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Weather forecasting for optimization of a hybrid solar-wind–powered reverse osmosis water desalination system using a novel optimizer approach

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ABSTRACT

The optimum design for a stand-alone hybrid desalination scheme, able to fulfill the fresh water demand of a remote area located in Davarzan, Khorasan, Iran, is determined and investigated. The scheme consists of a reverse-osmosis desalination unit powered by solar and wind electricity production systems with battery energy storage. To predict the energy production, data from many weather stations are required, and a new forecasting strategy is proposed for weather related parameters (solar irradiance, wind speed, and ambient temperature). The system is implemented and tested using real data from northeastern Iran. To determine the optimal values of parameters for the hybrid renewable energy system that satisfy the load in the most cost-effective way (minimizing the life cycle cost and not exceeding the maximum allowable loss of power supply probability), the use of harmony search and a combination of harmony search with chaotic search is proposed. As an efficient heuristic, harmony search is easy to implement and can escape from local optima. The decision variables (number of batteries, total swept area of the rotating turbine blades, and total area occupied by the set of photovoltaic panels) are optimized using a harmony search-based chaotic search for the most cost-effective system.

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 [1]. Additionally, freshwater scarcity is becoming an increasingly significant problem in many areas around the world [2]. Water desalination offers a promising and viable technology for providing drinking water [3], but its widespread use is impeded by its high economic cost, especially due to high energy consumption [2,4]. 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 [2,5].

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 photovoltaics and wind turbines [1,6,7]. The use of renewable energy sources for driving RO desalination units is particularly favored in remote areas [8,9]. 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. To predict energy production, data from many weather stations are required.

Because of the rapid rate of growth of renewable energy implementation, there is an increasing need for more accurate modeling and weather forecasting. These activities are useful for the control and optimization of intermittent renewable energy systems. Very short-term forecasting of renewable sources with a limited time horizon (about 12 h or less) is insufficient for optimization and efficient control of renewable energy systems. Forecasts for up to 24 h or more are needed to optimize the operations

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of stand-alone and hybrid renewable energy systems [10]. Hence, the development of more accurate methods is needed for modeling and forecasting renewable sources (hourly wind speed, hourly solar irradiance, and ambient temperature).

Computational intelligence (fuzzy logic, neural network, and hybrid system) has been applied with success for the modeling and forecasting of time series [10–12]. This can assist in forecasting weather related parameters.

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 wind turbines (WTs) and photovoltaic (PV) collectors can be used to drive high-pressure pumps in reverse osmosis plants. Batteries (energy storages) are required for sustaining the system operation when insufficient renewable energy (solar and wind) is available.

RO desalination units having various energy supply combinations have been reported, including PV/RO [13,14], WT/RO [15,16], diesel/RO [14], PV/battery/RO [17], WT/battery/RO [15,18], PV/diesel/RO [14], PV/WT/diesel/RO [19,20], and PV/WT/battery/RO [8,21]. Pestana et al. [16] studied an RO plant connected directly to a wind system without energy storage. Bourouni et al. [8] 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. Mokheimer et al. [21] proposed a model for the optimization of a hybrid wind–solar-powered RO water desalination system in Saudi Arabia. Al Malki et al. [22] 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. He et al. [2] 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. Spyrou and Anagnostopoulos [6] 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. Eldin et al. [23] used a mathematical model and a related computer program for sizing hybrid renewable energy systems combined with RO desalination. Koutroulis and Kolokotsa [1] 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 such that the 20-year total system cost is minimized, while simultaneously the consumer's water demand is completely covered. 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 [24] estimated and evaluated over a large time period energy and water production from a PV/WT hybrid system coupled to an RO desalination unit in southern Tunisia.

In the present article, an optimization model is developed for a stand-alone desalination system powered by renewable energy sources (PV/WT/battery/RO). The model is developed based on three decision variables related to the system components: number of batteries (an integer variable), total swept area of the rotating turbine blades (a continuous variable), and total area occupied by the set of PV panels (a continuous variable). Since optimal sizing in hybrid PV/WT/battery/RO systems is a non-linear and non-convex optimization problem and contains integer and continuous decision variables, a powerful optimization technique is needed for effectively solving such problems.

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. Also, it is observed in the literature that the numbers of components, namely, the number of wind turbines and PV panels, are usually used as the decision variables of the optimization model. This is a drawback that limits the optimization flexibility since the optimization problem is solved for a given type of wind turbine and PV collector; if the type of wind turbine or PV collector varies the optimization problem needs to be solved again. To overcome this drawback, two decision variables related to the areas of wind turbines and PV collectors are treated as decision variables in the optimization model in this study.

The systems, sizing and optimization of hybrid systems for power generation have been studied substantially over the last few years with a simulation analysis for a 1 day period i.e. for 24 h [10,25–30]. In the present article, hourly profiles are used of insolation, wind speed, and temperature during a year for forecasting strategy. According to the results forecasts, the simulation analysis has been done for 1 month period i.e. for 744 h.

Nevertheless, some optimization techniques for sizing hybrid systems have been reported [31–33]. Nonlinear programming [34] and HOMER (Hybrid Optimization Model for Electric Renewables) [35,36] 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 Optimization by Genetic Algorithms) developed by Bernal-Agustín and Dufo-López [37], 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 [32]. 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.

As a branch of artificial intelligence, heuristic algorithms (inspired by natural processes or phenomena) are robust optimization tools which have received considerable attention, especially for solving complex optimization problems. Heuristic algorithms such as genetic algorithm [31,38], simulated annealing [32,39,40], harmony search [33,41], and others [42,43] are techniques for sizing hybrid systems. Ekrena and Ekren [32] used the simulated annealing algorithm for optimizing the size of a PV/WT integrated hybrid energy system with battery storage. Comparing the optimum results obtained by the simulated annealing algorithm with results from other methods showed that the simulated annealing algorithm yields better results than the response surface methodology. Maleki et al. [33,44] optimized the components of a hybrid system using the discrete harmony search algorithm and found that discrete harmony search provides more accurate results than discrete simulated annealing. Sinha and Chandel [42] presented a literature review of sixteen types of optimization techniques including hybrid algorithms used in PV/WT based hybrid energy system research and development along with a PV/WT based hybrid system sizing methodology. It was demonstrated that