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Review

Evaluation of Solar Energy Powered Seawater Desalination Processes: A Review

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Abstract: Solar energy, amongst all renewable energies, has attracted inexhaustible attention all over the world as a supplier of sustainable energy. The energy requirement of major seawater desalination processes such as multistage flash (MSF), multi-effect distillation (MED) and reverse osmosis (RO) are fulfilled by burning fossil fuels, which impact the environment significantly due to the emission of greenhouse gases. The integration of solar energy systems into seawater desalination processes is an attractive and alternative solution to fossil fuels. This study aims to (i) assess the progress of solar energy systems including concentrated solar power (CSP) and photovoltaic (PV) to power both thermal and membrane seawater desalination processes including MSF, MED, and RO and (ii) evaluate the economic considerations and associated challenges with recommendations for further improvements. Thus, several studies on a different combination of seawater desalination processes of solar energy systems are reviewed and analysed concerning specific energy consumption and freshwater production cost. It is observed that although solar energy systems have the potential of reducing carbon footprint significantly, the cost of water production still favours the use of fossil fuels. Further research and development on solar energy systems are required to make their use in desalination economically viable. Alternatively, the carbon tax on the use of fossil fuels may persuade desalination industries to adopt renewable energy such as solar.

Keywords: seawater desalination; multi-effect distillation; multistage flash; reverse osmosis; photovoltaic and concentrated solar power; specific energy consumption; water production cost

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1. Introduction

Energy has a significant impact on the evolution of modern society, with major sectors relying on its proximity to human daily life. Many efforts were paid to investigate alternatives to this energy, with renewable energy being the most essential. It is self-evident that the sun provides nearly all of the world's energy resources. This energy has various advantages, such as being cost-effective in the long run and having no negative impact on the environment. However, the major disadvantage is that it is not available at all times such as at night and due to the change in weather conditions around the year and around the globe.

Due to population growth, climate change, a rise of complex sorts of pollutants, and improved standards of living beside the exponential growth of the industry sector, water desalination and water reuse are propelled as key factors for sustainability [1]. Desalination, which processes a variety of water sources including seawater, brackish water, and industrial water is a straightforward alternative for overcoming water scarcity. The goal of water desalination is to provide drinkable water from saline water with the expense of energy to power the associated units [2]. Overall, around 10,000 tons of fossil fuels per year are required to produce 1000 m^3/day of freshwater using seawater desalination [1]. The water desalination method can be commonly classified into two parts, thermal processes and membrane processes [3]. Thermal desalination requires heating of seawater and condensing the vapour as distilled water and therefore utilises electrical and thermal energy. A thermal desalination method is a preferable option in Arabian Gulf countries due to its capacity to desalinate high-salinity seawater [4]. Specifically, the high specific energy consumption which is recently met with expensive fossil fuels and high water production costs are the main limitations of thermal desalination techniques [5]. Membrane technology constitutes the enforcement of saline water to pass through a membrane medium from the high concentration side into the low concentration side under higher pressure than osmotic pressure to produce potable water with the utilisation of electrical energy [6].

The desalination market has dramatically grown due to the development of associated thermal and membrane technologies that were powered by fossil fuels. Due to its growing economy and abundance of fossil fuels, the largest thermal water desalination plants were developed in Asian countries and especially in the Arabian Gulf region compared to those countries with a shortage of fuel supplies [7,8]. These plants are directly connected to the electrical grid to ensure a continuous supply of power. However, due to the prospect of future oil crises, the desire to be free of reliance on the oil industry is painfully evident. As a result, both developed and developing countries are concerned about their reliance on a diverse range of renewable energy sources. The innovative integrated solar energy systems to thermal and membrane water desalination methods are the focus of this study.

Recently, the concept of water-energy nexus, as a novel phrase, has taken the attention of researchers as an inevitable option to securely balance the relationship between water and supplied energy in one chain. It basically means that any change in one sector will have an impact on the others, and vice versa. As a result, a persistent relationship exists between the energy and water resources of many applications that require simultaneous water production and energy conversion. This approach has been frequently utilised to assess the progress of smart cities since it allows for the integration of sustainability, economic, and environmental concerns [9]. However, the consistent relationship between water and energy can be impaired due to population growth, urbanization, climate change, and the increased cost of supplied energy [10]. The continuous demand for freshwater and low-cost energy resources is driving the search for new ways to safeguard these resources. In other words, the deployment of renewable energy to drive water desalination technologies would be a viable option for ensuring the supply of low-cost freshwater without relying on the excessive burning of fossil fuels. Undoubtedly, the initiative of renewable energy can be considered the most preferable option to be advanced to release the pressure on fossil fuels and power desalination technologies. The shift towards advanced renewable energy systems is a superior option to produce energy with the transformation from addiction to oil into sustainable resources [11].

Shahzad et al. [12] confirmed that around 1% of the total worldwide capacity of freshwater is produced by the integrated systems of renewable energy sources and water desalination methods. They reported, that 43% and 27% of water production with the use of photovoltaic cells and concentrated solar power systems, respectively. This demonstrates the lack of use of solar energy devices in the water desalination sector. Therefore, this study comes to bring attention to the superiority of solar energy systems and increases the motivation to deploy solar energy systems as the future source of thermal and electrical energy.

The main aim of this study is to assess the profitability, economic perspectives and the most associated concerns of utilising solar energy systems to power water desalination methods. This study focuses on the thermal (multi-stage flash MSF and multi-effect distillation MED) and membrane technology (reverse osmosis RO) of water desalination as they are considered the most worldwide applied methods. Figure 1 shows the global desalination capacities including shares of the selected desalination methods. Figure 1 clearly shows the superiority of the RO process compared to the thermal desalination methods of MSF and MED. The safe operation and low-energy consumption of the RO process compared to thermal processes are the main clues behind the spread of the RO process [13]. The ion exchange, electro-dialysis and vacuum distillation are examples of other desalination methods, however with a lower production capacity.

