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Design of a cost-effective wind/photovoltaic/hydrogen energy system for supplying a desalination unit by a heuristic approach

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ABSTRACT

The techno-economic assessment, optimization, and sizing of grid independent renewable energy systems affects not only the likelihood of deployment but also their reliability to supply potable water and electricity where needed. Despite many investigations on hybrid renewable energy systems (photovoltaic/wind), the reverse-osmosis desalination unit powered by solar and wind electricity production systems with hydrogen energy storage, and effects of integrating water desalination alongside meeting load demand, is rarely found. In this paper, a hybrid photovoltaic/wind/hydrogen/reverse osmosis desalination system is modeled and designed for increasing the fresh water availability and to meet the load demand to a stand-alone region in Iran. The configuration of the proposed hybrid system is optimally determined with respect to two optimization criteria, the life cycle cost of the economic evaluation and the loss of power supply probability concept for the reliability. For this aim, an efficient metaheuristic technique based on artificial bee swarm optimization is used. From the results it is seen that at a maximum loss of power supply probability set to 0–10% the photovoltaic/hydrogen/reverse osmosis desalination is the most cost-effective energy system and photovoltaic/wind/hydrogen/reverse osmosis desalination and wind/hydrogen/reverse osmosis desalination systems are in the other ranks.

1. Introduction

Water and energy are necessary for the existence and the development of modern societies. However, most water, approximately 97%, is saltwater in the oceans and the remaining 3% is freshwater, and about 25% of the world's population does not have access to adequate quantities of fresh water (Koutroulis and Kolokotsa, 2010). Additionally, freshwater scarcity is becoming an increasingly significant problem in many areas around the world (He et al., 2015). Water desalination offers a promising and viable technology for providing drinking water (Shannon et al., 2008), but its widespread use is impeded by its high economic cost, especially due to high energy consumption (Fritzmann et al., 2007; He et al., 2015). Furthermore, the current use of traditional fossil fuels as the main power source for desalination is increasing concerns about climate change and the need to reduce greenhouse gas emissions (He et al., 2015; Subramani et al., 2011).

Nowadays the method of reverse osmosis (RO) dominates globally because of its ability to desalinate water with relatively low energy requirements and costs, it requires only electricity, and can operate using renewable energy technologies such as wind turbines and photovoltaics (Garcí, 2003; Koutroulis and Kolokotsa, 2010; Spyrou and Anagnostopoulos, 2010). The use of renewable energy sources for driving RO desalination units is particularly favored in remote areas (Bourouni et al., 2011; Koroneos et al., 2007). So, desalination systems powered by hybrid renewable energy systems (HRESs) offer a promising option for many remote small villages and cities in mainland regions and many small cities and villages in coastal areas.

If desalination systems powered by HRESs are optimized, they can be more cost-effective and reliable. The main advantage of a desalination system powered by HRESs is the ability to develop small scale desalination plants. The electricity from photovoltaic (PV) collectors and wind turbines (WTs) can be used to drive high-pressure pumps in reverse osmosis plants. The fuel cell acts as a backup power supply for periods when the demand is high. The system includes an electrolyser to produce hydrogen from excess electrical energy generated by the renewable energy sources (solar and wind).

RO desalination units having various energy supply combinations have been reported, including PV/RO (Joyce et al., 2001), WT/battery/RO (Tzen and Morris, 2003), PV/battery/RO (Masson et al., 2005), WT/RO (de la Nuez Pestana et al., 2004; Koklas and Papathanassiou, 2006), PV/diesel/RO (Helal et al., 2008), PV/WT/

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diesel/RO (Setiawan et al., 2009; Voivontas et al., 2001), PV/WT/-battery/RO (Bourouni et al., 2011; MOkheimer et al., 2013), and PV/FC/battery/RO (Clarke et al., 2015). Al Malki et al. (1998) integrated renewable energy sources (solar and wind) to power an RO system for desalinating brackish water in Oman and demonstrated, for the first time in Oman, that solar power can be used to run an RO desalination plant to produce fresh water but that it needs a backup energy source for continuous operation. de la Nuez Pestana et al. (2004) studied an RO plant connected directly to a wind system without energy storage. Spyrou and Anagnostopoulos (2010) developed a computer algorithm to simulate and economically evaluate a stand-alone desalination system powered by renewable energy sources and a pumped storage unit. Stochastic optimization software based on evolutionary algorithms is implemented to optimize the plant design for various objectives, like minimization of fresh water production cost and the maximization of water needs satisfaction. Koutroulis and Kolokotsa (2010) presented a methodology for the optimal sizing of desalination systems, driven by PV modules and WTs. The purpose of the proposed methodology is to derive, among a list of commercially available system devices, the optimal number and type of units so that the 20-year total system cost is minimized consumer water demands are completely met. The total cost function minimization is implemented using genetic algorithms and it was found that the total cost of the desalination system is highly affected by the operational characteristics of the devices comprising the system, which affect the degree of exploitation of the available solar and wind energy potentials. Cherif and Belhadj (2011) estimated and evaluated over a large time period energy and water production from a PV/WT hybrid system coupled to a RO desalination unit in southern Tunisia. Bourouni et al. (2011) presented a new model based on genetic algorithms for coupling a small RO unit to renewable energy sources (PV/WT/batteries/RO) for Ksar Ghilène village in southern Tunisia. Hossam-Eldin et al. (2012) used a mathematical model and a related computer program for sizing hybrid renewable energy systems combined with RO desalination. MOkheimer et al. (2013) proposed a model for the optimization of a hybrid wind–solar-powered RO water desalination system in Saudi Arabia. He et al. (2015) proposed a novel RO seawater desalination plant powered by photovoltaics and pressure-retarded osmosis, and investigated the feasibility of two stand-alone schemes: salinity-solar powered RO operation and salinity powered RO operation. Although studies on various aspects of RO desalination-based hybrid systems have been reported in the literature, informative models and efficient optimization tools for optimal sizing and techno-economic analysis are seldom found.

