Renewable Energy 93 (2016) 101–114

Contents lists available at ScienceDirect

Renewable Energy

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

# Design and experimental performance of brackish water reverse osmosis desalination unit powered by 2 kW photovoltaic system

M.A. Alghoul [a, b, c, *], P. Poovanaesvaran [c], M.H. Mohammed [c], A.M. Fadhil [c], A.F. Muftah [c], M.M. Alkilani [d], K. Sopian [c]

[a] Energy and Building Research Center, Kuwait Institute for Scientific Research, P.O. Box 24885, Safat 13109, Kuwait
[b] Center of Research Excellence in Renewable Energy (CoRe-RE), Research Institute, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran 31261, Saudi Arabia
[c] Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
[d] Mechanical Engineering Department, Al Jabal Al Gharbi University, Libya

ARTICLE INFO

*Article history:*
Received 26 September 2015
Received in revised form
2 January 2016
Accepted 5 February 2016
Available online 1 March 2016

*Keywords:*
Desalination
Brackish water reverse osmosis ((BWRO) unit
PV power system
Design and sizing
Experimental validation and performance

ABSTRACT

Small-scale brackish water reverse osmosis (BWRO) desalination units are not a major commercial success compared to its large-scale counterpart. Integrating renewable power systems with small-scale units would theoretically aid in their deployment and subsequent commercial success. In fact, RO units are constructed using a modular approach; this would allow them to adapt to a renewable power supply. Small-scale PV-RO would be a promising form of desalination system in remote areas, where BW is more common. The aim of this study is to quantify the effect of climatic-design-operation conditions on the performance and durability of a PV-BWRO desalination system. A small-scale unit is designed, constructed, and tested for 6 months. The design was limited to a 2 kWp PV power system, five different membranes, a feed TDS of 2000 mg/l, and a permeate TDS of less than 50 mg/l. Data pertaining to solar radiation and temperature were subsequently analyzed to determine their respective influences on current and future operations of the unit. The results showed that the optimum RO load, membrane type, and design configuration were 600 W, (4″x40″ TW30-4040), and a two-stage configuration, respectively. The PV system was able to supply the load without any significant disturbances; while the RO unit showed stable levels of permeate flow and salinity. Operating the PV-BWRO system for 10 h during the day would produce 5.1 m3 of fresh water at a specific energy of 1.1 kWh/m3. It was confirmed that there are many hours of high temperatures during the operation of the PV module (exceeding 45 °C) and battery room conditions (exceeding 35 °C), both of which could negatively affect the power output and battery autonomy. This negative effect is compounded annually; therefore, optimizing thermal regulation of PV modules and battery bank room conditions is essential in maintaining excellent operating temperatures.



## 1. Introduction

Despite the biannual monsoon torrent, fresh water is a scarcity in the rural areas of Malaysia. The people living there are five times more likely to lack access to potable water compared to their urban counterparts UNICEF & WHO [1]. The lack of potable water results in illnesses and the loss of productivity. Children are especially vulnerable, as they are not strong enough to fight diarrhea, dysentery, and other illnesses. A study was carried out involving school children living in rural communities in Lipis and Raub districts of Pahang, and the results indicated that Blastocystis (intestinal protozoan) is prevalent amongst rural children; the source of this illness is traced back to their drinking water Abdulsalam et al. [2]. Therefore, desalination is required to allow residents to enjoy better living standards.

The most widely used methods for desalination include thermal and membrane processes. Reverse osmosis (RO) is a membrane process technique, which is more popular compared to the conventional thermal process technology, such as Multi Stage Flashing (MSF) and Multi Effect Distillation (MED). One of the biggest

* Corresponding author. Energy and Building Research Center, Kuwait Institute for Scientific Research, P.O. Box 24885, Safat 13109, Kuwait.
*E-mail address:* dr.alghoul@gmail.com (M.A. Alghoul).

http://dx.doi.org/10.1016/j.renene.2016.02.015
0960-1481/

advantages of the RO system is its low energy consumption compared to all other desalination systems [3–5]. Energy consumption contributes up to 45% of the total cost of an RO system Zhu etal [6]. The investment costs for energy supply of the RO systems in rural areas makes up almost 60% of the total budget Espino et al. [7].

A significant amount of energy in the RO unit is used for the initial pressurization of the feed water Alghoul et al. [8]. The initial pressurization for brackish water occurs at ~27 bars, whereas seawater desalination requires a high-pressure of ~70 bar Abdallah et al. [9]. RO systems are flexible in the context of feed water quantity and quality, site location, and system start-up and shutdown [10,11]. The critical factors for sizing of the RO unit are the daily per capita consumption, total population, as well as hours of operation of the unit per day Tzen et al. [12]. The optimum RO system would have high recovery ratio (maximum permeate flow and minimum permeate salinity) at minimum feed pressure, and a reasonable number of membrane modules. With a low feed pressure, the life span of the membrane could be increased; however, this could in theory compromise the recovery ratio Sarkar et al. [13].

