Development of a Methodology for Planning and Design of Microgrids for Rural Electrification

Diego Jiménez J.
Department of Electrical Engineering
University of Chile
Santiago, Chile
djimenezjimenez@ing.uchile.cl

Maria Vives S.
Department of Electrical Engineering
Andes University
Bogotá, Colombia
mv.vives90@uniandes.edu.co

Guillermo Jiménez E.
Energy Center
FCFM
University of Chile
Santiago, Chile
gjimenez@centroenergia.cl

Patricio Mendoza A.
Department of Electrical Engineering
University of Chile
Santiago, Chile
pmendoza@ing.uchile.cl

***Abstract*— Rural electrification brings economic and social welfare to communities through benefits such as power supply for medical centers, technology access, household tasks improvement and water quality, among others. However, due to low population density and low electricity demand, the cost of extending an existing grid to an isolated community can be very high, in comparison to a microgrid electrification scheme. This article presents a methodology for planning and designing a microgrid for rural electrification of remote off-grid locations. This methodology prioritizes the quality of life improvements of its inhabitants taking into account different variables such as: location, renewable energy resources availability, equipment prices, initial budget, operation and maintenance costs and equipment replacement costs.**

***Keywords*— Rural Electrification, Microgrid, Planning, Design.**

I. Introduction

There is a high correlation between the economic and social development of a country or region, and the access to electricity [1]. Electrification is a significant issue when other services such as access to drinking water, health and education depend on it. Nowadays, the percentage of the global population with access to electricity has been growing substantially, according to the policies implemented in different countries at worldwide level [2].

The electrification gap has been faced in different ways. A widely known criterion that has been applied is related to the population density, since the greater it is the less the *per capita* electrification cost is.

The electrification begins with the construction of large generation centers and the corresponding connection of these to the densest population centers, in other words, big cities. As electrification for large cities has been resolved, other priorities appear; such as energy quality improvement and electrifying less dense and farther away places which need to be electrified.

Traditional rural electrification alternatives are divided in two main approaches: electrification by interconnection to the grid and electrification through distributed generation [3], The latter has usually been done with traditional fuel based generators (i.e. diesel), while the former has been the optimal solution proposed in [4], The interconnected option allows the transmission grid to be extended to reach places within some distance where it is economically feasible to expand the grid, taking into account the future consumption of the population.

The microgrid concept is proposed as a solution to develop rural electrification that operates both in island mode and grid-tied mode, with the integration of Distributed Generation (DG) into the large-scale grid. Since there is no agreement on a single definition of microgrid, this article will use the definition given by the U.S. Department of Energy [5], that considers "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid" and can be operated in island mode or connected to the grid .

Several articles present different methodologies, however, these are focused on specific situations, as seen in [6-11]. This work presents a methodology for planning and designing microgrids from a broad perspective, with the aim of working as a system independent of the energy grid, having as priority the quality of life improvement of an isolated community inhabitants, maximizing the access to electrical energy.

This article is divided into sections as follows: Section II presents the literature review of the different specific methodologies. In section III the scope of the developed proposal is explained. Section IV proposes the methodology for the planning of microgrids and Section V proposes the methodology for the design of microgrids. Finally, the discussion and conclusions are presented in section VI.

II. Theoretical Framework

Even though the microgrid subject is relatively recent, different approaches to these technologies have already been made. The following are some approaches to methodologies in specific areas in different parts of the world.

In [6], the authors propose a methodology for renewable energies based microgrids for isolated communities. The proposal consists of 5 stages; stage zero is create a suitable team, stage one is technical and social feasibility, stage two is participatory planning, stage three is first impression and finally the fourth stage is a trial phase. These stages are presented in

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Fig. 1. In the stage 0, the current dynamics of the community are considered since this team must be multidisciplinary to ensure the success of the project. In stage 1 the viability is assessed by measuring the energy resource, estimating the community's future consumption and identifying stakeholders. At this stage, it is important to build trust between the parties and maintain a constant dialogue between them. In stage 2 decisions are made with the active participation of the community. Stage 3 monitors the implementation of the project, the real effect it produces in the community and changes in behavior patterns in terms of energy consumption. Finally, in stage 4 a long-term strategy is created to ensure the success of the project. This stage defines the indicators to be monitored, the responsibilities in the operation and maintenance, and define action plans for possible failures, among others.