Solar energy systems including photovoltaic cells and concentrated solar power are selected in this paper due to their massive implications to provide thermal and electrical energy to power water desalination methods compared to other renewable energy sources such as wind and geothermal energy. According to [14], solar photovoltaic energy accounts for 43% of all renewable energy used in water desalination plants, compared to 27% and 20%, respectively, for solar thermal energy and wind energy. The selection of an appropriate solar energy system is quite related to several factors including the plant size and location, water demand, seawater properties, weather and intensity of solar radiation. The relevant suggestions of this review hope to aid the decision makers to select the proper desalination method, thermal or membrane technologies, to be integrated with the solar energy system.

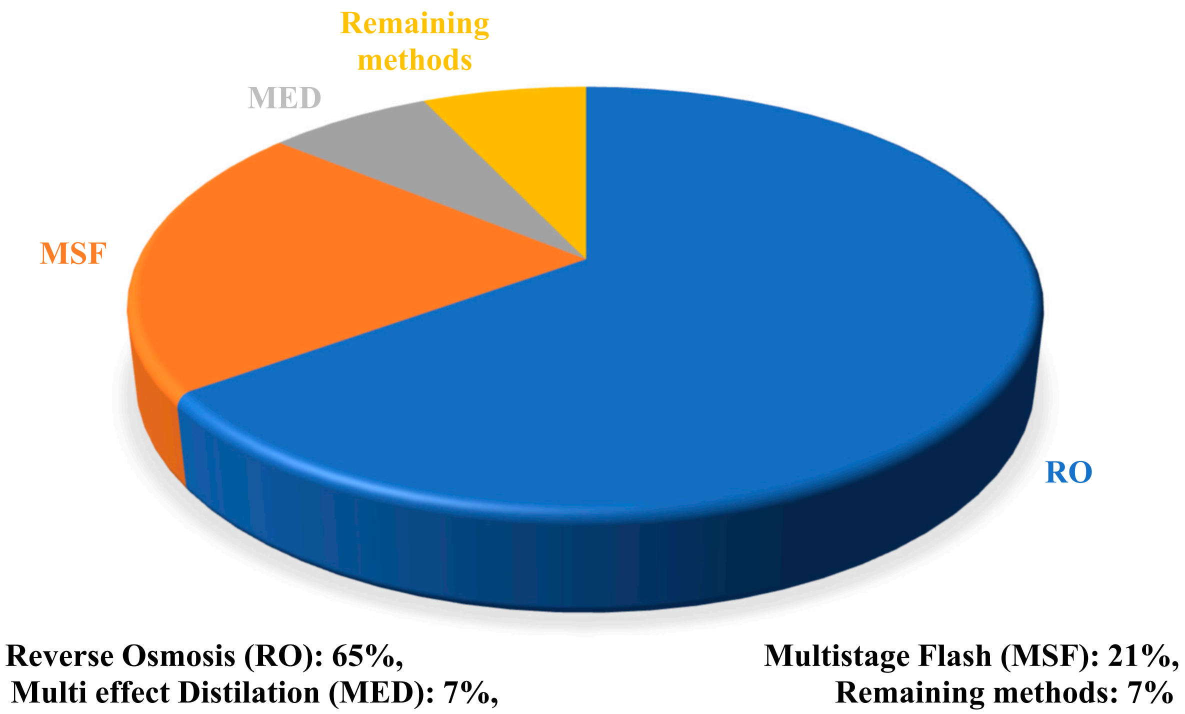

Figure 1. Shares of thermal and membrane water desalination technologies (Adapted from [15]).

2. Conceptual Design of Solar Energy Systems

Solar energy systems are basically designed as direct and indirect collecting methods. The simple direct method of solar still utilizes solar energy to desalinate saline water based on evaporation and condensation. However, indirect solar energy such as the photovoltaic and concentrated solar thermal processes are designed to produce electrical and thermal energy from supplied light and heat of the sun, respectively [16,17].

Solar thermal power plants transform radiant heat from the sun into thermal energy, which can be used directly or turned into mechanical or electrical energy [18,19].

Both semiconductors and solar collectors are included in the photovoltaic cells used to produce energy via absorbing solar radiation. Solar energy systems were integrated into several industrial implications including water treatment systems [20]. Indeed, solar energy can be converted into thermal energy to heat water for thermal desalination. However, solar electrical energy is the direct conversion of solar light into electricity through the use of semiconductor materials such as those found in photovoltaic (PV) solar cells [21]. Increased semiconductor efficiency, without a doubt, has a good impact on lowering the entire specific energy consumption. The freshwater production cost is inclusively corresponding to the specific energy consumption, which is defined as the required power to desalinate one cubic meter of fresh water. The generated thermal energy and electricity can be used to power the desalination systems. More specifically, solar thermal energy can be directly used to provide steam for MSF and MED while can be indirectly converted to mechanical or electrical energy to operate the RO process. Also, the photovoltaic cells and concentrated solar power collectors can, directly and indirectly, provide electricity to power the RO process, respectively. However, the intermittent production of fixed energy and the necessity of a massive construction area is the main limitation of these systems. Furthermore, this is a clear issue, especially for regions of low-intensity of sunlight such as European countries.

Photovoltaic (PV) systems comprise silicon solar cells that are specifically designed to convert sunlight into electrical energy. The PV arrays, inverter and energy storage system are the main equipment of the PV system. An intelligent sun tracker is an important part of PV to automatically follow the sun and guarantee to put the focal point on the cell. The simplicity of constructing PV with its long operational time is the main advantage. The PV systems are preferable technology to be integrated into specifically RO desalination plants due to their characteristics of very low air pollution, low maintenance and prolonged operation life [16]. The power generated from the PV system can be used directly to run the high-pressure pumps of the seawater desalination plant.