Despite the fact that small-scale brackish water reverse osmosis (BWRO) desalination units are simple desalination systems with minimum maintenance requirement, they have not seen major commercial success compared to large-scale desalination systems Ayoub and Alward [14]. Therefore, increasing the deployment of small-scale BWRO desalination systems is still a priority. The fact that the RO systems are constructed using a modular approach allows them to adapt to a renewable energy supply Lindemann [10]. Therefore, integrating renewable power system with a small-scale RO system would improve their commercial penetration [15–17]. PV-BWRO systems can be regarded as a promising desalination option in remote areas. In literature, there are many case studies of small-scale PV-BWRO desalination units at different locations around the world, such as in Egypt, powered by 19.84 kWp PV system Maurel [18], Spain (23.5 kWp) Peral et al. [19], Algeria (2.7 kWp) Kehal [20], Brazil (1.1 kWp) de Carvalho [21], Portugal (0.5 kWp) Joyce et al. [15], Oman (3.25 kWp) Loureiro D et al. [22], and Iraq (5 kWp) Al Suleimani and Nair [23]. According to Garcia-Rodriguez [24], photovoltaic energy is used to power small-scale BWRO desalination systems, resulting in a water production of up to 60 m3/day. Herold et al. [25] demonstrated a small PVRO system, which produces 1 m3/d of water at remote areas that lack grid electricity, have higher specific energy consumptions compared to its medium and large counterparts, but its initial cost is still lower compared to other desalination systems. Gocht et al. [26] investigated the technical feasibility and cost benefits of a PV-powered brackish water small-scale desalination plant in a rural area. They confirmed the socio-economic feasibility of desalination that is provided by a transient and discontinuously operated PV-coupled RO system. Generally, continuous operation is defined as a daily operation, whereas discontinuous operation is limited to 5–10 h a day, depending on the location and need for optimum operating hours. Continuous operating systems require large battery banks to provide power at night or during cloudy times; this requirement, however, increases the total costs. Another option is to store water in a storage tank to reduce the cost and the number of batteries needed [27].

The combination of renewable energy sources and water desalination systems require addressing challenges in the operation of an integrated system, specifically, the problem of unexpected fluctuations in energy production of a solar energy generation system requiring quick start units to cover shortfalls or absorb unscheduled energy generation [29]. One way to deal with these issues is through the use of integrated energy generation systems using solar energy with other renewable energy options. In recent years, there have been many researchers working on “smart” electrical grids, which is an extension of our traditional electrical grid, with distributed, medium-scale renewables-based energy generation systems and digital technologies, to meet the increasing energy demand and environmental regulations [28]. A supervisory model predictive control (MPC) was designed by Wei Qi et al. [29] to optimally operate an integrated solar/RO system, and the “smart” electrical grid able to coordinate the solar subsystems and the battery to provide enough energy to the RO subsystem to fulfill water production demands.

The main aim of this study is to learn and gain insights into the effect of climatic, design, and operation conditions on the BWRO and PV systems' performance and durability. Therefore, a small-scale BWRO unit powered by a 2 kWp PV system was designed, constructed, and tested. The RO unit was designed to treat a feed salinity of up to 5000 mg/l at permeate salinity values of less than 50 mg/l. Experimental work pertaining to this project will be conducted at the solar field of the National University of Malaysia (UKM), Bangi, Malaysia, which is located at 2° 56′ N, 105° 47′ E, corresponding to a GMT +08:00. Outdoor experimental performance of PV-BWRO system will be determined for multiple operating modes. The cost of a PV-BWRO desalination system, in the context of research purposes, will be detailed as well. Images pertaining to the PV and RO test units are shown in Fig. 1.

## 2. Materials and methods

### 2.1. Water salinity

The characteristics of the feed water vary from location-to-location, and to document these differences, samples were collected and tested from multiple sites at different distance from the sea at Mersing, Johor. The values were subsequently averaged and summarized, and the results are tabulated in Table 1. These data allowed us to conclude that the tested water was brackish.

### 2.2. Solar resources

Solar radiation is a geographically dependent feature. It is essential that we are aware of the amount of solar radiation received at a particular location at any given time [30]. Solar radiation in Malaysia is highest in the north of the Peninsular and the state of Sabah, with recorded values of 5.2 kW/m2, while the minimum solar irradiation is 4.2 kW/m2, recorded in the south of the Peninsular and the state of Sarawak [31]. The annual average solar radiation at this area is 4.794 kW/m2/day.

**Fig. 1.** Photo of PV and RO test units located in the solar field @UKM, Malaysia.