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Modus operandi for maximizing energy efficiency and increasing permeate flux of community scale solar powered reverse osmosis systems

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ABSTRACT

Photovoltaic powered reverse osmosis systems can only be made cost effective if they are made highly energy efficient. In this work we describe a protocol to maximize energy efficiency and increase permeate flux in a fully integrated installation of such a system. The improved system consisted of (i) photovoltaic array fitted with suitably positioned and aligned North–South V-trough reflectors to enhance power output from the array; (ii) direct contact heat exchanger fitted on the rear of the photovoltaic modules for active cooling of the same while safeguarding the terminals from short-circuit and corrosion; (iii) use of reverse osmosis feed water as heat exchange medium while taking due care to limit the temperature rise of feed water; (iv) enhancing permeate flux through the rise in feed water temperature; (v) turgo-turbine for conversion of hydraulic energy in reverse osmosis reject water into mechanical energy to provide part of the energy to replace booster pump utilized in the reverse osmosis unit. The V-trough reflectors onto the photovoltaic modules with thermal energy recovery system brought about an increase in power output of 40% and the synergistic effect of (i)–(iv) gave rise to total permeate volume boost of 59%. Integration of (v) resulted in 56% and 26% saving of electrical power when the reverse osmosis plant was operated by battery bank and direct photovoltaic array respectively.

1. Introduction

The two best used energy sources for desalination are thermal and electrical. Some of the latest developments in desalination involve, a solar powered humidification–dehumidification desalination system in operating conditions of Antalya, Turkey [1]; a portable humidification–dehumidification desalination system configured by a thermoelectric cooler [2]; a biomass boiler coupled to multi basin solar still for enhanced productivity [3]; a novel multi-effect solar still with enhanced condensation surface [4] and also stepped solar still with North–South reflectors in V-trough alignment and additionally fitted metallic condensers on the sides for enhanced output [5].

Electricity driven membrane-based desalination has grown fast in the last two decades and surpassed most of other desalination technologies universally. One of the cutting-edge technologies involve hybrid membrane system combining electrodialysis (ED) and forward osmosis (FO), driven by solar energy, to produce high-quality potable water from brackish water [6]. In another instance, the coupling between the low-temperature solar organic Rankine cycle (ORC) and seawater and brackish water reverse osmosis desalination units was done using butane, isopentane, R245fa and R245ca working fluids of the solar cycle [7]. The process through which forward osmosis and osmotic heat engines can produce clean water and yield electricity from low temperature geothermal or waste heat sources was also studied [8]. Precisely, reverse osmosis (RO) has been the most visible at domestic and community levels or as large plants. In general, low energy requirement for batch-mode reverse osmosis is highly advantageous. Researchers have carried out studies on concentration polarization of batch reverse osmosis processes [9]. RO desalination unit to desalinate seawater has also been proposed, wherein, the pressure required to initiate the process has been provided by utilizing the mechanical potential energy arising from the difference in heads between a high level column of seawater and a low level column of pure water [10]. A review to highlight the milestones achieved in RO technology in terms of membrane performance has been studied in details [11]. A combination of single-stage RO with a countercurrent membrane cascade with

