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Optimization of a biomass-based photovoltaic power plant for an off-grid application subject to loss of power supply probability concept

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HIGHLIGHTS

- Design of a biomass-based photovoltaic power plant is studied.
- Biomass energy is used to increase the reliability.
- The size of biogas generator and photovoltaic area are optimized.
- Biomass/photovoltaic is a cost-effective and reliable energy source.

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ABSTRACT

Using renewable energy sources is an efficient alternative to supply the electrical load of stand-alone remote areas. The main motivation of this paper is to optimize the size of a biomass-based PV power plant to supply the electrical power of agricultural wells located in Bardsir, Kerman, Iran. In an off-grid PV power plant, there must be a backup system to supply the demanded load in deficit conditions. Biomass energy generation systems could be complementary taking into account their different properties in reliability. As a result, the combination of PV and biomass systems could be an effective way to make a reliable and cost-effective hybrid energy system. In the proposed hybrid system, the area of the PV system and the size of the engine–generator of the biomass system are optimized for minimizing the total net present cost (TNPC) of the system during its lifetime. The reliability of the designed system is met by considering the loss of power supply probability (LPSP) concept. For the investigated region, the obtained results indicate that the PV/biomass generation system is more promising than a single PV system or a single biomass system.

1. Introduction

In comparison with the other energy sources which are concentrated in a limited number of countries, renewable energy sources exist over wide geographical areas. Owing to energy security, climate change mitigation and economic benefits, rapid deployment of renewable energy has attracted significant attention. Renewable power generation can help the countries to meet their sustainable development goals through provision of access to clean, secure, reliable and affordable energy. In recent years, renewable energy sources such as solar, wind, biomass, geothermal, tidal and hydropower have received much attention as effective alternatives for electricity generation [1].

In remote areas, due to the inaccessibility to electrical grid and high cost of constructing new transmission lines for long distances, renewable energy sources can be effectively used. The generation of renewable sources like wind and solar is very dependent on the weather conditions. Since no single source of energy is able to supply cost-effective, clean and reliable power, the combination of multiple power sources can be a viable way to achieve a reasonable solution [2]. In hybrid systems, optimal sizing is vital to achieve a cost-effective and reliable generation system.

As promising sources of energy, wind and PV sources are inexhaustible, the conversion processes are pollution-free and their availability is free. However, for stand-alone applications, a backup system should be used to supply the demanded load in deficit

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conditions. As a result, such systems are usually equipped with diesel generators to meet the peak load demand during short periods when there is a deficit in available energy. Diesel generators need fuel and should be controlled during operation. Therefore, the cost of their usage is reasonably expensive [3].

In comparison with many renewable energy options, biomass has the merit of dispatchability. This means that biomass energy is controllable and available when it is required. However, the disadvantage of such system is that the fuel needs to be procured, delivered, stored and paid for. One of the technologies for the extraction of energy from biomass resource is anaerobic digestion. Anaerobic digestion is a series of biological processes in which microorganisms break down biodegradable materials such as livestock manure, municipal wastewater solids, food waste, fats, oils and various other organic wastes in the absence of oxygen. One of the end products is biogas which is used to generate electricity and heat [4–11]. Biogas produced in anaerobic digesters consists of methane (45–75%), carbon dioxide (25–55%) and trace levels of other gases [12]. For conversion of bio-methane into heat and electricity, a biogas engine–generator is used [4,13].

Iran is one of the richest countries of the world in terms of various energy resources. In Iran either fossil fuels such as petroleum and natural gas or renewable sources such as solar, wind, geothermal, tidal and biomass are abundant. A country like Iran with abundant oil and gas reserves should not rely on fossil fuels and must plan for development all kinds of energy sources. In recent years, exploitation of renewable energy sources and development of theses energies application have become more consequential. In 2010, the Iranian government announced 2000 MW of renewable energy capacity would be built between 2010 and 2015. As of 2010, Iran had 8500 MW of hydroelectric capacity and 130 MW of wind energy capacity. As of 2010, private companies had signed contracts to build more than 600 MW of biomass systems and 500 MW of new wind energy projects [14].