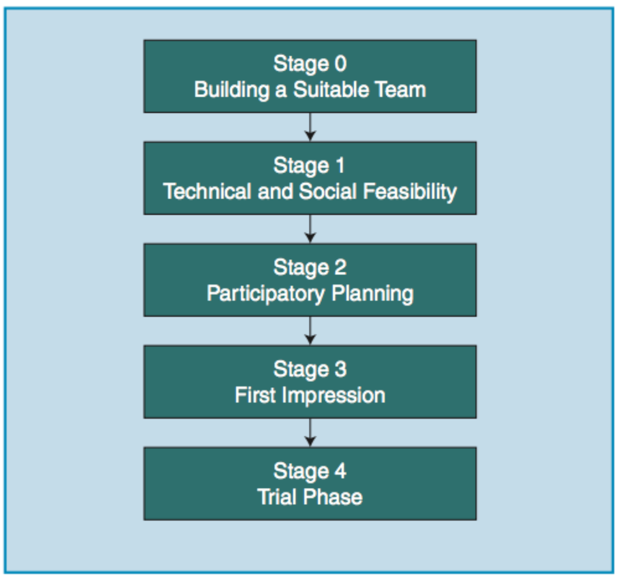

Fig. 1 Stages of the methodology for develop of microgrids [6].

In [7], the authors propose a co-construction methodology that promotes the sustainable development of rural/urban communities in northern Chile. The main focus is to develop energy based solutions where communities embrace technologies and social-technical resilient systems are established, with the former under a framework of successful energy transitions. The methodology consists in 4 stages: Socio-technical diagnostics and team building, Socio-technical design and sustainable plan, implementation and kick-off, and finally Operation, evaluation and dissemination. These stages are presented in Fig. 2.

In [8], the operational data of a microgrid system based on photovoltaic panels in the Sagar Island of India is analyzed in order to understand the problems that affect the community, such as connectivity, energy consumption, and the potential demand, proposing a planning and design approach for a decentralized system for rural electrification. First, the proposed methodology deals with the details of the place, where the town location and the consumption profile are analyzed, then is consider the amount of available natural resources. In addition, it considers the possibility of granting responsibility for the operation and maintenance (O&M) of the microgrid to a regional institution, and finally, the methodology proposes an analysis of the collected fees or associated costs for the microgrid development, planning and O&M. Finally, in the paper, there are some reasons why members of an isolated community do not agree on the implementation of a microgrid. In the first place, mentions are made of the lack of financial resources to cover the initial and monthly fees. Another drawback is that the houses are very distanced between them and in addition some owners already have domestic solar systems installed.

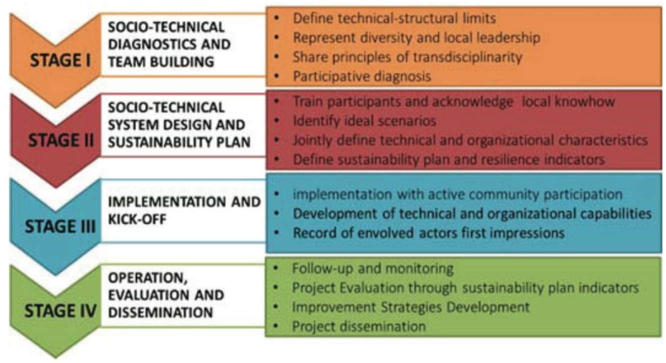

Fig. 2 Co-construction stages [7].

In [9], a methodology for the cost-effective design of microgrids based in composable tools using optimization is presented. The developed methodology is used in a photovoltaic based microgrid in Bhutan, where a student hostel distributed in seven blocks is proposed. The methodology first starts by sizing the photovoltaic system using solar radiation provided by NASA, then identifying the load profile by modeling the equivalent consumption to a measurement block. The next step is to identify the microgrid optimization scheme, in which the cost and lifetime of the PV panel and the batteries are entered, as well as the solar irradiation and the load profile. This establishes an acceptable probability of load losses, meaning the number of times it will be acceptable to remain without power supply. In [9] a scalability concept is used with the objective of readjusting pre-established values, finally analyzing the available funding for the construction of the microgrid. Here, the total cost of the system is evaluated during its life-time, using the net present cost, the initial investment cost, the cost of operation and maintenance and the cost of replacing batteries with the use of the HOMER software.

