Renewable and Sustainable Energy Reviews 73 (2017) 789–797

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Reverse osmosis desalination powered by photovoltaic and solar Rankine cycle power systems: A review

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ARTICLE INFO

Keywords:
Reverse osmosis
Photovoltaic
Rankine cycle
Water desalination

ABSTRACT

In this work, reverse osmosis water desalination plants powered by PV and solar RC cycle systems are reviewed in detail. This review focused on the display of different designs and software used to improve productivity of the desalination plants as well as the types of solar collectors used, membrane, heat transfer fluid and working fluid of the Rankine cycle. The specific energy consumption and cost of fresh water production are also of great interest in this work. According to the results presented in this review it is not recommended to use batteries with PV to drive RO desalination plants because of the high capital and replacement cost of batteries. It is also found that when the energy recovery devices are used, the pre-heating of feed water is not required, especially in the case of PV-RO systems. Currently most of working RO plants are driven by PV, whereas solar thermal power systems (usually using PTC with ORC) are still at the stage of theoretical research. Although, the PTC-ORC-RO desalination system is recommended, it has not yet been implemented on a large scale.

1. Introduction

The shortage of potable water is one of the most challenging issues facing governments especially in remote and arid areas, where the power grid is usually not available. It is known that the desalination process requires a large amount of energy. Thus, the cost of desalinated water per m^3 is relatively high. This high cost is increased even more in remote areas where the electricity grid connection is too expensive, as well as the fossil fuel transportation cost being also very high. So, it is necessary to search for alternative sources of energy suitable for water desalination technology in these areas. The utilization of solar energy as a renewable energy source is considered the best solution for water desalination technology especially in remote and arid areas.

A detailed review of solar water desalination technologies that have been developed in recent years are presented by Shatat et al. [1]. They divided solar water desalination into two main categories; the first, is direct solar desalination in which thermal desalination process takes place in the same device, such as solar stills. The other category is indirect solar desalination, in which the plant is separated into two subsystems: the solar collector and the desalination system. The solar collector may be flat plate, evacuated tube or solar concentrator. These collectors provide thermal energy to any desalination unit, such as multi stage flash (MSF), multi-effect desalination (MED), humidification-dehumidification (HDH) and reverse (RO) and forward (FO) osmosis. They also explored the challenges and opportunities of solar water desalination worldwide. The different types of solar stills are reviewed by El-Sebaii and El-Bialy [2], Rufuss et al. [3] and Chandrashekara and Yadav [4]. They reported all methods aimed to increase the still productivity by using finned [5–8] and corrugated [7] plate absorbers, stepped type basin [9–13] and multi-effect basin [14–16]. Shalaby et al. [17] experimentally investigated the v-corrugated solar still with using paraffin wax as latent heat thermal storage. They concluded that the use of paraffin wax as thermal storage material with the v-corrugated solar still increases the productivity by 12%.

But, the solar still is not suitable for high capacity production because of it needs a large area compared with other solar desalination technologies. Li et al. [18] reviewed all types of solar systems assisted by sea water desalination technologies. In their review, solar collectors assisted MSF [19–24] and MED [25–29] are presented. The RO, HDH, passive vacuum desalination and membrane distillation driven by solar energy technologies are also reviewed [18]. They also discussed the variety of possible combinations. They concluded that solar/fossil/desalination hybrid systems are more economical and could overcome the intermittence of solar energy. They expected that with the cost reduction of future solar systems and development of novel solar technologies, solar desalination could be a valid option for future desalination plants.

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http://dx.doi.org/10.1016/j.rser.2017.01.170
Received 10 March 2016; Received in revised form 12 December 2016; Accepted 29 January 2017
Available online 08 February 2017
1364-0321/

The reverse osmosis (RO) is the most applied process of water desalination around the world so far as 65% of the desalinated water worldwide is obtained by RO [30]. So, this study focused on reviewing the RO water desalination systems.

RO is an energy-intensive process, requiring approximately 4 kWh of energy to desalinate one cubic meter of water [31]. Lamei et al. [32] presented the cost of desalted water per m^3 for 21 RO desalination plants in North Africa and Middle East. They proposed an equation to estimate the cost of desalted water per m^3 of RO desalination plant as function of plant capacity, price of energy and specific energy consumption. They used this equation to estimate the unit production cost of the desalinated water using photovoltaic (PV), based on the current and future PV modules prices. They found that the specific energy consumption is 15 kWh/m^3 for the RO plant of the lowest capacity of 250 m^3/day. Whereas, the specific energy consumption decreases to reach 5 kWh/m^3 when the capacity of the plant increases to 50,000 m^3/day. Consequently, the unit production cost of desalinated water decreases from 3.21 to 0.86 $\$/m^3$ when the capacity of the plant increases from 250 to 50,000 m^3/day. It is also clear that the unit production cost of desalinated water of the RO plant driven by PV (one of which was constructed in the area of the Red Sea, Egypt) produces 350 m^3/day, which is inexpensive compared with others with capacities reaching 5000 m^3/day, when even driven by diesel or from electricity grid.