The concentrated solar power energy comprises a glass mirror to heat a medium fluid (usually water or molten salt) at a high-temperature range to get a high temperature between 400 °C to 1000 °C. The glass mirrors track the sun's location in real-time. The heat then will be converted to superheat a secondary fluid of the organic Rankine cycle to drive a turbine. In other words, the sunlight has been converted into electrical or mechanical energy to power the high-pressure pumps of the water desalination system using turbines [22]. The concept of concentrating solar radiation to create high-temperature heat for energy production within traditional electricity cycles employing steam turbines, gas turbines, or Stirling and other kinds of engines underpins concentrated solar thermal power technology. The parabolic trough, Fresnel mirror reflector, power tower, and dish engine are the four basic concentrating solar power (CSP) systems. CSP facilities are mostly used to produce energy, but they can also be used to desalinate water in a variety of designs. The best option for CSP/desalination coupling right now is the parabolic trough system, and two types of desalination processes, MED and MSF, are the best candidates for CSP coupling. Also, a set of batteries is connected to save energy and to be used as a source of power at night with an absence of solar radiation. However, the necessity of a large construction area for concentrated solar power is one of its limitations.

3. Conceptual Design of MSF, MED and RO Seawater Desalination Systems

Numerous water desalination methods were developed to provide fresh water from saline water. This paper focuses on the utilisation of examples of thermal and membrane technologies such as MSF, MED, and RO processes, respectively, for seawater desalination with integrated solar energy systems.

The MSF process is a distillation method for extracting fresh water from high-salinity water by converting a huge quantity of water into steam in a series of stages ranging between 4 to 40. The MSF unit's core architecture features a brine heater and a series of flashing chambers with condensers. The unit heated the seawater between 90 to 110 °C by the heating source. This heat is sufficient to raise the temperature of the saltwater to the appropriate top brine temperature (TBT). The heated saltwater then passes through a succession of flashing chambers, where the hot vapour begins to evaporate at a lower pressure (flash evaporation). The generated vapour is transformed into fresh liquid water and gathered in distillate trays after delivering its latent heat via the condensers to pre-heat the incoming feed seawater. The remaining brine of the specific stage will be transferred to the next stage for further flushing [23].

The MSF process requires both thermal and electrical energy. Thermal energy is important to supply steam to heat the seawater and to provide steam for the ejectors to maintain vacuum in different sections of the system. However, electrical energy is important to drive the pumps at different locations. Figure 2 shows a schematic diagram of the MSF seawater desalination plant.

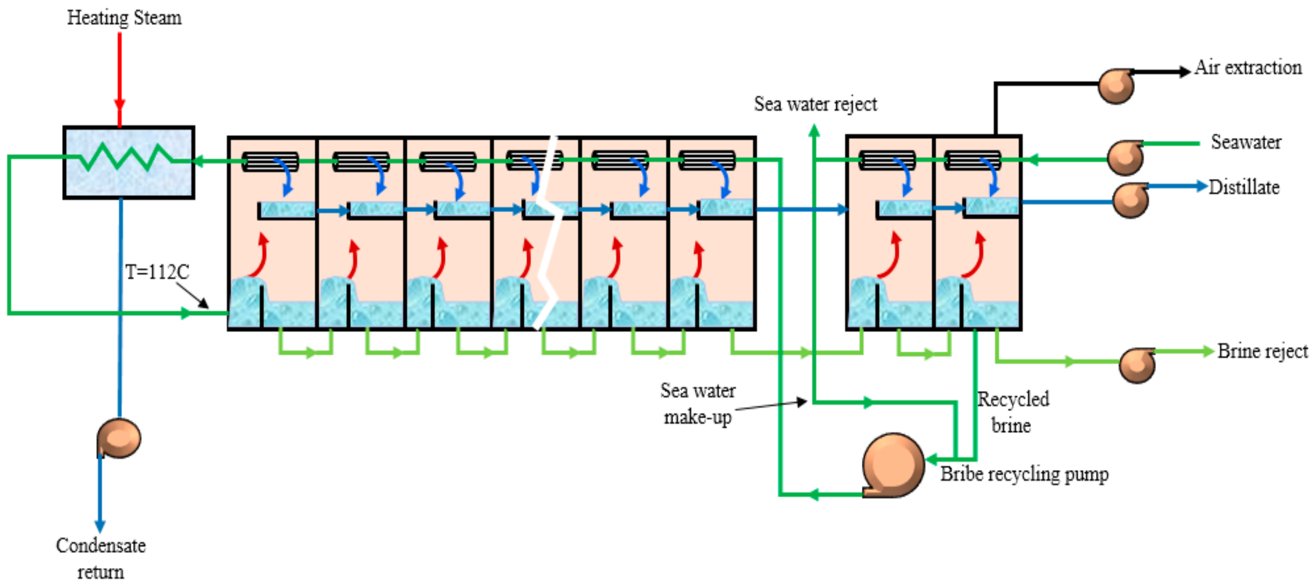

Figure 2. A schematic diagram of MSF seawater desalination plant.

The MED process is a combination of evaporation and condensation. It is, however, initially operated at low pressure, which corresponds to a decline in temperature and pressure from the first to the last stage. The MED system is made up of a sequence of falling-film evaporators, a condenser, and a thermo-compressor (steam jet ejector). The feed saltwater is fed to the first stage after preheating to around 70 °C using an external source of heat. The supplied brine of the first stage is evaporated and concentrated to create the brine stream for the following stage; as a result, the high-concentration brine is fed to the last stage. The first stage transfers heat from the thermal vapour compression system to prepared saltwater, resulting in a small amount of water vapour that is used to heat the seawater of the second stage. The latent heat of the vapour produced in the first stage is released in the second stage, and condensate forms inside the tubes. Similarly, in the second stage, latent heat is released, and a minimal vapour is formed, which provides heat for the third step. This cycle is continued for the other phases, with pressure and temperature gradually lowering until the vapour temperature reaches the feed seawater temperature. As a result, the feed is boiled in phases, with no need to give more heat after the first. In this system, three pumps are utilized to feed saltwater into the last condenser, reject the brine into the sea, and transport the produced water to the product tank [9]. Figure 3 shows a schematic diagram of the MED seawater desalination plant.