The main goal of this paper is to electrification to agricultural wells of a territory located in Bardsir, Kerman, Iran by solar and biomass energy sources where the solar radiation is suitable and there are many sources to use biomass energy. For this aim, a hybrid PV/biomass system is optimized to have a cost-effective and reliable energy source. In the proposed hybrid system, the area of the PV system and the size of the engine–generator of the biomass system are optimized for minimizing the total net present cost (TNPC) of the system during its lifetime. The reliability of the designed system is met by considering the loss of power supply probability (LPSP) concept. In order to find the optimum decision variables, a heuristic approach, namely, harmony search (HS) has been used. In comparison with the conventional search methods which are entangled in local optima, HS makes use of stochastic rules to escape from local optimal.

There are various investigations in the literature which study the different aspects of renewable energy systems, especially solar and wind energies [15–25]. Tao et al. [15] have introduced a pumped hydro storage to support a standalone microgrid hybrid solar–wind system for a remote island in Hong Kong. They have explored a new solution for the challenging task of energy storage. A mathematical model of the hybrid system has been developed and the operating principle has been introduced. Xiaonan et al. [17] have presented a methodology to systematically formulate a hybrid renewable energy system, which consists of solar, wind and diesel generator as a backup resource as well as battery storage, from the preliminary design stage to the optimal operation. Tao et al. [19] have proposed a detailed feasibility study and techno-economic evaluation of a standalone hybrid solar–wind system with battery energy storage for a remote area. They have used HOMER software to do the simulations and perform the techno-economic evaluation. Binayak et al. [21] have suggested two practical economical hybridization methods for small off-grid systems consisting entirely of renewable energy sources, specifically solar photovoltaic, wind and micro–hydro sources. They have presented a novel approach for connecting renewable energy sources to a utility mini-grid. Ismail et al. [24] have performed a feasibility study and a techno-economic analysis of a PV system with batteries and micro turbine acting as a backup supply for the system. Component sizing and optimization has been performed by iterative method to minimize the cost of energy (COE) production. Study of the literature indicates that the combination of biomass with PV or wind systems is seldom considered. Pérez-Navarro et al. [26] have presented a hybrid biomass gasification-wind power plant for reliable energy generation that is analysed to obtain main hybrid system design parameters. Bhattacharjee and Dey [27] have presented techno-economic assessment of a grid-connected hybrid system including grid, PV and biomass systems for electrification to rice mills of an Indian state, Tripura. In this study, HOMER software has been used for optimization. Ho et al. [28] have done the optimal design of a feasible energy system including biomass and solar energies for a smart eco-village in Iskandar, Malaysia. In order to design and optimally utilize renewable energy resources, they have developed a mixed integer linear programming (MILP) model. Tanim et al. [29] have designed a grid connected photovoltaic-biogas hybrid power system for a remote area using HOMER software. They have claimed that their system can be an excellent, cost-effective and a reliable solution to mitigate the existing power crisis. Eziyi and Krothapalli [30] have developed a hybrid renewable energy system based on PV panel, battery bank and biomass generator with gasifier. They have used HOMER software for optimal sizing of their system. It has been illustrated that the hybrid renewable energy system is about 30% cheaper than serving the electrical load demand of the rural community with petrol and diesel fuel.

In comparison with the previous literature, the main contributions of the current paper are as follows: (1) the feasibility of using a hybrid PV/biomass system is investigated to meet the electrical load of agricultural wells, (2) mathematical modeling of the hybrid PV/biomass system is described in details while in the previous literature mathematical formulation of a hybrid PV/biomass system is rarely found and (3) in the previous literature, the performance analysis is usually done by HOMER software which has some disadvantages while in this paper an efficient heuristic optimization technique, HS, has been used. HOMER disadvantages are as follows [31]:

- HOMER allows only single objective function for minimizing NPC and multi-objective problems cannot be formulated.
- After optimization process, HOMER makes chart for the optimized system configurations based on NPC and does not rank the hybrid systems based on the levelized cost of energy.
- HOMER does not consider depth of discharge (DOD) of battery bank which plays an important role in the optimization of battery-based hybrid systems.
- HOMER does not consider intra-hour variability.

The rest of this paper is organized as follows: Section 2 formulates the optimization framework of the PV/biomass system. The optimizer tool of harmony search is explained in Section 3. In Section 4, simulation results are reported and discussed and finally the conclusion is given in Section 5.

2. Mathematical modeling

Mathematical modeling of the hybrid system is an essential step before any phase of the optimal design. In the next subsections, modeling of the system components and optimization framework of the hybrid PV/biomass system are described in detail.