Applied Energy 118 (2014) 280–291

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Renewable energy projects to electrify rural communities in Cape Verde

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HIGHLIGHTS

- The design of 2 off-grid electrification projects in Cape Verde is developed.
- Configurations with hybrid renewable energy systems and micro-grids are considered.
- A detailed micro-scale wind resource assessment is carried out.
- An optimization model is used in order to support the design.
- The proposed system is economically beneficial in comparison with diesel generation.

ARTICLE INFO

Article history:
Received 28 June 2013
Received in revised form 11 November 2013
Accepted 21 December 2013
Available online 21 January 2014

Keywords:
Rural electrification
Off-grid generation
Renewable energy
Wind resource assessment
Microgrids
Cape Verde

ABSTRACT

Even though Cape Verde has high wind and solar energy resources, the conventional strategy for increasing access to electricity in isolated rural areas is by centralized microgrids with diesel generators. In this study, the design of 2 off-grid electrification projects based on hybrid wind–photovoltaic systems in Cape Verde is developed and analyzed. The design considers some significant novelty features in comparison with previous studies. First a detailed wind resource assessment is carried out combining meso-scale wind climate data and a specialized micro-scale wind flow model. Then a mathematical model is used for the design of off-grid projects considering a combination of individual systems and microgrids. In this study, locations far from the demand points are also considered as possible generation points. Various design configurations are analyzed and compared. The proposed configurations exploit the highest wind potential areas and are economically beneficial in comparison with diesel generator systems.

1. Introduction

Cape Verde is an archipelago located in the Atlantic Ocean with a total population of half a million people. Its electrical energy production relies largely on diesel thermal plants [1] and is highly dependent on (totally imported) fuel. Cape Verde electric power price is therefore highly affected by fuel price fluctuation and is currently around 0.40$/kW h, among the most expensive in Africa [1]. The electrification rate was around 70% in 2010, relatively high in comparison with other countries of its region [1]. During the last decades, the conventional strategy for increasing access to electricity in rural areas of Cape Verde has been to extend the national electricity grid or by autonomous microgrids with diesel generators [2]. Due to the complex geography and dispersed nature of villages in mayor islands of Cape Verde, the expansion of the electricity grid can only reach a limited number of people. Furthermore, during the last decade connections to the grid increased rapidly while installed capacity remained stable; as a result of this tight demand-supply balance, the incidence of blackouts more than tripled and became longer in duration [1]. On the other side, local microgrids powered by small diesel generators, which supply electricity for a significant proportion of isolated communities or municipalities [2], have some clear disadvantages and limitations, such as the high and variable cost of the fuel, the requirement of a continuous supply and the inherent carbon dioxide and other polluting emission.

Under these circumstances, stand-alone electrification systems that use renewable energy sources are a suitable alternative to provide electricity to isolated communities in a reliable and pollution-free manner [3]. Moreover, one of their main advantages is that they use local resources and do not depend on external

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http://dx.doi.org/10.1016/j.apenergy.2013.12.043

sources, which can promote the long-term sustainability of the projects. Specifically, Photo-Voltaic (PV) systems have already been widely used in the last decades, while wind systems, less used, are receiving increasing attention for off-grid generation [4]. In windy areas, the ratio investment/produced energy can make wind energy a very favorable technology, especially when demand increases and more powerful wind turbines are used (for instance, when supplying to groups of households with microgrids [5]). In this context, hybrid systems that combine wind and solar energy sources are a promising generation option [4].

Most stand-alone electrification projects based on wind and solar energies consist of installing individual systems [6,7]; that means each consumption point (for example, households, health centers or schools) has its own generators. As an alternative, microgrids can be used: a generation point produces energy for a number of consumption points. It is generally known that microgrids have several advantages in comparison with individual systems [8]. First, when using those configurations, user energy availability does not depend on the resource in its location. Second, equity between user consumptions is improved by relying on the same generators, i.e. all connected users share the same generated energy. Third, costs can be reduced by economies of scale (when installing more powerful generators a lower ratio between the generators cost and the energy produced could be reached). Finally, a greater flexibility in consumption is permitted: consumption can punctually be increased due to special days, admission of new users or the development of productive activities, i.e. the implementation of local businesses could involve higher energy requirements. Despite the advantages of microgrids, a too large extension may cause problems due to the increasing cable cost [9]. Thus, the design of stand-alone renewable energy projects is highly complex as it requires the characterization of both energy resources in every point of the community and aims to find a good compromise between microgrids' extension and individual electrification [5,10].