The RO method is at the top of seawater desalination membrane technologies, which are widely employed in various scales of water desalination plants without requiring thermal energy. Commonly, the RO seawater desalination plants are designed to involve both pre-treatment and post-treatment of the treated water beside the high-pressure pumps to drive water into the RO stages. The RO stages can be arranged in different configurations based on parallel, series, and tapered designs besides the possibility of using one and multi-passes of permeate reprocessing design. Seawater reverse osmosis is a hydrostatic pressure-driven separation method that uses a semi-permeable membrane to separate two mediums with varying solute concentrations. Because this technique uses a greater pressure than osmosis that ranges between 55 to 81 atm, water and a small proportion of some ions can pass through the membrane from the high concentration side to the low concentration side, while the majority of salts are repelled. Reverse osmosis seawater desalination plants are typically constructed as a multi-stage process to provide high-quality water at high recoveries [24]. Figure 4 shows a schematic diagram of a seawater desalination plant based on the RO process.

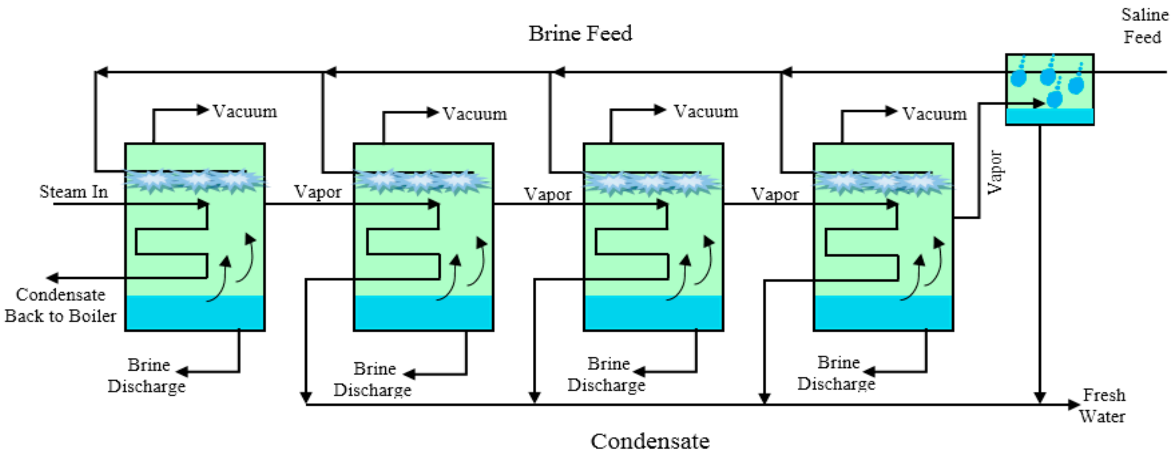

Figure 3. A schematic diagram of MED seawater desalination plant.

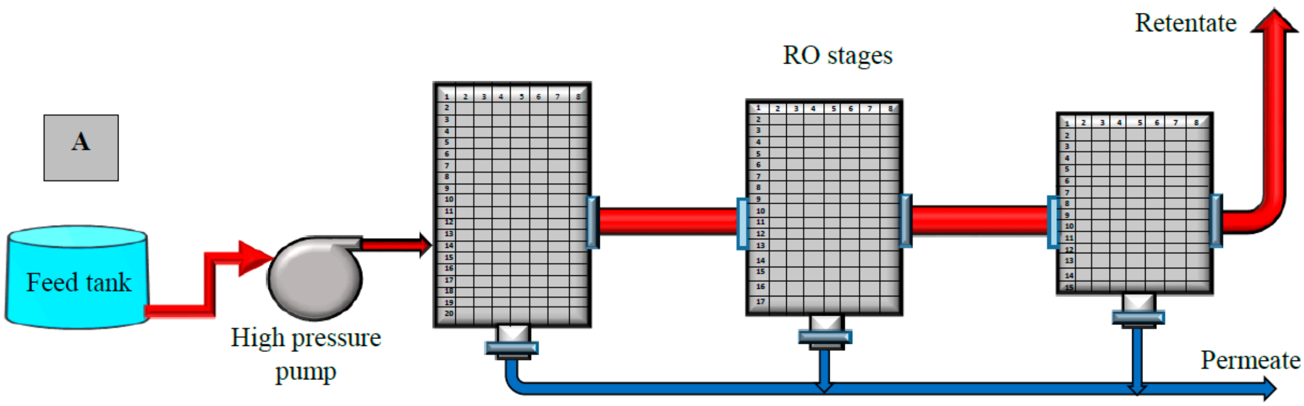

Figure 4. A schematic diagram of a conventional RO desalination plant (Adapted from [2]).

Table 1 summarises the advantages and disadvantages of the three selected water desalination methods.

Table 1. Advantages and disadvantages of selected water desalination methods [25–27].

Water Desalination Method	Advantages	Disadvantages
MSF	• Contains a heat recovery system, in addition to a heat rejection system, that enables to use of steam to heat seawater • Low plugging and scaling propensity • Deals with high salinity water • Delivers high-quality water compared to the RO process • High freshwater productivity compared to RO process	• Thermal process: Requires heat (steam, i.e., thermal energy) to produce fresh water • Higher scaling and corrosion problems due to high temperature compared to MED. This causes a reduction in the heat transfer area • Expensive. High water production cost • Very energy intensive. Consumes high specific energy compared to MED and RO • Higher capital equipment cost compared to RO • Volume and area required for MED are bigger than RO due to the bigger size of the equipment

