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A hybrid renewable energy system as a potential energy source for water desalination using reverse osmosis: A review

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ABSTRACT

The water needs of the inhabitants of Saudi Arabia are met by desalination powered by electricity generated from fossil fuel. Excessive burning of fossil fuels results in faster depletion and causes an adverse impact on the local environment. Reverse osmosis (RO) desalination based on a hybrid renewable energy system (HRES) has emerged as a cleaner alternative. The primary objective of this review is to assess the current status of utilizing renewable energy for small and large-scale water desalination plants. An overview of the expansion of domestic and global desalination plant capacities is presented with the evaluation of Saudi Arabia's renewable energy potential. Numerous studies on coupling various combinations of renewable energy sources to power desalination processes are reviewed. A comprehensive analysis of the trends and technical developments of PV-RO, Wind-RO, and hybrid PV-Wind-RO for a wide range of capacities over the past three decades is provided. Designing and modeling HRES-RO desalination systems using different combinations of renewable energy sources are thoroughly analyzed and the technical aspects of their performance are presented. The application of a range of optimization and sizing software tools available for conducting pre-feasibility analysis and the comparison of the available software tools for HRES-RO desalination are also presented. The study also demonstrated that the replacement of fossil fuel with renewable energy for desalination will significantly decrease greenhouse gas emissions. The review also highlights the effect of solar and wind profiles on the economics of desalination powered by renewables. The economic analysis indicates a significant decrease in the cost of water production by hybrid PV-wind-RO systems, implying good prospects for the technology in the near future. Finally, the study provides a flowchart depicting the steps involved in installing a hybrid PV-wind-RO system in KSA.

1. Introduction

Water and energy are the essential commodities in the present world for sustaining life. A major portion of the globe is covered by water bodies primarily in the form of oceans, seas, and bays, in addition to ground water and other salt water bodies. Only 3% of the total assets of water is available in the form of freshwater, while the remaining 97% is salt water [1]. Most of the freshwater is either available underground which is hard to reach or in the form of frozen glaciers, permafrost, and ice. Approximately 70% of the total consumption of water is used for agriculture, while industries account 20%, and the remaining 10% is used to meet the overall household needs. Water scarcity is the major problem facing by the world at present with increasing demands of good quality of water in many regions due to the massive increase in the population and the growth of the economies [2]. Water from seas and other saline water bodies are not suitable for direct human consumption, agricultural and industrial purposes. According to the World Health Organization (WHO) standards, the maximum allowable limit of total dissolved solids (TDS) in water is around 500 ppm. However, these water bodies have TDS in the range of 10,000–45,000 ppm [3]. Thus, shortage of freshwater in many areas can be alleviated by the desalination of saline water.

Desalination is the process of the removal of salts from the feedwater, typically containing a high concentration of salts (brine), to produce freshwater (containing a low concentration of salts) [4]. Desalination is one of the earliest forms of water treatment used by mankind, which has become a sustainable alternative solution for water scarcity problem in the residential and industrial sectors. Water desalination became lifesaving technology, especially in the Middle East and African countries where the rainfall is inadequate. Among the countries