In [10] it is pointed out that the success of microgrid projects depends on 3 edges: financial viability, technology used and geographic location. For the planning of electrification projects in rural areas there are many criteria to be used to choose the location of a microgrid, as it is shown in Fig. 3.

Finally, many authors agree that future success depends on the project management. In [11] the author points out how the experience in South Africa shows that small rural energy companies can thrive when given autonomy. Similarly, well-articulated public-private organizations can provide sustainable energy services. For the case proposed in [11], electrification was carried out through autarkic systems.

Criteria	Description
Electrification	• No grid electrification plans within the area for <5 years • No off-grid plans for the area
Consumer profile	• Potential off-grid institutional users such as schools, clinics, factories etc. • Clustered population density of >50 households/km^2 • Community commitment and ownership
Topography	• Consumer isolation from potential impact of revised grid electrification plans • Adequate renewable resources for the region • SMEs/Agricultural potential to promote regional productivity and economic sustainability
Human criteria	• Stable political landscape to facilitate communication and support • Regional security against theft and vandalism

Fig. 3 Selection criteria for microgrid for rural electrification location in South Africa [10]

III. Scope of the Proposal

In order to carry out the development of an isolated microgrid, the proposal is divided into four stages. Hereafter are described the most important processes of each. Fig. 4 shows the proposed stages for microgrid development.

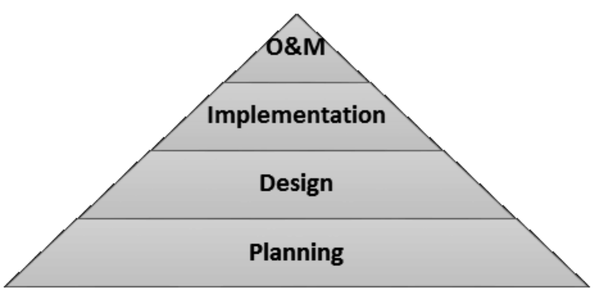

Fig. 4 Proposed stages for the develop of a microgrid.

The Planning stage is responsible for quantifying in general the technical, economic and social feasibility of making a microgrid in an isolated community.

The Design stage allows the sizing of the technological solution and the community's involvement in the project, which includes the management model in order to quantify the necessary resources for the development of the microgrid. In addition, it defines the way in which the community will become part of the project during its operation and maintenance, and the impacts of the project on the community and the environment.

The Implementation stage is the materialization of the microgrid design; in addition, in this stage the launching process of the project is accomplished and the changes produced by the electrification in the lifestyle of the population are verified.

Finally, the O&M stage allows the Operation and Maintenance scheme to established, with the purpose of ensuring an adequate operation of the microgrid project.

This article focuses on the initial processes, namely, the Planning stage and the microgrid Design stage, considering that an open methodology for rural electrification in isolated areas is developed.

IV. Methodology Proposal for Planning

Considering that electrification in remote locations can be done by grid extension and islanded microgrids [12], the main idea is to develop a planning strategy that allows the determination of the best way of electrification depending on the characteristics presented in each community. The methodology proposal is depicted in Fig. 5.

Fig. 5 Methodology for microgrid planning

First, it is necessary to define the universe of electrically isolated locations that could be electrified by microgrids. For this, a detailed analysis is carried out on the location of the community and the electrification plans for the next years, as presented in [10], Then, a technical-economic comparison of the necessary investment is carried out so the final decision on how to electrify (by grid extension or microgrid) is made [13].

With this, the possible universe to be contemplated for electrification by microgrids is defined. From the universe of feasible isolated microgrids the following necessary information is collected: current situation, energy resources, population (quantity, growth, population density), development and economic growth potential, in addition to electricity consumption (current, future).

Because in many cases this information will not be complete, it is necessary to estimate the missing data. For the analysis of the data obtained previously there are 5 selection criteria; Electrification Current Situation, Economic Viability, Human Criteria, Topography and Consumption, as seen in Fig. 6.

The Electrification Current Situation refers to whether the location has some energy source currently in use. Generally, some isolated communities have fossil fuel generators as their source of energy. It is important to know if there is a distribution grid and the status of it. Likewise, the government's electrification plans are evaluated to verify if the locality is part of them.