Table 1. *Cont.*

Water Desalination Method	Advantages	Disadvantages
MED	• Lower scaling and corrosion propensity due to a lower operating temperature compared to MSF • Can utilise hot water instead of steam compared to MSF process • Lower steam temperature compared to MSF • Deals with high salinity water • Delivers high-quality water compared to the RO process • High freshwater productivity compared to RO process • Low energy consumption compared to MSF • Higher heat transfer coefficients compared to MSF	• Thermal process: Requires heat (steam, i.e., thermal energy) to produce fresh water • Expensive. High water production cost • Consumes high specific energy compared to RO process • Higher capital equipment cost compared to RO • Volume and area required for MED are bigger than RO due to the bigger size of the equipment
RO	• Operates at ambient seawater temperatures. Steam and heat recovery sections are not required compared to thermal processes. Requires electrical energy • Very low scaling and corrosion propensity due to a lower operating temperature compared to thermal processes • Membrane process: Does not require heat to produce fresh water • Less expensive than thermal processes. Low water production cost • Consume less specific energy compared to thermal processes • Lower size of equipment compared to thermal processes • Lower capital equipment cost compared to thermal processes	• Inefficient desalination process at high salinity water due to high osmotic pressure • Plugging and fouling propensity • Lower freshwater productivity compared to thermal processes • Requires high-pressure pumps to drive water and therefore requires a high-pressure piping system • Requires an intensive pre-treatment process to remove colloidal matters

4. Solar Energy Systems Powered Thermal and Membrane Water Desalination Plants

The integration of solar energy systems into thermal and membrane water desalination methods is due to the high amount of energy required to power the associated units and to shift towards sustainable solutions of low emissions of greenhouse gases. Numerous experimental and theoretical studies can be found in the literature that outlined the integration of solar energy systems into seawater desalination including MSF and MED thermal and RO membrane systems.

As confirmed by [28], the world's first solar-powered seawater RO system was erected in Jeddah, Saudi Arabia, in the early 1980s with the idea of combining PV and RO systems. The RO system of two stages membranes with an overall water recovery of 22% was used to desalinate seawater at 42,800 ppm. The PV modules were connected to 40 batteries to drive the RO system with a production capacity of 6.48 m^3/day.

Tzen et al. [29] carried out an economic analysis of a small-scale autonomous PV and RO hybrid system to cover fresh water and other water needs of a rural community in Morocco. The RO systems have a capacity of 12 m^3/day used to desalinate high salinity water of 40,000 ppm. This study confirmed the feasibility of the PV to power the small-scale RO system with a freshwater production cost of 0.087 $/$m^3$.

Due to the abundance of solar energy and reduced dependency on imported fuels in Cyprus, Kalogirou [30] approved the possibility of partly powering RO seawater desalination systems from photovoltaic panels and powering distillation evaporators from thermal solar energy systems.

Thomson and Infield [31] studied the feasibility of a battery-less photovoltaic-powered small-scale RO desalination system (3 m^3/day) to desalinate seawater of 40,000 ppm instilled in Eritrea. The total freshwater production cost is estimated to be 2.44 $/$m^3$. The PV system provides excellent energy, especially in hot climates. Furthermore, it can be stated that freshwater production is quite related to the availability of solar power.

An array of PV cells can be efficiently combined with RO seawater desalination systems to provide electrical energy. Successful projects of PV/RO desalination systems can be found in rural regions with mostly low-size desalination systems. However, the high freshwater production cost is the most disadvantage of PV/RO systems due to the high cost of PV equipment [32].

Scrivani [33] studied the feasibility of three different scenarios of a PV-Diesel hybrid system to operate a seawater desalination system of RO process of 67.68 m^3/day and specific energy consumption of 4.86 kWh/m^3 with the intention to use excess energy of PV as possible with the smallest diesel produced energy. The three scenarios are the normal mode of only PV panels to operate the RO system, a mixed mode of both PV and diesel generators, and an emergency mode of utilising diesel generators to power the RO system. The inclusion of a diesel generator is an energy management technique as it can power the RO desalination system at the power discriminating periods.

A technical and economical experimental comparative study was conducted by [34] to investigate the proficiency of a direct coupled PV system of 18 panels without batteries with a small-scale seawater RO process equipped with a recovery energy device. The overall productivity of the RO system equipped with spiral wound membranes in winter is 0.35 m^3/day which required 4.6 kWh/m^3 of specific energy consumption. an economic analysis was carried out and ascertained the freshwater production cost of 8.24 \$/m^3 of the direct coupled system.

The first project of combined concentrated solar power (CSP) of parabolic trough configuration to MED seawater desalination system is at the Plataforma Solar deAlmerı'a (PSA) in Spain. The steam generated at 380 °C is expanded in a turbine to be used to heat feed seawater of the MED process at 70 °C [35]. Indeed, it should be noted that It should also be noted that the cost of producing fresh water with a PV and CSP system is more expensive than the cost of producing fresh water with a PV and RO system. This is due to CSP's higher equipment costs when compared to PV.

Aybar et al. [36] confirmed that PV is a more realistic technology to power small and medium scales seawater RO systems, especially in rural areas with high solar insulation. However, the high cost is the main problem with these technologies. In this regard, Aybar et al. (2010) presented a pilot-scale of five stages RO seawater desalination system powered by a PV array. The water productivity of the RO system varies between 0.05–0.1 m^3/day of fresh water.

Al-Karaghouli and Kazmerski [37] analysed the energy consumption and water production cost for the integrated solar energy systems to MSF, MED, and RO desalination methods.

For small communities in European Mediterranean countries, ref. [38] developed an integration system of photovoltaic/thermal solar collectors to simultaneously provide electrical energy and thermal energy for the MED seawater desalination process. A thermoseconomic analysis was carried out in this study to quantify the optimal design variables of the associated processes. The proficiency of the integrated system was confirmed in summer compared to winter as less satisfactory due to a dramatic reduction in thermal and electrical production. Several suggestions were made to improve the performance of the integrated system such as the utilisation of 14 effects of the MED system and the outlet temperatures from the solar field should be around 55 °C in the winter and 85 °C in the summer with the possibility of utilising a turning control system.

