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Integration of hybrid power (wind-photovoltaic-diesel-battery) and seawater reverse osmosis systems for small-scale desalination applications

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ABSTRACT

Desalination is a method used to produce water for human consumption and/or industrial use. Seawater treatment systems powered by renewable sources are regarded as sustainable methods for providing drinking water for coastal zones and islands where there is no electrical grid. This study evaluated the operations of seven different (off-grid) power systems (wind-photovoltaic-diesel-battery) used to satisfy the electrical energy demand of a small-scale reverse osmosis system with a capacity of 1 m^3/h used on Bozcaada Island, Turkey. The hybrid optimisation model for electric renewable (HOMER) software was selected to perform techno-economic analyses of the systems. On the other hand, the reverse osmosis system analysis model (ROSA) was used to determine the energy requirement of the reverse osmosis system examined in this study. The results of this study showed that the electricity cost was $0.308/kWh for the optimal system consisting of wind turbines with a rated power of 10 kW, a 20 kW PV panel, and a diesel generator with a rated power of 8.90 kW, while the water cost was $2.20/$m^3$. Additionally, the results showed that combining the hybrid power system and reverse osmosis system could be a cost-effective method for remote areas with good wind and solar power potential.

1. Introduction

The environment, water, and energy are indispensable shareholders in the sustainable development of civilisation. One of the major problems in the world today is the growing potable water demand [1]. Most of the existing water is either present as seawater or icebergs in the Polar Regions. About 3% of the planet's water is fresh water, while the remaining 97% is salty seawater [2,3]. Removing the salinity of seawater using several desalination approaches has the potential to solve the fresh water supply problem [4].

The two major desalination methods are thermal processes based on a phase change and membrane processes based on a pressure differential [4,5]. The principal thermal distillation processes used for obtaining fresh water include the multistage flash, multi-effect, and vapour compression methods. The most common desalination processes based on membranes include electrodialysis and reverse osmosis (RO). Reverse osmosis is a separation process that is driven by a pressure gradient, in which a salty solution disperses its solutes by diffusion across a membrane [6,7]. The desalination processes require significant quantities of energy [1]. Because of industrialisation, the supply of energy has primarily focused on centralised production based on fossil fuels. However, the continuation of this style of production has caused various issues such as energy supply security, environmental pollution, and the consumption of natural resources. For a sustainable future, localised production systems based on locally available resources have become important [8]. The most current information on desalination shows that only 1% of the total desalinated water is based on energy from renewable sources [9]. Thus, an effective integration of desalination and renewable energy technologies for fresh water production is a viable option to solve the water shortage problems in isolated and dry districts using local renewable sources (e.g., wind and solar energy) [2,4]. The use of power systems powered by such energy sources in desalination processes will help to reduce fossil fuel consumption and greenhouse gas emissions. Thus, because of the increasing demand for desalinated water in energy-importing countries and small islands, there is a large market potential for renewable energy-powered desalination systems worldwide [9].

Modelling an energy generation system before implementing a project is of paramount importance for decision making and pre-feasibility analysis. Various commercial and free software tools are used by researchers for assessing the available energy systems, such as the HOMER and RETScreen software [10–12]. The literature contains few studies on combinations of desalination and renewable energy technologies for either small- or large-scale water production. Koreneos et al. [13] proposed an integrated model for the use of renewable sources (wind, solar) with the aim of desalinating seawater and compared several alternative renewable energy source-desalination schemes for a specific case. They concluded that with a greater

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renewable source potential, the cost of the electricity supplied by the power generation unit will be smaller, and hence, the water production cost of the desalination unit will be smaller. Hossam–Eldin et al. studied the use of hybrid renewable energy systems in RO desalination with the aid of a mathematical model to determine the best power system combination for economically producing potable water [14]. The results showed that hybrid systems can be regarded as expensive power sources when used for remote power applications. Spyrou and Anagnostopoulos [15] conducted a study on the optimal design and operation strategy for wind and solar energy production units and RO desalination units that could provide potable water for islands or coastal regions. The typical projected water costs in this study were 1.5–3.0 €/m^3. Khalifa [16] studied various power supply systems that used renewable and conventional energy sources for a RO desalination unit and simulated the performance of a hybrid power supply system. In this study, the lowest water cost was found to be 1.8 \$/m^3 for an RO unit powered by either a diesel generator or hybrid system consisting of a combination of a diesel generator, wind turbine, and solar panel. When the power system relied solely on renewable energy, the water cost was 2.3 \$/m^3 for solar and 2.4 \$/m^3 for wind. Setiawan et al. [17] studied the design of a small-scale hybrid power system that included renewable energy sources, a diesel generator, and a desalination plant based on the RO process for remote areas by considering the economic and environmental constraints during the project life time. The results showed that a hybrid power system could deliver better performances in terms of both the electricity production and water supply, but both were economically and environmentally viable, based on a stand-alone diesel system. Mentis et al. [18] conducted a study on the development of a tool that could design and optimise renewable energy and desalination units, taking into account the resource availability, performance, and economic data for three islands in the Southern Aegean Sea. The results of the study showed that the water costs ranged from 1.45 €/m^3 to 6 €/m^3 for the considered islands. Cherif and Belhadj [19] projected the energy and water production potential of using a hybrid photovoltaic–wind system connected to a RO unit in Tunisia. The analysis results showed that using a hybrid photovoltaic–wind system to supply the RO desalination unit used to produce potable from brackish water was a suitable solution for Tunisia. Based on the literature, it can be concluded that using desalination systems powered by renewable energy sources could play a significant role in controlling the growing load demand, reducing energy and water generation costs, and decreasing global warming, which affects climate change. For the purpose of comparison, Table 1 lists RO desalination systems powered by various power generation units, along with the plant capacity, specific energy consumption, and potable water cost.