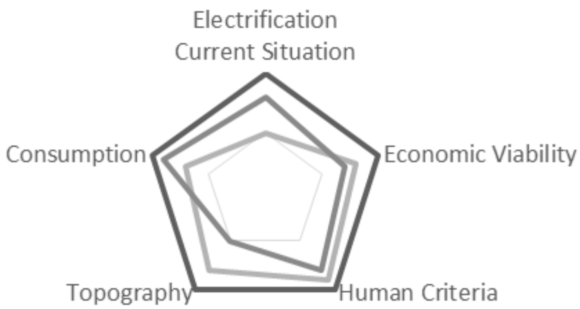

Fig. 6 Selection criteria for prioritization of locations for microgrids. Pentagons show possible combinations corresponding to different criteria

The Economic Viability can be determined by estimating the costs of the microgrid by equation 1 proposed in [14].

$$min_{\{E_0, I_m, P_{m,a,d,h}\}} PVC_P + PVC_W + PVC_B + PVC_G \quad (1)$$

Where PVC refers to the Cost Present Value of each of the possible sources of generation $m = \{P, W, B, G\}$, where P refers to solar photovoltaic, W to wind, B to batteries and G to diesel generator. The decision variables E_0, I_m and $P_{m,a,d,h}$ refer to the initial energy of the battery bank, the installed power in the generation source and the power generated by m in the year a, day d and hour h, respectively.

The Human Criteria refers to decision variables such as the Human Development Index (HDI), political support and stability of the region, security in the locality, as well as the possibilities of improving the productivity of the region or community.

The Topography Criteria evaluates the energy resources available at the geographic location. This article considers the natural resources sun and wind.

The consumption of the community is then evaluated. For this is consider variables such as current population, and population density. Additionally, an analysis of the current consumption is made to estimate the future consumption due to the new access of electrical energy.

Finally, an analysis is made considering the 5 selection criteria explained above in order to prioritize the order of the communities in which microgrids will be developed.

V. METHODOLOGY PROPOSAL FOR DESIGN

Hereafter, a methodology is proposed for application in isolated communities, where it is not viable to carry out an electrification by grid extension. When the geographic location where the microgrid project has been defined, the design shown in Fig. 7, is applied.

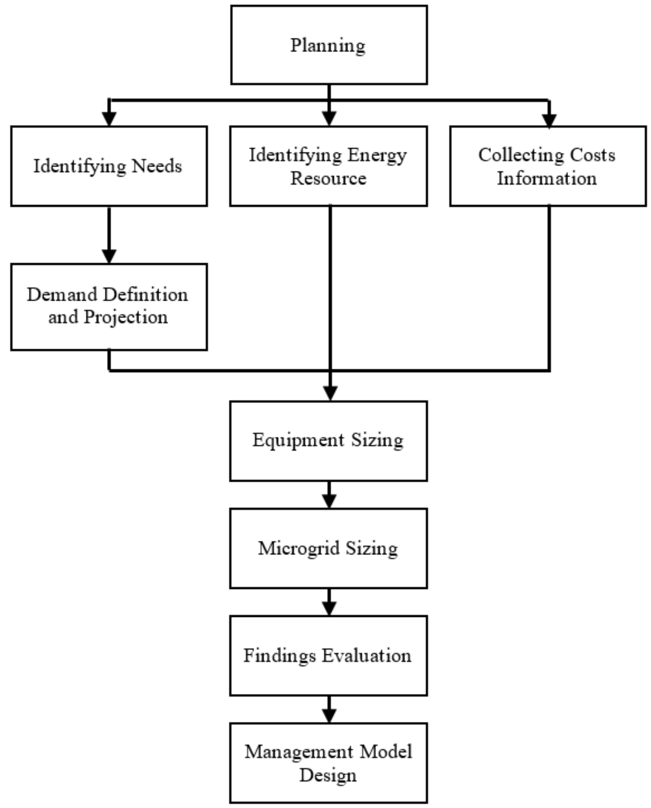

Fig. 7 Methodology for microgrids design

A. Identifying Needs

Considering that the planning stage, previously mentioned, defines the feasibility of the microgrid, in this stage the social and economic aspects are detailed. In the first place, the collecting of the main variables according to the stakeholders should be carried out, as mentioned in [13]. Interviews with the local government, the investors, and community should be held. In this stage, the main goal is to define the design key points such as; budget, energetic needs, availability of payment, among others. Among the energy needs identified, it should be distinguished the need for public lighting, residential consumption, productive activities and pumping water for aqueducts. It is important to involve the community in identifying these needs to obtain satisfactory results and avoid problems as mentioned in [15]. In addition, the economic objectives of stakeholders are identified, such as the time horizon of the project, minimization of emissions, availability of investment by the community, among others.

