Applied Energy 195 (2017) 204–221

Contents lists available at ScienceDirect

Applied Energy

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

Novel methodology for microgrids in isolated communities: Electricity cost-coverage trade-off with 3-stage technology mix, dispatch & configuration optimizations

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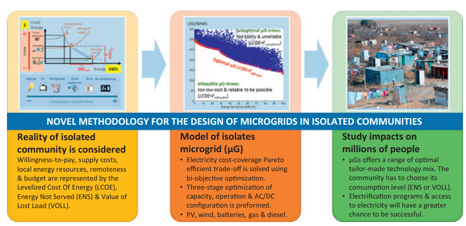
HIGHLIGHTS

- Designing microgrids to feed near 80% of the load reduces μG cost substantially.
- μG design for fridge, light & cellphone could boost electrification dramatically.
- Huge impact on electrification & on millions of people without electricity.
- Threefold optimization for μGs: capacity mix, operation and AC/DC configurations.
- Cost-coverage trade-off: Pareto efficient bi-objective optimization calculation.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 5 September 2016
Received in revised form 27 January 2017
Accepted 8 February 2017

Keywords:
Isolated community
Access to electricity
Pareto trade-off
Electricity coverage
Electrification programs
Microgrid economics

ABSTRACT

Around the world, 1.1 billion people are severely affected by their lack of access to electricity. Other vulnerable communities receive low quality access, or face expensive prices that force them to restrict their consumption because of suboptimal technology choices made by their suppliers, which are sometimes forced by local regulation. Microgrids, properly sized and managed, may represent the best option to overcome these dilemmas, offering a tailor made supply. Today's standard methodologies to design isolated microgrids optimize the cost of supply as well as the cost of the energy not served with an exogenous per unit value for the lost load. They do not include community's restrictions, such as willingness-to-pay, consumption level, budget constraints or its particular (endogenous) value of lost load. We developed a novel methodology that offers a range of microgrid designs to an isolated community, where each of them is optimal for a particular consumption pattern and value of lost load, from which the community may choose the one that best suits their needs. For this purpose, a Pareto optimal cost-coverage trade-off was constructed for an isolated community in northern Chile. A three-stage optimization was done: capacity (Genetic Algorithm), operation (robust optimization and mixed integer linear programming) and configuration (*DC* or *AC*). Diesel, gas, PV, wind and storages were modeled and 176 designs were found in total. More expensive microgrids (and with a larger electricity coverage) have hybrid mixes (conventional and renewable) and have an almost linear total cost from 298 to 249 USD/MW h for *ENS* from 0% to 28%. Lower quality microgrids are fully renewable, providing a very cheap but unreliable supply. The direct impact of lower-cost/limited supply microgrids offered here is the improvement of the

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http://dx.doi.org/10.1016/j.apenergy.2017.02.024

quality of life of millions of vulnerable people, but it requires adjustments in the country's public policies of electrification programs.

1. Introduction: access to electricity is critical for billions of people worldwide and microgrids are a potential solution

Access to electricity is critical for the development of countries and societies around the world. Despite this fact, 1.1 billion people (around 17% of world's population) have no access to this energy source [1,2]. A large body of literature shows that access to electricity reduces poverty, enhances access to health-care and education, and boosts economy, thus reducing poverty and improving quality of life [3]. For example, an isolated community with a new electrical grid can deploy drinking water systems, irrigation systems, internet services, and enables the arrival of new shops and industries. Although access to electricity is not sufficient to reach economic and social development, it is a barrier that must be overcome [4].

Therefore, important efforts have been made to boost electricity access by extending the central distribution grid [5], raising the worldwide electrification rate from 83% in 2010 to 85% in 2012 (222 million people gained access). Still, however, rural and remote communities are lagging behind due to the high cost of extending the grid to remote and scattered population [2,6]. Microgrids are the most feasible alternative in these cases.

1.1. Access to electricity in Latin America and the Caribbean impacts 25 million people in rural areas with scattered population

In Latin America and the Caribbean (*LAC*), around 25 million people[1] have no access to electricity. For a region that aims to emerge from underdevelopment this is a very poor electricity coverage when compared to the developed world, e.g. *OCDE* counties have electricity coverage of 100% [2].