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Nomenclature

m^3	Cubic meter
ppm	Parts per million
TDS	Total dissolved solids
RES	Renewable energy system
SW/BW	Seawater / Brackish water
ERD	Energy Recovery Drive
V	Volts
W	Watts
kW	Kilowatt
MW	Megawatt
GW	Gigawatt
PW	Petawatt
kWp	Kilowatt peak
kWh/m^3	Kilowatt-hour per cubic meter
GWh	Gigawatt hour
TWh	Terawatt hour
Ah	Ampere-hour
m^2	Square meter
h/day	Hours per day
l/day	Liters per day
L/min	Liters per minute
m^3/day	Cubic meter per day
m^3/h	Cubic meter per hour
m/s	Meter per second
LCOE	Levelized cost of Energy
\$/m^3	US dollar per cubic meter
\$/kWh	US dollar per kilowatt hour
i_{pvc}	PV module current
V_{pv}	PV module voltage
I_{ph}	Photo-generated current in a PV cell
N_s	No. of solar cell is series
N_p	No. of solar cells in parallel
η	Ideality factor of diode
I_{RS}	Reverse saturation current
v_T	Thermal voltage
P_{max}	Maximum power output of a PV module
λ	Tip speed ratio
ω	Wind turbine speed
v	Wind speed
C_p	Maximum power coefficient
β	Blade pitch angle
A	Swept area of the blade
I_{PV}	Total current of a PV system
I_{WC}	Total current of a wind system
I_L	Load current
Q	Charge transfer in a battery
C_{bat}	Battery capacity
η_c	Battery coulomb efficiency
Δ	Self-discharge coefficient
E_{deg}	energy generated by the diesel engine
P_{deg}	Rated power of diesel generator
η_{Deg}	Diesel generator efficiency
$\eta_{overall}$	Total efficiency of the generator
Q_F	Feed water flow
Q_B	Brine water flow
Q_P	Portable water
Ω_f	Motor pump angular speed
θ_{vr}	Valve reject opening
C_e	Feed water salinity
Q_p	Permeate flow
CoW	Cost of Water

in the Middle East, Saudi Arabia is a vast country with its inhabitants distributed far and wide. Thus, the country has resorted to seawater desalination and transportation of sweet water by various means to the interior regions to meet its freshwater demands.

A detailed analysis of the global, regional, and domestic or residential utilization of sweet water and the available renewable energy sources in Saudi Arabia are provided in this section. In Section 2, the state-of-the-art technological advancements for water desalination based on renewable energy, such as wind, solar, and hybrid renewables are discussed. The goal of this review is to survey the leading desalination technologies based on renewables and demonstrate the suitability of renewable-energy-based water desalination for both small and large-scale sweet water production. Renewable energy sources such as wind and solar are abundant in almost every part of the Kingdom of Saudi Arabia. Hence, renewable energy can be economically utilized for the distributed small-scale production of sweet water in remote areas. This approach will reduce the dependency on fossil fuel for water desalination and minimize the cost and risk of water distribution to remotely located populations of Saudi Arabia. As sweet water can be produced close to remotely located populations, the utilization of renewable energy for water desalination will minimize the sweet water transportation costs.

1.1. Global desalination capacities

Water desalination technologies were developed several decades ago due to the fact that 42 cities of the 71 largest cities that do not have access to adequate freshwater resources are located along a coast [5]. International Desalination Association (IDA) indicates that currently, about 18,500 desalination plants operating in 150 countries with a maximum contracted capacity of around 99.8 million cubic meters of water per day as of 2017 [6]. The largest producers of desalinated water according to the IDA are Saudi Arabia, UAE, Spain, Kuwait, and Algeria [7]. Despite the fact that desalination technology is an energy-intensive process, it is best suited for remote areas where there is no other alternative. One example of oil abundant Middle East countries where energy is available at a low cost but the cost of transportation of sweet water is high [8]. Recent estimates indicate that about 53% of the world's desalination potential is installed in the Middle East and North Africa (MENA) regions followed by North America and Asia [9] as shown in Fig. 1.

In the United States, 325 desalination facilities are operational. According to the Texas Water Development Board [10], Florida is the leading region utilizing desalination technology in states with 150 operational desalination plants and their capacities to increase by another 25% by 2025, equivalent to 33 million cubic meters per day [11]. Texas has 46 desalination facilities with an aggregate capacity of 465,605 m^3/day [10]. About 1,000 desalination plants are operational in India with

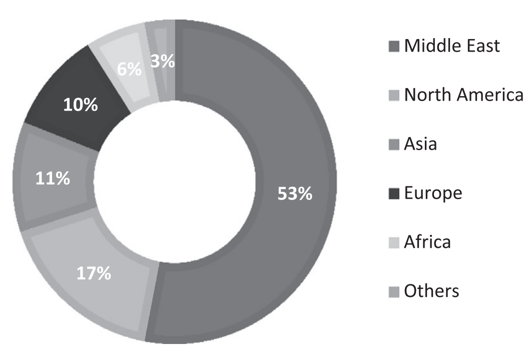

Fig. 1. Distribution of worldwide desalination capacity adapted from [9].