B. Demand Definition and Projection

After defining the main variables, a demand profile must be built for the isolated community. The construction is performed by analyzing the measurements done or by estimating demand behavior as explained in [16]. The measurement analysis integrates that process inputs such as, number of inhabitants, number of houses, number of schools, individual surveys per house, number of public lighting luminaires, classifier module based on self-organized maps (SOM), module of heuristic search, database and modules of generation of specific profiles in order to obtain the community's total electrical demand.

The estimation is made of considering the growth that will have the load for the defined time horizon, this growth depends on the natural increase of the population, in addition to the projection of improvements because of the access to electricity. There are several methods of demand estimation with classical approaches such as, multiple regressions, exponential smoothing and Kalman filters among others [17]. Apart from that, there are artificial intelligence methods such as expert systems, neural networks and fuzzy logic. Currently are in used hybrid methods that combine several strategies in order to complement the technique of pre-processing data or generate variants in their algorithms in optimization stages.

C. Identifying Energy Resource

Having registered the geographic location of the microgrid, we proceed to identify the availability of energy resources, for this are characterized mainly renewable resources such as solar irradiation and wind speed. In situ measurements or estimates using tools such as Surface Meteorology and Solar Energy (NASA) are normally use. Some countries have their own data base and meteorological centers to better estimate energy resources. In addition, other important variables such as air density for the wind case and temperature for the solar energy case, should be taken into account.

D. Collecting Cost Information

Traditionally, fossil fuel generators have been used as a distributed generation solution for rural electrification. This resource is also considered as an optional backup in the design of the microgrid, thug it is necessary to calculate the cost of fuel and transportation to the selected community.

In addition, the collection of information for the equipment costs is required for the sizing of the microgrid, both investment costs and replacement costs if necessary. O&M costs must be considered in order to estimate the community´s future cost after implementation and launching.

E. Equipment Sizing

An evaluation of the project should be carried out in order to do the sizing of the units of the microgrid [18], considering the size and technical characteristics of the necessary equipment among them; wind turbines, photovoltaic panels, power inverters, battery banks and diesel generator in accordance with the requirements established by the demand profile.

F. Microgrid Sizing

There are available different design tools for microgrids in the market, among which stand out the software of optimization of distributed systems HOMER. This software allows the evaluation of different configurations of energy systems through a simulation process. The general scheme of design of the microgrids consists of a representation of two transfer bars: a DC bar where the photovoltaic array and battery bank are connected, making the transfer of energy through a bidirectional converter (inverter-charger) to and from an AC bus, where the wind turbines, the diesel generator, the main grid and loads are connected. HOMER optimization algorithms determine the best configuration for a hybrid system based on power balance, technological options, costs, specification of components and available resources, in order to select the optimum scenario according to the isolated community previously identify needs.

G. Findings Evaluation

Considering the needs presented initially and through an analysis of the results of the HOMER, an approach can be selected according to the needs and objectives of the stakeholder. This is done in conjunction with local government, investors and the community. In isolated microgrids, it is important to minimize the energy cost perceived by community members, under a social approach and to favor the insertion of low-cost technologies based on renewable energy sources. The most important variables in making the final decision are the availability of renewable resources and the level of electrical demand, in addition to the associated investment costs and O&M costs of each technology. Finally, the design selected should be optimal for most the expected scenarios, not depending on the main power grid.

H. Management Model Design

The management model depends mainly on the responsible of the project: the community or an external entity (private company, donor company, government). In any case, it is necessary to include the community as an active entity in the microgrid planning and development, since it is of great importance that participates in the management of the proposed system to ensure future sustainability [19]. That is why the design of the management model considers the current dynamics of the community for its structure. Usually the community already has an administrative body set up as a neighborhood council or a community council. In the operational microgrid, two management visions have been proposed [20]; through the community and its current structure or a hybrid system involving the community and private or governmental entities.