The PV powered RO desalination system is a practical method of providing freshwater [33]. PV technology developed in the last decade has become available at a price. Most of the RO plants around the world are using PV systems due to its low price compared with solar thermal plants [34]. Recently, there is significant research activity to improve the thermal performance of solar organic Rankine cycle (ORC) powered RO desalination systems and reduce its cost. Torres and Rodriguez [35] reported design recommendations for solar ORC powered RO desalination. The design recommendations includes selection of the Rankine cycle working fluid, solar field configuration, solar ORC features, maximum and minimum operating temperature of ORC, cooling system for heat rejection, RO subsystem design, connection between ORC and RO subsystem and thermal energy storage. Different technologies of solar organic Rankine cycle powered reverse osmosis desalination systems are reviewed by Tchanche et al. [36]. Among the reported solar assisted RO seawater desalination research, PV driven RO and solar Rankine cycle (RC) driven RO are the most widely studied [18].

There is no detailed review on both PV and solar RC powered RO desalination systems which includes the detailed design and economic data for the purpose of comparison. Therefore, in this work a detailed review on the utilization of PV and solar RC for RO desalination plants are presented. The different designs of PV and solar RC systems are introduced. The specific energy consumption and the fresh water production cost of each design are also indicated. Some conclusions and recommendations for future work are drawn.

2. Reverse osmosis plants powered by PV

The PV plant is the famous method used for supply RO plant because of it still the cheapest method so far. The conventional PV system consists of the PV modules, charger controller, batteries and DC/AC inverter. Due to the high capital expense and running cost of batteries, the PV system is modified to operate without batteries by connecting the PV directly to the DC motor driven pump or via a super capacitor as electrical regulator.

2.1. RO powered by PV using batteries

Reverse osmosis derived by PV with batteries for electrical energy storage was installed by Herold and Neskakis [37] for desalted water production of 0.8–3 m^3/day. The PV system consisted of 64 monocrystalline Si modules (ATERSA, model A-75) with total power 4.8 kW, a DC/AC inverter (TRACE, model SW4548E) of nominal power 4.5 kW and batteries (TUDOR, model 10TSE80) of nominal capacity 1240 A h, 48 V. The RO desalination unit consists of spiral- wound membrane (Filmtec HR3040) of 3 m^3/day capacity. The feed water is pre-treated using two cartridge filters. In order to obtain the optimal operation parameters they tested the desalination plant, when the feed pressure is varied in the range of 45–63 bar. They developed three different operation strategies to achieve a higher flexibility of the plant operation. These operation strategies, based on the start-up and shut-down times of the plant, depend on the charging batteries level. They found that when the pressure of the feed water is 45 bar, the plant must be operated for 6.5 h to achieve the minimum required production of 0.8 m^3/day with salinity 450 ppm and specific energy consumption of 16.3 kWh/m^3. Whereas, at feed pressure of 63 bar, the plant achieve 0.155 m^3/h with salinity 330 ppm and specific energy consumption of 15 kWh/m^3.

Alghoul et al. [38] designed 2 kW PV with batteries in order to drive RO water desalination plant. They used ROSA software to design RO unit when the feed water salinity is 2000 mg/l and the produced fresh water TDS is less than 50 mg/l. Dependent on the simulation results, the RO unit is constructed with two stage configuration using one vessel of one membrane (Dow Filmtec TW30-4040) at each stage. Malti-media and five micron Sediment filters are also used as pretreatment. In order to validate the simulation model, the desalination unit is tested and good agreement between theoretical and experimental results has been obtained. They concluded that the desalination unit can produce 5.1 m^3/day if it operates for 10 h/day. They also concluded that the specific energy consumption for the proposed desalination system is 1.1 kW h/m^3.

2.2. RO powered by battery-less PV

The Matlab Simulink model is used by Thomson and Infield [39] to design a complete battery-less PV-RO desalination system for fresh water production of 3 m^3/day. For this purpose, a PV array of total 2.4 kW power with single axis tracking is used. They used a Spectra Clark pump as the energy recovery device (ERD), so the preheating of feed water is not required. They also presented a complete cost analysis assuming the life time of the whole plant was 20 years, with pump and RO membrane replacement every 5 years and 12 months, respectively. They found that the cost of produced water was \$ 2.8/m^3 (£2/m^3). The basic mechanism of the Spectra Clark pump as an energy recovery device for small capacity RO systems is presented by Thomson et al. [40]. They found that a specific heat of less than 3.5 kWh/m^3 can be obtained with this type of ERD.

A mathematical model of an RO plant driven by a battery-less PV plant is formulated by Kumarasamy et al. [41]. The optimization problem of this system is analytically solved and it is used to determine the optimal operation of two cases, without storage and, with permeate storage. They also used ROSA software as a proxy for real process to generate the input/output data which are subsequently used for estimating the model parameters. They concluded that, in the case without using storage, the production increases by 5% if the feed pressure is varied compared with constant pressure operation. Whereas, in the case of using a permeate buffer tank with varying feed pressure, the production is 36% and 28% higher than that of constant and variable pressure operation of the plant without using a buffer tank, respectively.

Helal et al. [42] studied the economic feasibility of three designs for 20 m^3/day RO plants suitable for remote coastal areas in Abu Dhabi, UAE. The proposed designs are for a diesel-assisted PV-RO plant, a fully diesel-driven RO plant and a fully solar-driven PV-RO plant. They found that the fully solar-driven PV-RO plant has the lowest total operating cost of 29938 \$/year compared with 32,469 and 35,309 \$/year for the diesel-assisted PV-RO plant, a fully diesel-driven RO,