because of this, this energy source is chosen over wind and solar energy sources because it does not require thermal storage tanks or battery storage to preserve energy.
- To secure the target temperature for MSF, which is in the region of 90–110 °C, the extracted geo-fluid well should be between 2 and 3 km deep.
- It has been noted that producing water with geothermal energy is less expensive than conducting this with photovoltaic solar energy. Nonetheless, the primary obstacles to fully utilizing geothermal energy sources are the high upfront costs associated with discovery and well drilling, as well as the length of the payback time.
- Utilizing solar geothermal pre-heating units has an optimistic and significant impact by reducing the specific energy consumption, ranging between 24.33 and 35.79% and 18.69 and 22.87% in the scenarios of brackish water and seawater desalination, respectively.
- Using waste heat from large-scale wind turbines to power MED desalination units is a viable solution for producing freshwater in isolated and coastal areas at a reasonable cost.
- The solar-powered MED plant reduces the effects of climate change by 10 kg of CO_2 equivalent for every m^3 of freshwater produced. This is not like the standard MED plant.

Finally, note that nuclear-assisted desalination plants are also a viable alternative for desalination. Unlike renewable energy, they do not require batteries for storage and a lot of land for energy-harvesting systems. In addition, they provide reliable carbon-emissions-free thermal energy and electricity. Accordingly, future investigations should critically analyze nuclear-assisted desalination in a specific review study.

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