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A novel framework for optimal photovoltaic size and location in remote areas using a hybrid method: A case study of eastern Iran

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ABSTRACT

Photovoltaic (PV) energy generation is one of the more promising renewable energy technologies. However, determining optimal specifications (e.g., size, location) for PV systems is a significant challenge for planners and investigators of distribution systems. In this paper, a framework is provided for integrating geographical information systems, artificial bee swarm optimization, and simulation to determine the optimal size and location for PV panels on an annual basis. A geographical information system module is developed first to determine the suitable location and capacity for a stand-alone PV system in rural areas, taking into account the technical, environmental and socio-economic criteria affecting the site selection process of stand-alone PV systems. Then an efficient heuristic approach, namely artificial bee swarm optimization, is proposed for optimum sizing of a stand-alone PV system to continuously satisfy the load demand with minimal cost and enhanced energy system reliability. For this aim, the maximum allowable loss of power supply probability is also considered. The proposed framework is applied to a real case study in eastern Iran and the results show that it can effectively be used for off-grid photovoltaic projects in rural areas considering both power quality and cost.

1. Introduction

Problems regarding climate change, depletion of fossil fuel reserves, and pollution associated with conventional energy resources have recently increased interest in environmentally benign and sustainable energy resources, such as renewable energy sources (RESs). Still, over 1.5 billion people in the world do not have access to grid electricity, mainly in small and remote villages that are far and isolated from utilities [1]. Extending electrical grids to such regions is challenging due to economic and geographical factors. Of all RES technologies, photovoltaic (PV) devices for harvesting solar energy are among the most promising for satisfying electrical demands in remote regions. Two significant challenges of renewable energy systems based on one technology are their dependency on environmental factors like the temporal variation of solar radiation, and the fact that solar radiation temporal variations may not coincide with the temporal variation in electrical demand. Significant reliability concerns consequently exist regarding system design and operation. A battery storage can be used to enhance system reliability.

Technical and financial limitations usually cause the electrification of regions lacing electricity to take several years. Since all remote areas cannot gain access to electricity at the same time, the location of stand-alone renewable energy systems (especially solar energy systems) should be optimized based on some criteria, so that autonomous power systems are established earlier in appropriate areas as a priority.

Optimal placement and sizing of hybrid systems are important issues for distribution system planners and researchers. For hybrid systems that are cost-effective and have good power quality, optimal placement and sizing are necessary. Oversizing can mitigate reliability issues, but can be costly. Optimum sizing of rooftop PV systems is determined by the number of system components needed to satisfy the demand while the total cost is minimized.

Stand-alone hybrid systems that use RESs recently have attracted much attention [2–9]. Prasad and Natarajan [10] proposed an optimization methodology for PV-wind systems with a battery bank that incorporates several relevant technical parameters (relative excess power generated, deficiency of power supply probability, unutilized energy probability) and economic parameters (levelized energy cost, life cycle cost (LCC), life cycle unit cost of power generation). Borowy and Salameh [11] proposed the loss of load probability for optimal sizing of a hybrid system combining PV and wind technologies. A methodology has been developed using energy generation simulation for determining the optimal size of a hybrid system [12], while hybrid PV-wind systems design using energy balances have been described [13]. Diaf et al. [14]

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size-optimized a hybrid system on the basis of levelized cost of energy and loss of power supply probability (LPSP), while others have determined the optimal number and type of units, for a stand-alone hybrid wind-PV-diesel energy system, via a deterministic algorithm for that ensures energy availability and minimizes total system cost [15]. Kazem et al. [16] developed an optimization method for the tilt angle and capacity of an off-grid PV system, seeking enhanced performance and lower energy costs, in remote areas near Sohar, Oman. Bakelli et al. [17] developed a sizing model that optimizes the capacities of components of a PV-based water pumping system incorporating a water tank storage and accounting for the pumping system. The model is based on two optimization criteria: LCC for economics and LPSP for reliability.

Optimizing the size of a hybrid system is a non-linear and non-convex optimization problem, requiring powerful optimization methods. Heuristic algorithms have been used to investigate various aspects of hybrid energy systems [18–25]. Heuristic algorithms are a branch of artificial intelligence and are powerful optimizers that can solve complex optimization problems. As a consequence they have received much interest and have been applied to many renewable energy optimization problems [2,26–30].

Although studies on various aspects of hybrid renewable energy systems and various approaches used for the optimization of such systems have been reported, informative models for stand-alone solar systems coupled with battery energy storage and efficient tools for optimizing the location and optimal sizing of such systems to meet electric loads are seldom found. Mentis et al. [31] provided a geographical information system (GIS) based framework for optimizing the mix of electrification options for Ethiopia considering a range of variables affecting electrification planning. These variables are similar to those used by the same authors in previous work [32]. They used such variables as density of population, electricity tariffs, fuel and technology costs, power plant and transmission grid performance, and economic factors. In particular, it is noted that no study has been reported aimed at developing a GIS-ABSO (artificial bee swarm optimization)-based model for optimizing the location and optimal sizing of stand-alone PV systems.