Bilton, and Dubowsky [39] demonstrated an optimisation study to configure the hybrid system of PV and RO systems. The optimisation is carried out based on a validated conceptual model of the associated processes. This in turn has introduced the economic and operational characteristics of different configurations of PV/RO to be instilled in different locations. The RO system has been designed to produce different capacities of fresh water of 1 m^3, 5 m^3, and 20 m^3 at a freshwater production cost of 4.71 \$/m^3, 3.45 \$/m^3, and 3.01 \$/m^3, respectively.

Al-Aboosi and El-Halwagi [40] studied the possibility of utilising solar energy to operate MED and RO seawater desalination plants without the need for grid electricity.

Considering the solar diurnal fluctuations, [40] optimised the integrated systems to accomplish maximum water production with a proper selection of the best design of solar energy, thermal storage and fossil fuel resource.

Rahimi et al. [41] studied the feasibility of integrating PV with on-grid and off-grid to power 2000 m^3/day of RO seawater desalination plant in a coastal city in Iran that suffers from a water shortage with high solar radiation. Different scenarios of integrating energy recovery devices, energy storage and membrane characteristics were assessed using a simulation-based model. The sensitivity analysis identified the best scenario of a grid-connected RO system with the lowest fresh production cost of 0.76 $/$m^3$.

Ajiwiguna et al. [42] carried out a theoretical optimisation study to investigate the optimum sizing of RO units, battery-less PV modules, and water storage tanks to fulfil the lowest freshwater production cost that suits the water demand. Two scenarios of fixed and variable water demands were assessed. Accordingly, the freshwater production cost has been found to be 1.74 $/$m^3$ for fixed water demand and 2.59 $/$m^3$ for a variable water demand based on-grid system.

Shalaby et al. [43] developed an efficient nano-fluid cooling/preheating system for the PV-RO water desalination pilot plant. The RO powered by the improved PV was tested at different salinities of brackish water when the preheating technique was implemented. The hybrid PV-RO desalination system was able to produce 366 L/day when brackish water of salinity 3000 ppm was used.

The combination of PV with hybrid systems of membrane and thermal technologies is progressively researched in the open literature. However, this aspect is beyond the scope of this study and therefore will not be discussed thoroughly. Two examples are selected from the open literature. Filippini et al. [44] looked into the possibilities of combining a desalination plant of a hybrid system of MED and RO processes with a photovoltaic (PV) solar farm to generate power at a low cost and in a sustainable manner. Data from four locations, including Isola di Pantelleria (IT), Las Palmas (ES), Abu Dhabi (UAE), and Perth (AUS), was utilised to assess the economic feasibility of constructing the proposed plant, particularly the PV solar farm. The results showed that the installation of the combined system would reduce the freshwater production cost by a maximum of 34% in Isola di Pantelleria (IT) compared to the non-renewable option. Also, Okampo and Nwulu [45] proposed an integrated system of RO process and electro-dialysis (ED) and crystallization methods as an efficient design of brine management with zero brine disposal. These processes are operated via a combination of grid power, wind power and PV solar power. In this regard, a multi-objective optimisation was utilised to explore to optimal sizing of renewable energy sources that guarantee the lowest carbon emission, lowest freshwater production cost and lowest environmental effect of disposed of brine. To carry out this optimisation, the model was developed to comprise the techno-economic perspectives of the integrated processes.

5. Economic Considerations and Associated Challenges of Solar Energy Systems Powered Water Desalination Methods

Energy consumption is the main factor that affects the economics of water desalination. This section emphasis evaluating the thermal and membrane water desalination methods in terms of economic considerations and specific energy consumption to systematically appreciate the contribution of solar energy systems including photovoltaic cells, photovoltaic solar collectors and concentrating solar power. Undoubtedly, the enhancement of the economic feasibility of water desalination systems is an important task that can be achieved via the investment of energy-intensive technologies as a practical solution to mitigate the overall water production cost. This in turn would limit the negative effects of a water desalination plant on the ecosystem as a result of a reduction of emission of greenhouse gases.

Table 2 shows the overall specific energy consumption and water production cost besides the water capacity of individual thermal and membrane seawater desalination methods and integrated ones with the solar energy systems, in particular, CSP and PV.

First of all, Table 2 indicates that the conventional thermal desalination methods of MSF and MED consume higher specific energy consumption compared to the membrane technology of the RO process. This is also confirmed by [46–48] who ascertained the energy consumption of large-scale seawater RO desalination systems and MSF desalination systems between 2.5 and 4.75 kWh/m^3 and 10 and 20 kWh/m^3, respectively. However, the small-scale RO process of low productivity powered by PV consumes a higher energy consumption compared to a large-scale system due to the interrelationship between the water production capacity and freshwater production cost. Recently, He et al. [49] represented that the RO process of 48,000 m^3/day has the lowest freshwater production cost of 0.52 \$/m^3 compared to 1.1 \$/m^3 of MSF of 24,000 m^3/day.

Table 2 demonstrates that the total water production of thermal and membrane technologies of water desalination has inevitably increased as a result, to be integrated into CSP and PV systems. It is also important to mention that the water production cost is substantially related to daily solar irradiance and seawater salinity. In this regard, Bilton and Dubowsky [39] has constructed three low-capacity RO systems (10 m^3/day) powered by PV panels in three locations to investigate the influence of water salinity and daily solar irradiance on the water production cost. They confirmed that water production costs are 7.01, 5.64 and 4.96 \$/m^3 for Boston, Los Angeles, and Saudi Arabia, respectively. They attributed these values to the solar intensity of 4.4, 5.6 and 6.6 kWh/m^2/day and feed salinity of 32,664 ppm, 33,505 ppm, and 38,340 ppm for Boston, Los Angeles, and Saudi Arabia, respectively. The corresponding specific energy consumption was estimated to be 2.92 kWh/m^3, 3 kWh/m^3, and 3.3 kWh/m^3, respectively.