To improve electrification coverage in *LAC* countries, governments have made important efforts during the 1990s and 2000s. Thus, *LAC*'s electrification coverage has improved significantly over the last years, increasing from 88% in 1990 to 96% in 2012, and has remained high, well above the world's average. As in the rest of the world, this improvement is mainly due to the expansion of the distribution system within areas under concession to a utility where they are obliged to provide service. These concession areas are very usual in *LAC* (e.g., Argentina, Bolivia, Chile and Peru) [7] and tend to be defined around densely populated areas.

In rural areas, difficulties have emerged due to low population density [8] or geographic remoteness (e.g., Amazon and Andes regions). Within these areas, governments – not as successful as they had hoped – have supported isolated communities by subsidizing stand-alone systems with specific technologies such as diesel, PV or wind. For a more in-depth review of the different rural electricity programs implemented in Latin America in the last 25 years see Annex B of Montecinos [9].

1.2. Electrification programs have often provided electricity at high prices (e.g. diesel) while failing to recognize that higher prices imply less consumption

The lack of success of electrification programs in rural remote areas can often be explained by their failure to recognize at least three dimensions of the problem: (i) the different values a community assigns to distinct energy services, (ii) the organizational and social challenge around an isolated microgrid and (iii) the estimation of the potential community's electricity demand.

The potential demand (iii) of an isolated microgrid is very hard to estimate both due to the inexistence of historical consumption patterns in communities without electricity access [5], as well as limited availability of studies on socioeconomic and cultural drivers of electricity demand (although some attempts have been made using neural networks [10]). The organizational and social challenge (ii) is relatively new for power systems and can represent a barrier as well as an opportunity due to the increasing involvement of communities [11,12]. Some authors have explored this challenge for small-scale remote microgrids and other electrification alternatives, showing that solutions are successful for specific cultural contexts. This means effective experiences in some places are not always transferable to others. Schnitzer [5] identifies some critical social and organizational factors which enable a microgrid to enter a virtuose (successful) or vicious (unsuccessful) cycle, such as strategic planning, operational design and social context. Yadoo [8] compares dealership approaches, concessionary models and strengthening of small to medium energy businesses and argues in favor of cooperative business. Montecinos proposes a self-managed electrification for isolated indigenous communities in Chile [9] and Saez [13] a specific participatory model for the Mapuche's culture, indigenous inhabitants of southern South America. Most authors point to community involvement, community leaders' engagement, local maintenance, self-protecting design, and partial community financing as key drivers for success.

Communities assign different values to distinct uses (i) of energy. Electrification programs have failed to recognize this critical fact, especially outside areas undersupply obligation by public utilities. Outside these areas, when a community has reached electricity prices around 40 USD/MW h, it's implied that it will satisfy almost all its needs, including high levels of sophistication. Conversely, when electricity is supplied at much higher costs (200–300 USD/MW h) in limited income areas, only a small amount of the potential needs of the community are satisfied, forcing them to prioritize, e.g. lighting a few hours a day, refrigeration of critical food, TV, etc. Electrification programs have failed to recognize this reality, sometimes providing electricity at very high costs, greatly depriving the community from the use and benefits of this electricity. The supply has usually been diesel at very high costs so communities often reduce their use to only a couple of hours a day.

1.3. Microgrids can improve electrification by reducing costs and enhancing electricity coverage by considering local reality

Electrification programs in *LATAM* have also neglected the fact that nowadays an optimal combination of renewable and conventional generation (together with energy storage systems) may reduce costs and increase electricity coverage substantially if local costs are taken into account (e.g. renewable energy costs due to local energy potential, and fuel & technology costs due to the isolation of a community). These optimal – tailor made – hybrid systems are possible today with the use of microgrids [14–18]: small electricity grids (usually under a few kW) that can be isolated or connected to the distribution system and have microgeneration

[1] This number was calculated considering 623 millions inhabitants [83] and a 96% electrification [2].