Nevertheless, some optimization techniques for sizing hybrid systems have been reported (Ekren and Ekren, 2010; Maleki and Askarzadeh, 2014b; Merei et al., 2013). Nonlinear programming (Roy, 1997) and HOMER (Hybrid Optimization of Multiple Energy Resources) (Fazelpour et al., 2014; Sen and Bhattacharyya, 2014) are two common algorithms for the optimal design of hybrid systems. HOMER energy modeling software is a particularly powerful tool for designing this type of system, but when the number of possible design points is very high; this method can require excessive calculation time. Another design tool, HOGA (Hybrid Optimisation by Genetic Algorithms) developed by Bernal-Agustín and Dufo-López (2009), uses an evolutionary algorithm for the design of hybrid systems. HOGA is capable of applying an enumerative algorithm and is useful for validating the results reached by means of the evolutionary algorithm (Ekren and Ekren, 2010). Therefore, we propose here using heuristic methods, such as heuristic algorithms, to solve these kinds of optimization problems, based in part on the usefulness of heuristic algorithms in solving such time-consuming optimizations. Heuristic algorithms such as harmony search (Maleki and Askarzadeh, 2014b), genetic algorithm (Mellit et al., 2010; Merei et al., 2013), simulated annealing (Ekren and Ekren, 2010; El-Naggar et al., 2012; Garlík and Křivan, 2013), particle swarm optimization (Maleki et al., 2016a), and others (Maleki et al., 2015; Sinha and Chandel, 2015) are techniques for sizing hybrid systems.

In this article, we consider the continuous variables (photovoltaic area and the swept area of wind turbines) and the integer variable (number of hydrogen tanks) in the optimization model for a hybrid PV/WT/hydrogen/RO system. We propose an efficient version of heuristic algorithms for optimally designing stand-alone desalination systems driven by renewable energy sources (PV and WT) in the remote area of Davarzan, Khorasan, Iran. For achieving this objective, an artificial bee swarm optimization (ABSO) algorithm is proposed for determining the optimum sizing of the PV/WT/hydrogen/RO system.

2. Mathematical modeling

Fig. 1 presents the structure of the hybrid energy system which forms the focus of this study. This structure consists of wind turbine (WT), photovoltaic (PV) panel, a fuel cell (FC) coupled to an electrolyser, DC/DC converters and an inverter which is used to interface the DC voltage to the consumer load AC requirements. The WT module and the PV work together to meet the load demand. If the total electric energy generated by the renewable energy sources is greater than the load, the excess electric power is used to operate the electrolyser and produce hydrogen. When power shortage takes place, stored hydrogen converts into electrical energy by using FC which is considered as a secondary power source. The optimization of a hybrid renewable energy system (HRES) is important and leads to a good balance between performance and cost. A water tank is used to store the surplus desalinated-water produced, which is not used directly by the desalination system consumer.

2.1. Basic models

2.1.1. Modeling of PV power

The output power of a PV panel can be obtained as follows:

$$P_{PV}(t) = \eta_{PV} R_t A_{PV} \tag{1}$$

where P_{PV} is the power generated by PV panels (kW), R_t is the solar insolation (kW/m^2), A_{PV} is the total area occupied by the set of PV panels (m^2) and η_{PV} represents the efficiency of the PV panels, which is given by Bakelli et al. (2011):

$$\eta_{PV} = \eta_r \eta_{pc}\left[1 - \beta\left(\left(T_{air} + \left[\frac{NOCT - 20}{800}\right]R_t\right) - T_{ref}\right)\right] \tag{2}$$

where η_{pc} is the power conditioning efficiency (equal to 1 if a perfect maximum power tracker is used), η_r is the reference module efficiency, T_{ref} is the cell temperature at the reference conditions (usually set to 25 °C), β is the photovoltaic panel efficiency temperature coefficient (-3.7×10^{-3} °C^{-1} for mono and polycrystalline silicon (Ismail et al., 2013)), T_{air} is the ambient air temperature (in °C), R is the solar radiation, and $NOCT$ (normal operating cell temperature) is the nominal cell operating temperature (43 °C here), typically stipulated by the manufacturer.

2.1.2. Modeling of wind power

The output power of a wind turbine is calculated as follows (Caballero et al., 2013):

$$P_{WT}(t) = \begin{cases} 0, & v(t) \leqslant V_{ci} \text{ or } v(t) \geqslant V_{co} \\ \frac{P_r \cdot v^3(t)}{(V_r^3 - V_{ci}^3)} - \frac{P_r \cdot V_{ci}^3}{(V_r^3 - V_{ci}^3)}, & V_{ci} < v(t) < V_r \\ P_r, & V_r \leqslant v(t) < V_{co} \end{cases} \tag{3}$$