DISTRIBUTION NETWORK PLANNING FOR ISOLATED MINI-GRIDS: A NOVEL APPROACH

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Overview

Ensuring universal access to affordable, reliable and modern energy services was established as one of the United Nation Sustainable Development Goals in 2015. Since then, the population without electricity has dropped from 1.2 billion to roughly just below one billion (Karplus and Von Hirschhausen, 2019). Most of these potential end-users are located, however, in remote and sparsely populated areas, making traditional grid extension an expensive way of providing access. High hopes are vested, instead, in isolated mini-grids for a number of reasons, including low technical barriers, ability to provide sufficient capacity for productive uses, and availability of renewable energy sources. Indeed, as of today, the success of mini-grids for rural electrification depends more on socio-economic challenges than on technical ones.

Among other concerns, accurate network planning is crucial to ensure the economic sustainability of mini-grid projects – financial viability for the investor and affordability for the end-users (Peters, Sievert and Toman, 2019). The present work addresses this issue and focuses, in particular, on the often overlook fact that the investment required to build the electricity distribution infrastructure, together with the associated maintenance and operation expenditures, has a considerable weight on the total cost of a mini-grid project. Several aspects, such as the number and distribution of end-users, the terrain, the use of a single-phase or a multiple-phase configuration, determine the use of materials and the network topology. However, a network requiring longer lines not only implies higher capital and operational expenditures, but also higher energy losses. Planning an optimal feeder routing is, therefore, a decisive step towards minimizing the total cost of a mini-grid project.

Although previous work on rural electrification includes a few models that pay specific attention to network planning (Lambert and Hittle, 2000; Parshall *et al.*, 2009; van Ruijven, Schers and van Vuuren, 2012; Mentis *et al.*, 2015, 2017), none of the existing planning tools combines the possibility to optimize the low voltage system with the option of dividing the distribution network into multiple mini-grids, while considering geographical restrictions (e.g., waterways or roads), and including a highly detailed characterization of the end-users' load profiles. The goal of the present work is to contribute filling this gap. To this end, an original network planning model, RETEP-N, is first developed, using a greedy algorithm. To show the model's ability to capture the geographical restrictions of a given area and as well as the advantage of including a multiple mini-grids option, RETEP-N is then applied to a study case.

Methods

RETEP-N employs the so-called Kruskal algorithm to find the optimal distribution network topology which connects all generation units and end-users in a given area, while minimizing the total length of feeders. This algorithm is preferred over other greedy solutions (i.e., Prim and Dijkstra), due to the possibility to separate the grid into clusters (Moret and Shapiro, 1991). Indeed, when geographical restrictions are present, the model can search for an alternative route or separate the network in multiple mini-grids. An important, additional feature of the model is the inclusion of a maximum length limit, which is useful when the project is subject to budget constraints. In those conditions, building lines longer than an established length is considered unfeasible, due to excessive construction costs.

The model is coded in Visual Basic for Applications (VBA) to create an intuitive, easy-to-use software tool, with low machine specs requirements. The model's inputs include the end-users' and generation units' geographical coordinates (e.g., from Google Maps), the existing geographical restrictions, the maximum line length, the end-user's load profiles, and the optimized size of the generation capacity (from a generation capacity planning model). The model's output consists in the total length of the distribution grid, a graphical representation of the optimized network topology, and additional detailed information including the number of mini-grids and feeders per mini-grid. This information is then used to calculate two economic indicators: the Net Present Cost (NPC) for the project and the Levelized Cost of Electricity (LCOE).

Results

The study case regards an existing village in Ethiopia, with 141 end-users and two geographical restrictions: a road and a river. An initial simulation is carried out with no restrictions nor limitations. The model finds an optimal solution with a total length of feeders of 6.9 km (Scenario 1). When the presence of the river is considered, the model divides the distribution network in two mini-grids, for a total length of feeders of 6.5 km (Scenario 2). Differently, the presence of an existing infrastructure (the road) forces the feeders into a predefined path and increases the length of the network to 7.2 km (Scenario 3). When both restrictions are included, the optimal network has a total length of 7.8 km and connects all users via a single mini-grid (Scenario 4). The optimal plan under a maximum length per single feeder limitation (170 m), leads to four mini-grids (one stand-alone system, two small mini-grids and a large mini-grid connecting 113 end-users) with a total length of feeders of 6.7 km (Scenario 5).

An analysis of the project's economic indicators under alternative scenarios shows that the cost of the network represents between 22% and 27.5% of the total NPC. As expected, the lowest percentage values are obtained in those scenarios where the network is the shortest. As for the absolute value of the NPC, the question is whether multiple microgrids with multiple generation units lead to more expensive solutions than having only one generation unit and a single network connecting all the users. The answer depends on the scenario, illustrating how RETEP-N is a useful model for a user interested in comparing alternative configurations.

Taking the point of view of the end-users, the estimation of the LCOE similarly leads to a number of useful insights when results are compared across scenarios. For instance, the lowest cost per kWh is achieved under Scenario 5, which is the one with the most restrictions and limitations. Also, while LCOEs vary across scenarios by a few percentage points, the total amount of savings generated over a year can be of the order of a few hundred Euros, an amount which can make a significant difference for an end-user in an isolated region.

Conclusions

The first contribution of this work is the construction of an original, easy-to-use model for identifying the optimal distribution network topology of mini-grid projects. RETEP-N fills a gap in rural electrification methodologies and provides useful information regarding the main technical and economic indicators of alternative network configurations. Secondly, this work provides supporting evidence of the relevance of optimizing the length and structure of the distribution network, when cost minimization is the objective in rural electrification projects. Finally, RETEP-N enables the user to quantify the impact of alternative network configurations on the energy cost for end-users. This feature is essential as affordability plays a crucial role in the provision of electricity access.

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