The progress of solar energy systems has a positive influence on reducing the overall water production of integrated RO and PV systems and corresponding specific energy consumption. To systematically present this fact, Thomson and Infield [31] appraised the freshwater production cost of a small-scale seawater PV/RO desalination system of less than 100 m^3/day to be between 11.7 to 15.6 \$/m^3. However, Alsheghri et al. [50] reported 0.825 \$/m^3 as the water production cost of the PV-RO desalination system constructed in Abu Dhabi with a capacity of 200 m^3/day. Seemingly, Tzen et al. [29] and Herold et al. [51] reported 18.5 kWh/m^3 and 18.75 kWh/m^3 as the specific energy consumption of PV-RO seawater desalination systems of 3.7 m^3/day and 0.8 m^3/day in Morocco (40,000 ppm) and Gran Canaria (35,000 ppm), respectively in 1998. This is compared to the reported specific energy consumption of Thomson and Infield [31] of PV-RO seawater desalination system 2.65 kWh/m^3 in Eritrea (40,000 ppm) in 2003 with a capacity of 3 m^3/day. In other words, the inefficient PV technology available in 1998 is the main cause behind the elevated water production cost and specific energy consumption.

Table 2. A summary of economic aspects of thermal and membrane seawater desalination methods.

Water Desalination Method	Total Capacity (m^3/day)	Specific Energy Consumption (kWh/m^3)	Water Production Cost (\$/m^3)	References
MSF	50,000–70,000	13.5–25.5	0.84–1.6	[1]
MED	5000–35,000	6.5–28	1.21–1.59	[1]
CSP + MED	>5000		2.5–3	[1]
RO	15,000–320,000	3–8	0.7–0.66	[1,37,52–54]
PV + RO	<100	4–5	11.7–15.6	[31,55,56]
PV + RO	1000	2.4	1.74–2.59	[42]
PV + RO	50,000–190,000	2.5–6.6	0.89–1.8	[57,58]

For two different cooling system designs of PV-RO systems, Shalaby et al. [43] reported a cost of 0.74–1.58 $/m^3$ for a salinity range of 1000–3000 ppm.

In this regard, the RO, MED, and MSF require 2 to 4 kWh/m^3, 14.45 to 21.35 kWh/m^3, and 19.58 to 27.25 kWh/m^3. The incorporation of photovoltaic energy systems into the RO, MED and MSF has reduced the specific energy consumption.

The most associated challenges and possible remediation methods of solar energy systems integrated with thermal and membrane seawater desalination methods are summarised below;

- To run the desalination plant consistently at static loading, an energy storage device or an auxiliary energy source is essential. The intermittent generated power as a result of fluctuated solar radiation intensity during daylight hours is the core problem of a photovoltaic system, the integration of different sources of power such as wind turbines can be effectively applied to reinforce the feasibility of solar energy systems and lessen its disadvantages. Indeed, the connection of PV to the national grid would continually preserve a fixed generated power besides the possibility to be incorporated into other renewable energy sources. For instance, the wind turbine can be switched on at night to generate electricity or compensate for the energy storage system. To be more specific, the hybrid system of a wind turbine, concentrated solar energy and photovoltaic cells can produce thermal, mechanical and electrical energy simultaneously [59]. Germany is a good example of investing in photovoltaic cells and wind turbines that assures the generation of 59.1% of its electricity on 3 October 2013 [11]. However, due to the existence of several effective parameters such as seawater salinity, overall water production capacity, water production cost, climate, geological and topographical circumstances, the accurate selection of renewable energy methods in the hybrid system with solar energy systems to power the water desalination plants is quite questionable.
- The concept of a hybrid system of different processes is a plausible option to overcome the limitations of an individual process. The exploitation of hybrid systems of renewable energy involving solar energy systems should be advanced under specific governmental support to provide uninterrupted energy for seawater desalination plants.
- It should be noted that CSP requires a massive construction area due to a high number of mirrors to concentrate solar light into photovoltaic cells besides a considerable amount of water for cooling and condensation, which presents the most limitations that retards its investments. However, the necessity of cooling water can be resolved by constructing a water desalination plant next to the sea. Thus, it can be said that the successful operation of CSP would be in the Middle East and North Africa regions.
- Fouling, dust, humidity, and climate change are well-known challenges of photovoltaic cells that can retard the overall performance and reduces its implications [17]. However, the most pressing issue confronting solar energy researchers is that of dust and cleaning solar energy equipment. According to an ongoing study, if solar collectors that get sunlight are not cleaned for a month, more than half of their solar energy efficiency is lost. Thus, continuous cleaning at intervals of no more than three days is the best technique to get rid of dust [11]. Moreover, the ambient temperature is demanded to ensure a high-performance operation of photovoltaic cells. In this regard, the presence of dust can increase the panel's temperature that limiting its efficiency to convert sunlight into electrical energy. Thus, the implication of a cooling system to cool the PV cells is important to maintain a fixed performance of generated power. Apparently, the investigation of a reliable cleaning and coating method is an essential task for upcoming research.
- Despite the freshwater production cost of solar energy systems combined with thermal and membrane seawater desalination systems being higher than the conventional seawater desalination systems, it is fair to expect an improvement in freshwater production cost to be decreased as a result of the improvement of solar energy systems. The improvement of PV panels is the main clue behind introducing a reliable source of solar energy. The beneficial properties of nanoparticles should be thoroughly

