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Modeling and optimization of hybrid wind–solar-powered reverse osmosis water desalination system in Saudi Arabia

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ABSTRACT

A hybrid wind/solar powered reverse osmosis desalination system has been modeled and simulated. The results of the simulation have been used to optimize the system for the minimum cost per cubic meter of the desalinated water. The performance of the hybrid wind/solar powered RO system has been analyzed under Dhahran, Saudi Arabia, weather data for a typical year. The performance has been evaluated under a constant RO load of 1 kW for 12 h/day and 24 h/day. The simulation results revealed that the optimum system that powers a 1-kW RO system for 12 h/day that yields a minimum levelized cost of energy comprises 2 wind turbines, 40 PVs modules and 6 batteries and the levelized cost of energy of such system is found to be 0.624 $/kW h. On the other hand, for a load of 1-kW for 24 h/day, the optimum system consists of 6 wind turbines, 66 PVs modules and 16 batteries with a minimum levelized cost of energy 0.672 $/kW h. Depending on the salinity of the raw water, the energy consumption for desalination ranges between 8 and 20 kW h/m^3. This means that the cost of using the proposed optimum hybrid wind/solar system for water desalination will range between \$3.693/m^3 and \$3. 812/m^3 which is less than the range reported in the literature.

1. Introduction

The scarcity of fresh water is a growing international problem that challenges many countries. Saudi Arabia that witnesses a rapidly increasing population and industrial growth depends mainly on the sea water desalination as the main source of fresh water. This is a very expensive and energy consuming process. In addition to the high cost and energy consumption of the seawater desalination process, the transportation of the fresh water to the highly populated region in the central areas of Saudi Arabia and to the small cities and villages over large distances across Saudi Arabia adds to the cost considerably [1,2]. The need for potable water in many of small cities and villages on the coastal areas as well as in many of the remote small villages and cities in the central regions of Saudi Arabia opens the door for the use of renewable energies to power small sea and brackish water desalination due to the availability of solar and wind energies in these open desert areas [3,4]. Saudi Arabia as well as many of the Arab countries occupies a large area of the sun belt. This makes the solar energy as attractive source of renewable energy. However, the sun is not available over night. This makes the wind energy a competitive source of renewable energy especially in the coastal regions where seawater desalination plants is to be built and the in the remote areas where there is no electric grid and where brackish water needs to be desalinated. The use of solar and wind energies as well as many other renewable resources as renewable source of clean energy, the use of renewable energy to power desalination plants has tremendously grown over the last decade. In this regard, Voivontas et al. [5] explored the potential market for desalination systems powered by renewable energy in Greece. The economic analysis of water desalination over the last few year showed that the desalination cost is decreasing. The review of these economic studies of different desalination methods [2] revealed that the membrane (mainly Reverse Osmosis (RO)) methods are the optimal choice even for large systems and this is attributed to the low energy consumption due to the recent advances in the membrane technologies over the last few years. Recent studies of the rapidly emerging technologies [6–28] showed that some of these technologies are feasible and economic while others still need more research and development.

On the other hand, the use of solar assisted water desalination systems has tremendously expanded over the last few years. Many review articles summarized the advances and development in solar-powered water desalination systems [29–32]. These reviews revealed that there are many ways to integrate solar energy with water desalination technologies. However, the solar-powered desalination systems can be categorized into two main categories; one is based on the thermal effect of solar energy and the other one is based on the photo-voltaic effect of the solar energy. The solar thermal systems are usually integrated with direct or indirect water distillation systems while the solar PV systems are usually