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recycle has been studied for an energy efficient RO process [12,13]. The widespread of RO system may be attributed to the modular nature and other developments made in the membrane quality. Whereas the RO system is much more energy efficient than thermal processes of desalination, several water starved, but sunny remote localities do not have access to grid power. In such locations, small scale solar photovoltaic (PV) powered RO systems have the potential to provide fresh potable water to the residents. PV-RO systems are modular in nature and can be installed according to the local demand, has hassle free maintenance and are environmentally benign. A study on viability of PV-RO systems in remote locations showed that the feasibility was a function of location due to variation in solar resource, water type, system demand and local governmental policies [14]. Computer-based modular design of PV-RO systems helped to determine the best configuration for a small community without expertise [15]. Smart control algorithms to increase system efficiency of PV-RO systems are important for implementation [16]. Stand-alone PV-RO systems in remote locations can be made to run on DG sets or battery power whenever there is shortage of sunshine. A typical de-centralized PV-RO system comprises of the RO plant connected to the PV array via battery bank and charge controller. The battery bank allows operation of the RO plant at a constant pressure, but increases the maintenance cost and can also result in environmental complications [17]. Today there are numerous PV-RO plants globally; the capacities starting from 50 to 50,000 litres per day. A batteryless PV operated brackish water hybrid ultrafiltration-nanofiltration reverse osmosis system was installed in outback Australia. On a typical sunny day, the system produced 1.1 m^3 permeate with 28% recovery with average specific energy consumption of 2.3 $kW\,h\,m^{-3}$ [18]. A RO unit with an average water production of 0.8–3 $m^3\,day^{-1}$ was installed in Gran Canaria Island [19]. Another PV powered RO system was installed in a village in the northern part of Jordan with a capacity of 0.5 $m^3\,day^{-1}$. The system consisted of 432 Wp PV modules and storage batteries [20]. Drinking water supply to a rural community in semi-arid Brazil through use of PV-RO system has also been studied. This system had a specific electrical consumption of 3.03 $kW\,h\,m^{-3}$ and a recovery ratio of 27% [21]. A small-scale PV-RO system to desalinate brackish water was designed at variable flow/pressure conditions for stand-alone applications in equatorial areas [22]. The experimental results of a small sea water RO desalination system in Athens attached to a Clark pump for energy recovery was presented by researchers. The system produced a maximum of 2.6 $m^3\,day^{-1}$ fresh water [23]. Experiments on a laboratory household PV-RO unit was performed using water with two different total dissolved solid (TDS) concentrations. The effect of temperature was studied in details and was found to be the most significant aspect [24]. In addition, cost computation of producing 1 m^3 of fresh water using the small PV powered RO water desalination system in desert area has been described [25]. Some basic work involves sizing approach for PV/thermal systems to operate RO plants [26,27].

Although the use of solar PV is an attractive option in localities devoid of electrical grid connectivity, an important constraint in the promotion of solar powered desalination is the high cost of power generation through the use photovoltaic modules. The major fraction of the total cost of a PV-RO system is taken up by the PV modules and as a result the cost of water from the PV-RO system increases substantially. Efforts are needed to decrease the power requirements for community scale RO units and save every joule of energy going as waste in the form of the RO reject water pressure.

The present work describes an energy efficient community scale PV powered RO desalination unit, such effectiveness brought about by:

(i) use of V-trough concentrated photovoltaic system having multiple PV modules. More specifically, arranging the modules in form of long rows with overall aspect ratio ⩾8 without recourse to any tracking. In order to boost the electrical energy output over a day, North–South reflectors were positioned at the edges of the array and aligned through seasonal adjustments of angles following computational methods.
(ii) using direct contact heat exchanger fitted on the underside of the PV modules for active cooling and use of RO feed water as heat exchange medium while taking due care to limit the temperature rise of feed water.
(iii) enhancing permeate flux from RO unit through the rise in feed water temperature.
(iv) use of turgo-turbine for conversion of hydraulic energy in RO reject water into mechanical energy to operate the booster pump utilized in the RO unit and thus save expensive PV power.

Table 1
Detailed system configuration of the PV-RO system.

Description	Detailed specification
PV Module	Kotak Urja Pvt. Ltd.
Peak power voltage (V_{mpp})	17 V
Open circuit voltage (V_{oc})	21 V
Short circuit current (I_{sc})	4.7 A
DC motor for high pressure pump	
Type	PMDC
Maximum power	746 W
Rated voltage	48 V
Maximum current	19.5 A
Rated rotational speed	1500 rpm
DC motor for booster pump	
Type	PMDC
Maximum power	746 W
Rated voltage	48 V
Maximum current	19.5 A
Rated rotational speed	3000 rpm
High pressure pump	
Type	Reciprocating 3 Pistons
Maximum pressure	400 psi (27.57 bar)
Rated flow rate	20 lpm
Booster pump	
Type	CRNI-8
Maximum pressure	362.59 psi (25 bar)
Rated flow rate	1800 lpm
RO membrane module	
Type	Spiral wound thin film composite
Model	CSMCRI 4040
Max operating pressure	400 psi (27.579 bar)
Max operating temperature	45 °C
Max feed flow rate	1500 LPH
Product water flow rate at max pressure	420 LPH
Min salt Rrejection	98%

2. Outline of system description

2.1. Location

Experiments were performed at latitude 21.77 N and longitude 72.15 E at CSIR-CSMCRI terrace, Bhavnagar, a coastal city on the eastern coast of Saurashtra, Gujarat (western part of India).

2.2. PV-RO system

The PV-V-trough system consisted of PV modules (size 1.2 m × 0.55 m) each having maximum power output of 75 W. The array consisted of 32 modules and were named Array 1,