investigated in order to improve the semiconductors in PV cells and ensure a high conversion of sunlight into electrical energy. Undoubtedly, this would lower the overall water production cost of integrated PV and RO systems and pave the way for traditional water desalination plants to be converted to a high degree of sustainability.
- The arrangements of PV panels and angle adjustment using an optimisation approach should be utilised to test its influence on the overall performance of this system.
- It is essential to improve the integration of PV and seawater RO process via the improvement of high-performance energy recovery devices such as pressure exchangers besides the development of battery-less PV systems with electronic power converters.
- Storage energy is another concern of photovoltaic solar cells which depends on the quantity of solar energy and usage time. The corrosion of thermal solar collectors due to the presence of salts in water in heating cycles is the most remarkable issue of thermal solar systems. Thus, the improvement of storage energy would inevitably enhance the overall performance of PV panels.
- For the RO process, the improvement of water permeation through the membrane pores via membrane synthesis with decreasing the concentration polarization via process design besides the utilisation of an efficient energy recovery device will play a vital role to alleviate the overall water production cost of the RO process integrated into solar energy systems.
- The pretreatment and post-treatment steps of membrane technology are predominantly used to mitigate the propensity of membrane fouling scaling especially for the treatment of high-salinity seawater at high hardness levels. This in turn would add another source of power consumption. Thus, solar energy systems can be incorporated into these steps to implicitly reduce the overall energy consumption and associated water production cost. Furthermore, the interest of researchers should be directed to critically empower the disinfection steps, a dominant treatment against membrane biofouling, of water desalination plants.
- The water desalination methods including thermal and membrane technologies are designed to dispose of huge amounts of high salinity water (brine) to the ecosystem. Therefore, it is essential to improve the desalination methods by incorporating solar energy systems to mitigate the disposal of brine. An intensive effort should be paid to reinforce this field of research and optimise the control variables of the associated processes to efficiently minimise the overall amount of disposed of brine. Brine management can also be conducted by diluting the disposed of brine with seawater before discharging it into the sea. Other feasible methods were invented such as heat storage in molten salt which permits the generation of electricity. However, the improvement of brine disposal should not be at the expense of water production costs.
- To further reduce the overall energy consumption of thermal desalination technologies such as MSF, it is suggested that thermal power be replaced with low-grade steam and waste heat generated by a thermal power plant, as well as linking specific streams of connected thermal power and seawater desalination plants. This is a credible option to be used in the integrated systems of solar energy and thermal desalination systems to further reduce overall energy consumption.
- Indeed, energy security will play an important role, especially in times of fluctuating prices of oil. It is therefore important to apprehend the interdependence between different technologies to attain energy security via the deployment of the water-energy nexus. Nowadays, the oil price hits $120 a barrel, besides, the steady cost reduction of renewable energy systems would possibly stimulate to increase in the investment of this sector with governmental subsidies. Due to its high initial cost, the upcoming research should be emphasized to reduce the capital cost of photovoltaic solar energy systems.
- Due to the expected depletion of fossil energy resources (coal, gas and oil) besides the continuous impairment of the ecosystem with the absence of a worldwide remediation protocol, it is imperative to develop a flexible governance framework and new vision

by innovative enterprises considering the market regulations, economic, environmental aspects, climate conditions, water pollution and escalating water demand to construct a pioneering hybrid system of different renewable energy systems and water desalination plants. For instance, the sustainability index can be adopted to drive future projects of water desalination in order to sustain a high level of sustainability and release pressure from non-sustainable energy resources besides assuring high productivity of water at an acceptable salinity. Also, the orientation of renewable energy would be an efficient option for reliable consequences to reduce the emission of greenhouse gases into the environment.

To summarise the profitability of utilising solar energy systems to power the thermal and membrane technologies of seawater desalination, it is worth noting that the integration of solar energy systems will be of significant benefit if they are applied to small and medium sizes of seawater desalination units, as there is no economic feasibility to apply them to a large size seawater desalination plant. This is due to several economic and technological issues and therefore, there is a necessity to encourage the improvement of solar energy systems to reduce the overall production cost and extend the overall performance. This in turn would have a considerable reduction in seawater desalination cost with guaranteeing a prolonged production of fresh water at plausible prices.

6. Conclusions

Amongst the renewable energy resources, solar energy systems are widely integrated into water desalination plants due to their capacity to produce sustainable thermal and electrical energy. This paper focuses on evaluating the economic consideration and relevant challenges of the hybrid systems of solar energy and thermal and membrane water desalination methods. It can be stated that the utilisation of solar energy systems to power seawater desalination methods is of interest and should be harnessed to increase sustainability and maintain a greener environment despite supply uncertainties.

The most interesting finding of this study is that fossil fuels are still the primary global energy source and the overall water production costs of integrated solar energy systems and water desalination plants are higher than those of conventional water desalination plants due to the high cost of solar energy systems. Further research is therefore required to improve the performance of solar systems within a competitive synthesis cost to push down the overall water production cost and widen the experience of integrated solar energy in water desalination plants.

Further, as the cost of fossil fuels rises, solar-powered desalination will become more practical for large-scale applications. However, adjustments to traditional desalination processes are also required to make them more suited for integrated systems. In other words, improving the design and technical operation of both integrated processes is essential to mitigate the overall freshwater production cost.

The most associated challenges of utilising solar energy systems were addressed in this paper. First, solar desalination necessitates large collecting areas, which drives up the price more than traditional fossil-fuel-based methods. Consequently, the commercialization of solar desalination systems is contingent on cost reductions in the conversion of solar energy to electrical and/or thermal energy. Second, Solar desalination costs today outweigh conventional desalination by at least a multiplier of four. More initiatives are required on a global scale to lower the cost of renewable energy for desalination applications. These actions should be carried out in conjunction with both renewable energy and water experts. Although renewable desalination systems cannot now compete with traditional technologies in terms of the cost of water generated, they are nonetheless useful in isolated and dry places, and they are anticipated to become a viable solution on a broad scale in the coming years.

For solar energy-powered seawater desalination plants, it can be stated that half of the freshwater production cost is corresponding to the price of solar collectors, and therefore the improvement of solar collecting efficiency is viable. The intermittent generation of thermal energy and electrical power from solar energy systems can be addressed by upgrading the conversion of sunlight into energy at high efficiency using high-quality solar panel materials. Also, the combination of photovoltaic cells with batteries, fossil fuels, and wind turbines would prevent intermittent energy.

Governmental and stakeholder research investments are essential to go further in this field in order to reach commercial objectives. This will result in a game-changing technology for the long-term production of clean energy and potable water, ensuring their supply and security. In this regard, renewable energy and desalination installation should not be appraised solely on the basis of cost; rather, the total environmental impact and sustainability should be addressed.

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