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Nomenclature

C_B	the charge capacity of battery bank
C_{bat}	cost of the battery bank, Eq. (26)
C_{PV}	cost of the PV modules, Eq. (26)
C_{wind}	cost of the wind generator, Eq. (26)
EXC	energy excess percentage
F_c	is the factor representing connection loss
F_o	is the coefficient representing power loss caused by other factors
i_{pv}	module optimum operating point current at arbitrary conditions (A)
i_{sc}	module short circuit current (A)
i_{mp}	module maximum power current (A)
I	the irradiance on a horizontal plane (kW/m^2)
I_o	the extraterrestrial total solar irradiance (kW/m^2)
I_T	total radiation incident on tilted plane (kW/m^2)
I_{st}	standard light intensity (1000 W/m^2)
k_t	is the daily clearness index
$LPSP$	is loss of power supply probability
LCE	levelized cost of energy
n	is the day of the year
P_T	is the total energy generated by PV array and wind turbines
P_L	is load demand at the time (t)
p_{pv}	is the energy generated by the PV module
P_w	is the output power of wind turbine at wind speed
R_b	is the ratio of beam radiation on the tilted surface to that on a horizontal surface
RC	is the renewable contribution
RO	Reverse Osmosis
r_d	is ratio of diffuse radiation in hour/diffuse radiation in day transmittance absorbance product
T	is time period, Eq. (22)
T_A	is the ambient temperature at arbitrary conditions (°C)
T_{st}	is the standard temperature (25 °C)
T_c	is the cell temperature (°C)
T_r	is the reference temperature for the cell efficiency (°C)
ΔT	is the deference between the cell temperature and the standard temperature
V_{pv}	module optimum operating point voltage at arbitrary conditions (V)
v_{oc}	module open circuit voltage (V)
v_{mp}	module maximum power voltage (V)
ΔV	is the difference between module optimum operating point voltage at arbitrary conditions and module maximum power voltage Eq. (2)
v	is the wind speed at hub height (z) (m/s)
v_o	is wind speed at the reference height (z_o) (m/s)
v_c	cut-in wind speed of the wind turbine (m/s)
v_r	rated wind speed of the wind turbine (m/s)
v_f	cut-off wind speed of the wind turbine (m/s)
WE	wasted energy
α	is the ground surface friction coefficient
α_o	module current temperature coefficient (A/°C)
φ	latitude (°)
β	tilt angle of plane to ground (°)
β_o	module voltage temperature coefficient (V/°C)
δ	is the declination of the sun (°)
η_r	is the module reference efficiency
η_m	is the module efficiency
η_{pt}	the efficiency of power tracking equipment, which is equal to “1” if a perfect maximum power point tracker
η_{inv}	is the efficiency of inverter
η_{batt}	is the charge efficiency of battery bank
σ	is the self-discharge rate of the battery bank

integrated with membrane (mainly RO) desalination systems. However, water desalination technologies that are based on integrating solar thermal energy with membrane desalination technologies have been emerged and used over the last years [29].

Al Malki et al. [33] presented the experience of integrating renewable energy, mainly wind and solar energy, to power a reverse osmosis desalination systems to desalinate brackish water in Oman. The study showed that solar energy can be feasibly used for water desalination but it needs backup for continuous operation. On the other hand, average wind speed of 3 m/s was enough to pump and desalinate ground water at a rate of 86 m^3/day by 20 h pumping every day from a well of 30 m head. Abdul-Fattah [34] considered five options of solar desalination systems to select an optimally operating system that meets a predefined set of objectives. The study showed the solar-powered reverse osmosis desalination systems as the most optimally operating desalination system that meets this pre-defined set of objectives in providing fresh water to remote arid zones under Saudi Arabia weather conditions. Delgado-Torres et al. [35] and Delgado-Torres and García-Rodríguez [36] introduced preliminary designs for solar powered low temperature organic Rankine cycle that is used to power reverse osmosis desalination systems. The two studies focused on the effect of the working fluid on the performance of the system. Kosmadakis et al. [37] carried out a theoretical parametric analysis to assess the effect of various parameters on the performance of a two stage solar Rankine cycle for RO desalination system. The analysis showed that the slope of the collectors as well as the number of solar collectors and the duration during which the system is operating under full load conditions has an impact on the system performance. Various aspects of renewable energy hybrid desalination system performance have been studied by many researchers [38–52]. The thorough literature cited above revealed that there was no trial to investigate the feasibility of using hybrid PV-wind powered reverse osmosis system water desalination in Saudi Arabia despite the urgent need for fresh water in many of remote areas in Saudi Arabia that has abundant solar and wind energy. The main objective of the present article is to introduce the development of simulation software that can be used to optimally size the component of an autonomous hybrid PV-wind powered reverse osmosis desalination system under Saudi weather conditions. The simulation software is based on the mathematical modeling of the system components including the energy conversion and performance in addition to the capital and operation cost of the system. Both solar energy and wind energy were calculated and estimated by the help of collected weather data for the studied region. The optimization procedure was implemented using MATLAB software Package.

2. Approach and methodology

The configuration of a PV-wind hybrid system considered in the present work comprises of wind generator(s), PV array, an RO system and a battery bank. Because most of electric motors use AC power supply, an inverter is used before the RO system. The assessment and optimization for sizing of the hybrid PV-wind power generation system were carried out according the following steps:

- The first step of the analysis is the development of the mathematical model that comprises all the required equations to model each component of the hybrid system (e.g. PV, wind generator, battery, etc.).