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Technical and economic evaluation of freshwater production from a wind-powered small-scale seawater reverse osmosis system (WP-SWRO)

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HIGHLIGHTS

- Penetration of wind power for reverse osmosis desalination has been analyzed.
- Cost calculations of energy and water production have been calculated by levelised cost method.
- Wind-powered freshwater production is economically and technically reasonable for site.
- Off-grid desalination systems have 2-3 times higher LCOW value than grid connected-wind turbine.
- High penetration of wind energy for desalination can greatly reduce the CO_2 emissions and energy cost.

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ABSTRACT

Wind-powered desalination is an attractive and sustainable method for providing potable water in isolated arid and coastal zones and islands. In this study, a techno-economic analysis of a wind-powered small-scale seawater reverse osmosis system (WP-SWRO) is presented. Levelised unit costs for electricity and water (LCOE and LCOW) were estimated for Gökçeada Island, Turkey. The energy requirement of the system showed that water can be produced at a cost between US$2.962 and US$6.457 $/m^3 for all wind turbines (with rated capacities ranging from 6 kW to 30 kW) at various discount rates when considering off-grid operations. For a grid connected-wind turbine system, the levelised cost of water was predicted to be in the range from US$0.866 to US$2.846/m^3. The levelised costs of electricity are predicted to be US$0.077 to US$0.155/kWh for an 8% discount rate using a 30-kW wind turbine based on the turbine-specific cost. According to the results from an emission reduction analysis, using a 30-kW wind turbine for a reverse osmosis system permits a reduction of 80.028 tonnes of CO_2 annually. The results show that wind-powered potable water production is economically and technically reasonable for the site.

1. Introduction

Water is at the centre of sustainable progress. From food and energy security to human and environmental health, water affects the livelihood of all of humanity [1]. The increasing potable water demand is one of the world's major problems associated with climate change and clean energy supplies. Fresh water accounts for only 3% of the planet's water sources, whereas the remaining 97% is salty seawater [2]. Fresh water production from seawater using various desalination processes has held the promise of solving the water scarcity problem to meet global water demand. There are various methods used for water treatment. These methods are classified into two groups: phase change/thermal processes (e.g., multi-effect distillation [MED], multi-stage flash [MSF], and mechanical vapour compression [MVC]) and membrane processes (e.g., reverse osmosis [RO], nanofiltration [NF], and electrodialysis [ED]) [3]. Reverse osmosis is a separation process that is driven by a pressure gradient in which a saline solution disperses its solutes by diffusion across a membrane [4,5].

Seawater treatment via desalination is an energy-dependent process. A large portion of the desalination facilities in the world are powered by fossil fuels that cause greenhouse gases. Because of the environmental concerns and increasing cost of fuel, alternative energy sources have been suggested to meet the energy requirements of desalination plants. The use of renewable energy sources for small-scale desalination plants is already occurring [3]. Today, desalination systems powered by renewable sources are becoming an encouraging option, particularly in isolated and dry districts where the use of conventional energy is expensive or unrealistic.

Among available water desalination systems, reverse osmosis plants have been extensively employed in recent years, primarily by virtue of their low energy requirements compared to other reasonable methods

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[6]. It is one of the most appropriate desalination processes for combining with various renewable energy sources, such as wind and solar. Coastal zones have high wind energy potential, which is often the most attractive renewable energy source for power production. Thus, wind-powered desalination is a promising alternative for coastal and island communities, whereas solar desalination technologies are more appropriate for arid regions with extensive solar energy potential.

