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A heuristic method to design autonomous village electrification projects with renewable energies

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ABSTRACT

Systems relying on renewable energies demonstrated to be a reliable and sustainable option to electrify isolated communities autonomously. Hybrid systems that combine different energy resources and distribution microgrids are the most efficient design configurations. The design of these systems requires the use of decision support tools, while projects' promoters generally dispose of low design resources. This study presents a heuristic method to design off-grid electrification projects based on wind and solar energies considering micro-scale resource variations and a combination of independent generation points and microgrids. The method considers generation far from users and a pre-selection process is presented in order to screen the initial pool of potentially infinite generation points. Different algorithm versions are evaluated and performances are compared with existing tools: VIPOR, known software for microgrids design, and a recently developed mixed integer linear programming (MILP) model. The proposed heuristic performs better than VIPOR with mean improvements of around 6% and, for communities of more than 40 users, considerably enhances solutions obtained by the MILP model with a much lower computational time (1 min against 1 h). The method is a complete and simple tool that can efficiently support the design of stand-alone community electrification projects with renewable energies.

1. Introduction

Over the last decades, systems relying on renewable energies demonstrated to be a reliable and sustainable option to electrify isolated communities autonomously [1,2]. These systems produce electricity in a clean way, their cost is often lower than national grid extension and they are not dependent from external resources, therefore increasing projects long-term sustainability [2]. In particular, systems relying on wind and solar energies are one the most promising electricity generation options [3]. When designing rural electrification projects based on renewable energies various issues should be taken into account for the correct operation of the systems, especially the variability of the renewable resources and the dispersion of the energy demand that depends on houses locations. In particular, wind resource is the most scattered and significant resource variations can be encountered within the same community in mountainous areas [4].

In this context, the configurations that proved to be the most reliable design options are hybrid systems that combine different generation resources [3,5] and distribution microgrids, where the energy is produced in a certain point and distributed through an electric grid to other consumption points [6,7]. Hybrid systems improve the system efficiency and reliability of the energy supply and reduce the energy storage requirements compared to systems comprising only one single renewable energy resource [5]. Distribution through microgrids could lead to an important decrease in the final cost of the system in comparison with independent generation points, i.e. a demand point that generates energy just for its own consumption, and enhance the flexibility of the system [6,7]. However, in scattered communities with isolated users the combination of independent generation points and microgrids is generally the cheaper design solution [8].

When considering hybrid systems and distribution microgrids, the complexity of the design increases and requires the use of optimization/decision support tools [9]. Many tools have been developed in recent years in order to define the best combination of energy resources in one point but without designing the distribution through microgrids [5,9–13] and several software tools are available for designing hybrid systems, such as HOGA, HOMER and

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Nomenclature

Demand point (or user) location of a consumption point, such as a house or a public building, with certain energy and power demands
Community a group of users
No-demand point location (that is not a demand point) where it is possible to install generators
Microgrid set of demand points fed by a generation system placed in a demand or no-demand point
Arch segment of electric cable that connects two points of a microgrid
Solution set of microgrids

HYBRID2 [14]. These tools are currently applied for the design of different projects all around the world [15–17]. On the other side, just few studies focus on the design of off-grid electrification systems taking into account hybrid systems and the design of microgrids [18,19].

Ref. [18] developed a mixed integer liner programming (MILP) model that optimizes the design and localization of microgrids, wind turbines and solar panels defining all electric equipments to be installed, taking into account voltage drops along the cables and wind resource variability. The model assumes that generation points must be located close to the users. It has been efficiently used to design off-grid electrification projects in Peru [18] and Cape Verde [20]. However, due to its high computational requirements, the application of the mathematical model may be unreliable when the size of analyzed community (e.g. the number of demand points) increases. Furthermore, recent studies have shown that considering generation far from demand points could substantially decrease initial investment costs taking advantage of best resource areas [20,21]. Therefore, the generation point could be potentially every point in a certain area, further significantly increasing problem complexity.

It should be noted that promoters of rural electrification projects generally dispose of low resources for project design, making it preferable to use simple and fast tools in order to support the design [22]. At the same time, different project configurations should be preferably evaluated in order to take into account not only technical aspects but also social aspects specific of each community [23]. In this context, heuristic methods (or simply “heuristics”) are a technique commonly used in combinatorial optimization problems [24] in order to accelerate the solving procedure or to make viable the solution to problems that cannot currently be optimally solved even by super-computers. Heuristics will generally not guarantee the optimal solution but, when well designed, the obtained solutions can be expected to be fairly close to the optimum value [25].

As resulted from literature analysis, the only heuristic method for the design of off-grid electrification projects considering microgrids, hybrid generation systems and resource spatial variations is VIPOR [19,26]. VIPOR designs the distribution system (electric cables) and where generation should be located but does not define the number of equipments required for generation (generation system). Other drawbacks of VIPOR, that reduce its range of application, are the limited pool size (10 as maximum) of possible grid generation points, the no-consideration of some electrical constraints, such as the voltage drop, and the assumption of a uniform resource in the area for independent generation points.

Recently, some indicators have been proposed to support the design of off-grid community electrification projects [27]. The indicators could be used to select most promising generation points in a certain area and to heuristically evaluate how much some a-priori characteristics of a point indicate that it should be reliably connected to a microgrid or should be an independent generation point producing energy just for its own consumption [27]. A simple heuristic procedure in order to obtain fast solutions with a single microgrid is also presented in Ref. [27].

In this study we present a heuristic method to design community off-grid electrification projects based on wind and solar energies considering micro-scale resource variations and a combination of independent generation points and microgrids. Unlike existing tools, generators locations are not forced to be close to demand points and their number is not limited, therefore a generation point could be potentially every point in the studied area. The indicators described in Ref. [27] are used in order to design the heuristic algorithm. The performance of the proposed method aims to overcome the performance of currently available heuristics [19,27]. The results of the heuristics are also compared with the solutions obtained by the MILP model [18].

The rest of the paper is organized as follows. Section 2 presents the components of a general off-grid electrification project and the problem to be solved. The heuristic algorithm is described in detail in Section 3 and in Section 4 the performances of the proposed heuristic are compared with existing procedures. Section 5 deals with the conclusions.

2. Autonomous village electrification project design: problem statement

In this section, the problem to be solved (i.e. the design of an off-grid community electrification project with wind and solar energies) is defined. Firstly the input data are described (Subsection 2.1), the components of a hybrid off-grid electrification system are resumed (Subsection 2.2) and finally the objective function and constraints of the problem are defined (Subsection 2.3).

2.1. Input data

Input data for an off-grid electrification project design could be generally divided into three types: social, technical and energy data of the community.

The characteristics resulting from the social evaluation are the following:

- Users' position;
- Electrical energy and power demand of each user.

The technical and energy characteristics are the following:

- Resource available in the area (i.e. daily energy production with all types of generators in every possible generation point);
- Technical data of generation, storage, control and distribution equipments;
- Costs of all the equipments.

The involved area in an off-grid electrification project is generally between 1×1 till 10×10 km^2 and the number of households of a community is generally between 10 and 100 users [7,28]. Wind resource could vary considerably within the area of a community, especially in mountainous areas [4], while the solar resource is generally considered uniform at this scale [29].

2.2. Components of an off-grid electrification system

The scheme of the elements involved in a wind - photovoltaic autonomous electrification system is as follows (Fig. 1):