Various papers study the design of autonomous electrification systems at village level in developing countries through the use of renewable energies [4,10–14]. In this context, most studies basically focus on defining the best combination of renewable generation sources without considering energy resource spatial variations [11–14]. HOMER developed by NREL is the most widely used decision aid tool, which simulates and compares lifetime costs of different alternatives of electrification [13,14]. However, recent rural electrification projects confirmed that significant wind resource differences could be present between houses of a community in hilly terrain [15]. In these cases, a single wind resource data, as considered by e.g. [2,11–14], is not representative of the whole area and detailed resource studies are required for defining generators locations. Moreover very few studies focus on the design of microgrids and the definition of the system, but with some limitations [16,17]. ViPOR [17] uses the output from HOMER to design a distribution system combining microgrids and individual systems. However, this tool limits the possible generation points and the number of microgrids; furthermore it does not consider voltage drops in microgrid design. To overcome these limitations, a mixed integer linear programming (MILP) model was developed for the design of wind electrification systems, considering the detail of wind resource, the demand of each consumption point, the storage in batteries and the distribution through microgrids [5]. Recently, solar energy has been included in the previous model, to obtain the optimal combination of wind-PV technologies for every selected generation point [10].

Cape Verde is located in a sub-tropical region and receives a significant solar radiation during the whole year. Furthermore, tropical trade winds are well developed over most of Cape Verde islands and exposed sites have a large wind resource [18,19]. In the last years different studies have been carried out showing the reliability of renewable energy projects and proposing an increase of the penetration of renewable energy sources in Cape Verde [2,19–21]. In particular, a recent study [2] focusing on the communities of Figueiras and Ribeira Alta (in the island of Santo Antão), proposes the replacement of the current diesel systems with hybrid systems combining diesel, wind and solar energies. However, in that study the wind energy production was roughly estimated by wind data of a far off meteorological station and was considered uniform around the community area. Therefore, the design of the projects was just preliminary and mainly focused on the economical comparison with current diesel systems.

In this context, this paper develops accurate studies to design off-grid rural electrification projects with wind and solar energies in 3 communities of Cape Verde: Figueiras and Ribeira Alta in Santo Antão Island and Achada Leite (currently not electrified) in Santiago Island. The design considers some novelty features in comparison with previous studies and is composed by two main steps. Firstly, a high resolution wind resource assessment is realized combining generalized wind climate data and a specific wind flow model that takes into account real topographical wind speed changes to detect micro-scale wind resource variations [15]. Then, the previously mentioned MILP model [10] is applied. The model optimizes the technical design of the electrification system minimizing the cost and specifying the amount and size of the equipment to be installed. Moreover, in this study, locations with a good resource far from the demand points, i.e. users, are considered as possible generation points, while generally generators are forced to be installed close to the users [5,10].

The final proposed electrification systems are totally based on renewable energies and take advantage of best resource areas. Besides avoiding greenhouse gas emissions and reducing the external dependency on fuel importations, they result to be economically beneficial in comparison with diesel generator systems and even with the hybrid wind–solar–diesel system proposed in ref. [2]. The systems designed in this study can be used as pilot projects in order to facilitate governmental investments on renewable energy and spread their utilization in rural electrification projects in Cape Verde.

The rest of the paper is organized as follows. First the studied communities are described (Section 2) and the micro-scale wind resource assessments are carried out (Section 3); in Section 4 the optimization model for off-grid electrification design is summarized. Various design configurations for the electrification of the studied communities are analyzed in Section 5. In Section 6 an economical and environmental analysis of the proposed solutions in comparison with diesel generation option is carried out. Finally (Section 7) the conclusions of the study are exposed.

2. Communities descriptions and previous studies

Cape Verde is a 10 islands archipelago located in the Atlantic Ocean 500 km off the West African coastline, covering an area between longitude 22–26°W and latitude 14–18°N (Fig. 1). The analyzed communities are Figueiras and Ribeira Alta in Santo Antão Island, and Achada Leite in Santiago Island. Their location is shown in Fig. 2. The first two communities (Figueiras and Ribeira Alta) are studied together due to their proximity. From now on, the 2 studied projects will be referred to as "Santo Antão project" and "Santiago project".

The solar resource of Cape Verde is high and rather uniform with a mean global irradiance generally varying between 5 and 7 kW h/(m^2 day) along the year, according to NASA climate database with a resolution of 0.5° (around 50 km) [22]. As spatial variation of global irradiance is lower than 5% in areas of less than 30 × 30 km even in mountainous areas [23], the solar resource is