There are different approaches that can be taken when designing wind-reverse osmosis desalination systems. Literature studies [6–14] on desalination plants powered by renewable energy include optimal design, mathematical modelling, hybrid system (PV-wind turbine) analysis, and performance and cost evaluation. Koklas and Papathanassiou [6] performed a simulation related to system operations by employing various control strategies and different configuration options when sizing the main components (wind turbine, desalination plant, etc.). The annual amount of fresh water was calculated and an economic evaluation was carried out to predict the water production cost. In this study, the results regarding the optimal sizing of the system components and the operating strategy were proposed. Smaoui and Krichen [8] presented a study on the design and energy control for a stand-alone hybrid wind/photovoltaic/fuel cell power system for supplying a desalination unit. The sizing of the components, such as the photovoltaic generator and wind turbine in the hybrid system, was investigated. Dehmas et al. [9] performed a comprehensive analysis of wind energy resources for seawater reverse osmosis treatment in Ténès, Algeria. In the study, an environmental economic analysis was performed to determine the financial investment hazards and CO_2 emission reduction. The paper shows that wind energy can be effectively applied as an energy source for a SWRO desalination plant in the region. Hejman et al. [10] investigated a system that used a direct mechanical drive pump in the reverse osmosis process. Additionally, a simple energy recovery system was used to ensure a constant recovery of approximately 20%. The system installed functioned for various operating conditions. Peñate et al. [11] assessed the most appropriate design for SWRO desalination powered by stand-alone wind energy systems. A design based on variable capacity with nominal production of 1000 m^3/d in the study was compared to a fixed capacity desalination plant. The results show that because of the intermittent nature of wind resources, the gradual capacity desalination plant is able to fit the available energy and maximise the annual water production. Cherif and Belhadj [12] predicted energy and water production from a photovoltaic-wind hybrid system coupled to an RO desalination unit in Tunisia. The results of the analysis show that the RO desalination unit driven by the photovoltaic-wind hybrid system for producing fresh water from brackish water is an appropriate solution for Tunisia. Park et al. [13] compared the performance and water cost of several small wind turbines coupled with membrane systems for Ghana using wind data. In the study, the results show that a 1-kW wind turbine provides the best performance for the lowest cost and is therefore the most appropriate power supply for coupling with the membrane system. The effects of the key parameters on the levelised cost of potable water such as climatic conditions, wind turbine power, salt concentration of water, plant arrangement and capacity, operating conditions, cost of RO modules and the wind turbines were investigated by Garcia-Rodriguez et al. [14]. Providing the solutions to rapidly increasing environmental issues and water scarcity has recently become a very attractive area of research. Due to prospective fresh water scarcity in future, desalination projects powered by renewable energy should be studied further for water production using clean and economic electricity production methods.

The main aim of this study is to assess the cost-effectiveness of a small-scale reverse osmosis system, which considers both wind-powered (off-grid) and grid-assisted options for the production of clean drinking water in Gökçeada Island, Turkey. The levelised cost method is applied to examine the unit energy and water costs in terms of various economic parameters (specific cost of wind turbine, discount rate etc.) and wind turbine power. The energy requirements of the reverse osmosis system are determined by means of the reverse osmosis system analysis (ROSA) model [15].

2. Site properties and model description of the wind-powered seawater reverse osmosis system

2.1. Wind data and seawater properties

The small-scale reverse osmosis system to be evaluated in this study is assumed to be installed on Gökçeada Island, Turkey. Fig. 1 shows the island as it sits in the Aegean Sea [16]. The island is affected by winds blowing from the north and northwest throughout the year. The north part of the island is affected by a Marmara climate, whereas the south part is a Mediterranean climate. Wind speeds are recorded using a cup anemometer at a height of 10 m above ground level at the wind observation station built on the island. The wind speed varies with height. Therefore, it is important to ensure prediction accuracy for the energy production to know the wind speeds at the various heights. The power law, which is given in detail in the literature [17], is used to extrapolate the wind speeds to obtain the conditions at the hub heights of a proposed wind turbine. The water properties of the Mediterranean Sea are used for the water to be treated on the island, and the physical and chemical characteristics of the Mediterranean Sea are listed in Table 1 [18]. The TDS (Total Dissolved Solid) value of the feed water used in this study is 37,864.4 mg/L.

2.2. System description

2.2.1. Seawater reverse osmosis system (SWRO)

The proposed small-scale RO system driven by wind energy in this study consists of a wind energy conversion subsystem and a reverse osmosis subsystem. The reverse osmosis subsystem includes a pump, membranes, and a storage tank. Fig. 2 shows a schematic diagram of a small-scale RO unit powered by a wind turbine system. This system aims for 1 m^3/h of potable water production under both wind-powered (off-grid) and grid-assisted options. The World Health Organization (WHO) and UN-based organisations propose that in semi-arid situations, a person requires approximately 20 L of fresh water per day [19]. Assuming a region consists of 1200 people, its total water requirements are 24 m^3/day. The type of the membrane chosen in the investigation is a FILMTEC SW30HRLE-370/34i, which delivers high performance over its operating lifetime and meets WHO and other drinking water standards. The membrane element has various properties, including a high-elimination, high-productivity element for use in high fouling or tough feed water conditions, smooth operations and to ensure low water cost [20]. A technical description and operating limits for the membrane are given in Table 2. For water treatment using the reverse osmosis method, energy consumption is the main consideration. The power requirements of the system include power for pumping and chemical treatment. The total power needed to pressurise the stream is calculated by:

$$P_T = \frac{27.77 Q_F P_F}{\eta_{HP}} [W], \quad (1)$$

where Q_F is feed flow (m^3/h), P_F is feed pressure (bar), the constant is the unit conversion factor, and η_{HP} is the motor and pump efficiency [21]. The energy required by the reverse osmosis system (E_D) is calculated by Eq.(2):

$$E_D = SEC \cdot Q_P [kWh] \quad (2)$$

where SEC is the system specific energy consumption in kWh/m^3 and it is defined as the energy by the system per of produced potable water. Q_P is also the fresh water production (m^3) [22]. In this study, specific