Solar Energy Systems into Seawater Desalination

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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.

Keywords: seawater desalination ; solar energy systems ; solar power

1. 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 [1][2].

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 [3][4].

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 [5]. 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 [6]. 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 [1]. 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 [7]. 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.

2. 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 [8], 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. [9] 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 research 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 [10] 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 [11] 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 [12].

Scrivani [13] 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 [14] 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 [15]. 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. [16] 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 [17] 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. [18] developed an integration system of photovoltaic/thermal solar collectors to simultaneously provide electrical energy and thermal energy for the MED seawater desalination process. A thermos-economic analysis was carried out in this research 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 [19] 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 [20] 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, [20] 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. [21] 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. [22] 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. [23] 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 research and therefore will not be discussed thoroughly. Two examples are selected from the open literature. Filippini et al. [24] 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 [25] 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.

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