There have been few studies on hybrid renewable energy–desalination systems that considered both a prediction model and techno-economic model to enable the integration of renewable energy sources into the desalination-fresh water production systems. To obtain the maximum utilisation of energy sources in view of the approaching fresh water scarcity, a suitable energy–desalination coupling arrangement should be further investigated for water production using pollution-free and cost-effective electrical energy production methods.

This paper considers the scenarios (diesel generators and combinations of renewable power systems) of the various off-grid power systems with the aim of supplying electricity for an RO system to meet the potable water demand on Bozcaada Island, Turkey. The HOMER software was used to seek the best power system combination. The energy demand of the RO system was determined using the ROSA model [23].

2. Methodology

The seawater desalination system proposed in this paper comprises a power generation subsystem and an RO subsystem. The RO subsystem consists of a pump, membrane, and storage tank. This system aims at 1 m^3/h of potable water production using various power generation units. The UN agencies and World Health Organization (WHO) suggest that one person in semi-dry conditions needs about 20 L of fresh water a day [4]. Accordingly, the amount of water obtained from the desalination system investigated in this study could meet the daily demand for 1200 people. The technical specifications of the RO system considered in this study are listed in Table 2. The methodology of this study includes identifying the available resources, estimating the power demand for the RO unit using the ROSA software [23], modelling the optimal power system using the HOMER software [24], and calculating the water production cost. The ROSA software is a RO design program

Table 1
RO desalination configurations powered by various power generation units.

System configuration	Plant capacity (m^3/day)	Specific energy consumption (kWh/m^3)	Fresh water production cost (\$/m^3)	Ref.
Wind-RO	24	4.38	0.86–2.84	[4]
Wind-Battery-RO	35	2.33	0.53	[5]
Wind-PV-Battery-RO			0.57	
Wind-Diesel-Battery-RO			0.74	
Wind-PV-Diesel-Battery-RO			0.74	
Wind-Diesel-RO			0.79	
PV-RO			0.82	
Diesel-RO			1.04	
PV-Battery-RO			1.05	
PV-Wind-RO	45	2.5	0.49	[6]
		5.0	0.85	
		7.5	1.21	
PV-RO	500	n.a	3.75[a]	[13]
Wind-RO			2.01[a]	
Wind-RO	150	7.3	1.6	[14]
Wind-PV-Diesel-RO	300	4.6	1.25	
Wind-RO	50	n.a	2.4	[16]
PV-RO			2.3	
Diesel-RO			1.8	
Wind-PV-RO			2.2	
Wind-Diesel-RO			2.1	
PV-Diesel-RO			2.1	
Wind-PV-Diesel-RO			1.8	
PV-Wind-RO	400	4.0	1.59	[18]
PV-RO	100		2.46	
PV-Diesel-RO	20	7.73	7.21	[20]
Diesel-RO	20	7.74	7.64	
PV-RO	44	7.33	7.34	
PV-RO	10	3.41	5.32[b]	[21]
Diesel-RO			5.47[b]	

[a] The cost of water production was recalculated using dollar-euro parity on the date of publication of the article [22].
[b] Site specific analysis results for Limassol, Cyprus.

Table 2
Technical specifications of reverse osmosis system considered in this study.

Characteristic	Unit	Value
Feed pressure	Bar	40.23
Pump efficiency	–	0.85
Feed flow	m^3/h	3.333
Fouling factor	–	0.85
Permeate flow	m^3/h	1
Recovery	%	30.00
Power requirement	kW	4.38
Specific energy consumption	kWh/m^3	4.38
Membrane	–	SW30HRLE-370/34i
Total area	m^2	206.24
Membrane element numbers	–	6
Permeate TDS	mg/L	433.93