In the present article, a combined approach using GIS and the ABSO method is described to classify the possible locations for solar farms in eastern Iran, into ordered categories of merit according to multiple evaluation criteria. The spatial model optimizes the location of PV systems from socio-economic, technical, and environmental perspectives. Also, for optimum sizing of a stand-alone PV system is proposed to continuously meet the load demand by maximizing the loss of power supply probability ($LPSP^m$) and minimizing LCC, subject to technical constraints.

This article extends the work reported in the literature by presenting several important innovations. Most significantly, a hybrid optimization approach is developed for an off-grid hybrid system, incorporating a solar-battery system, to classify the possible locations for solar farms in eastern Iran into ordered categories of merit according to multiple evaluation criteria. The spatial model optimizes the location of PV systems from socio-economic, technical, and environmental perspectives. Also, a method for optimum sizing of a stand-alone PV system is proposed to continuously meet the load demand by $LPSP^m$ and minimizing LCC, subject to technical constraints. Furthermore, our study addresses the optimization problem of a stand-alone hybrid system for a high-energy consuming residential sector, in a realistic manner accounting to technical details of the hybrid system. Finally, a novel framework for optimal photovoltaic size and location in remote areas using a new hybrid method (GIS-ABSO) is introduced.

This paper is structured as follows. After the Introduction, an overview of the proposed methodology is given in Section 2. Section 3 identifies optimal sites for the case study. In Section 4, the optimum sizing of the photovoltaic system is described. Section 5 provides results and Section 6 conclusions.

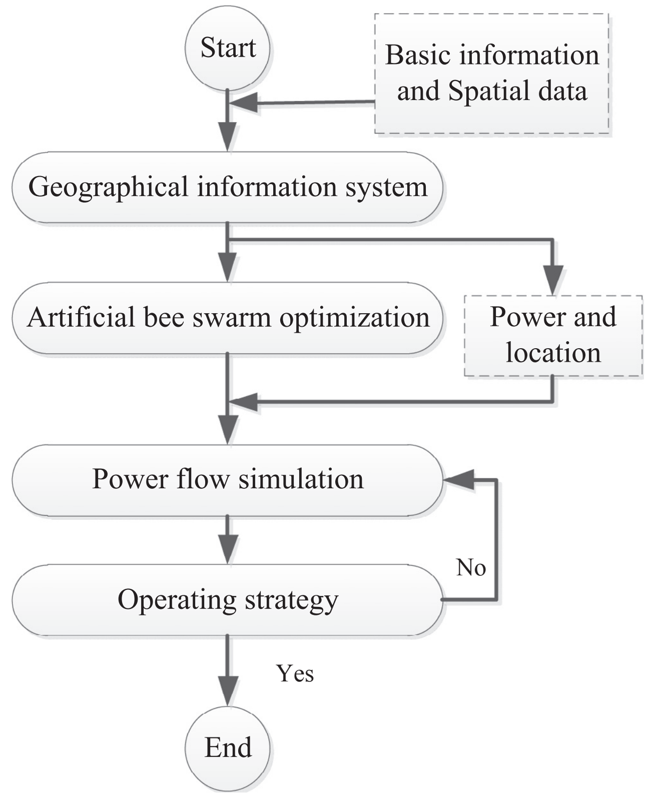

Fig. 1. Overview of the proposed modeling and analysis framework.

2. Methodology

In this study, stand-alone PV systems for meeting electrical demands are designed and modeled. First, a spatial model is developed for the optimization of the location of stand-alone PV projects in rural areas using GIS. The spatial model optimizes the location of PV systems from socio-economic, technical, and environmental perspectives. The criteria used in the model are thoroughly described in Section 3.1. Then an efficient heuristic approach, namely ABSO, for optimum sizing of a stand-alone PV system is proposed to continuously meet the load demand by $LPSP^m$ and minimizing LCC, subject to technical constraints. This optimization problem includes integer and continuous decision variables. An overview of the proposed modeling and analysis framework is shown in Fig. 1.

3. Identifying optimal sites in case study

At first, a set of criteria influencing the site selection process for villages is specified by reviewing the related literature, a task made complicated by the fact that no similar research has been reported on providing a GIS-based framework for optimizing the location of autonomous PV systems. Then, by defining a spatial model and conducting a site selection process, the optimal sites in rural areas for the establishment of autonomous PV systems are identified. Last, the output maps of the spatial model are presented. The procedure used for identifying optimal sites for off-grid PV installations is shown in Fig. 2 in the form of a block diagram.

3.1. Criteria for site selection

Since work has not been reported on optimizing villages for electrification projects, a comprehensive set of criteria affecting the process of site selection was developed. The spatial model developed in this study comprises ten criteria considering environmental, technical and socioeconomic factors. These are now described.