The main responsibility for managing the microgrid is O&M in such a way as to ensure the sustainability of the project. In addition, it is responsible for scheduling preventive maintenance, coordinate technical assistance when necessary and collect economic resources for continuous operation. The latter is of high importance because a considerable number of electrification projects stop operation due to lack of resources.

Within the human operating team of the microgrid there must be a person with the technical knowledge necessary to solve the basic problems, this is done by preparing and training a technical team within the community. The lack of trained staff has proven to increase failure to sustain future projects as discussed in [21].

VI. Discussion and conclusions

This article presents a methodological framework focused on a general vision for the planning and design of microgrids in isolated communities where concepts are presented from planning to operation and maintenance of microgrid for rural electrification.

The planning proposal is responsible for quantifying in general the technical, economic and social feasibility of a microgrid through the analysis of a multi-disciplinary team capable of identifying all stages concerning the selection criteria in order to prioritize the isolated localities and select the communities suitable for the creation of a microgrid.

The design proposal allows to size the technological solution and the community's involvement in the project, which includes a management model to ensure a future sustainability of the microgrid. In addition, this stage defines how the community will be part of the project in its operation and maintenance, and the future impacts of the project on the community and environment.

It is considered as a future research the possibility of studying in detail the stages of Implementation and O&M shown in section III. In addition, other future work is the study of the behavioral change in the demand of the electrified community with the purpose of making a better projection and estimation of this due to the increase of load because of the access to energy.

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References

[1] M. Kanagawa and T. Nakata, "Assessment of access to electricity and the socio-economic impacts in rural areas of developing countries," *Energy Policy*, vol. 36, no. 6, pp. 2016–2029, 2008.

[2] C. Pirlogea and C. Cicea, "Econometric perspective of the energy consumption and economic growth relation in European Union," *Renew. Sustain. Energy Rev.*, vol. 16, no. 8, pp. 5718–5726, 2012.

[3] D. F. Barnes, "Effective solutions for rural electrification in developing countries: Lessons from successful programs," *Curr. Opin. Environ. Sustain.*, vol. 3, no. 4, pp. 260–264, 2011.

[4] S. C. Bhattacharyya, "Energy access programmes and sustainable development: A critical review and analysis," *Energy Sustain. Dev.*, vol. 16, no. 3, pp. 260–271, 2012.

[5] D. T. Ton and W. T. P. Wang, "A More Resilient Grid: The U.S. Department of Energy Joins with Stakeholders in an R&D Plan," *IEEE Power and Energy Magazine*, vol. 13, no. 3. pp. 26–34, 2015.

[6] G. A. Jimenez-Estevez, R. Palma-Behnke, D. Ortiz-Villalba, O. N. Mata, and C. S. Montes, "It Takes a Village: Social SCADA and Approaches to Community Engagement in Isolated Microgrids," *IEEE Power and Energy Magazine*, vol. 12, no. 4. pp. 60–69, 2014.

[7] P. Ramírez-Del-Barrio, F. Valencia, A. Marconi-Vargas, I. Polanco-Lobos, and P. Mendoza-Araya, "An alpaca fiber processing solution based on Solar energy for an isolated location in Chile following a co-construction approach," *2017 IEEE Mexican Humanitarian Technology Conference (MHTC)*. pp. 130–136, 2017.

[8] T. Kobayakawa and T. C. Kandpal, "Photovoltaic micro-grid in a remote village in India: Survey based identification of socio-economic and other characteristics affecting connectivity with micro-grid," *Energy Sustain. Dev.*, vol. 18, pp. 28–35, 2014.

[9] H. Duus, S. Mandelli, M. Molinas, and O. B. Fosso, "A methodology for supporting the planning of microgrids based on composable tools: A case in Bhutan," *2015 5th International Youth Conference on Energy (IYCE)*. pp. 1–6, 2015.

[10] Z. Xu and S. Chowdhury, "A review of rural electrification through micro-grid approach: South African context," *Power Engineering Conference (UPEC), 2013 48th International Universities'*. pp. 1–6, 2013.

[11] X. Lemaire, "Off-grid electrification with solar home systems: The experience of a fee-for-service concession in South Africa," *Energy Sustain. Dev.*, vol. 15, no. 3, pp. 277–283, 2011.

[12] B. J. van Ruijven, J. Schers, and D. P. van Vuuren, "Model-based scenarios for rural electrification in developing countries," *Energy*, vol. 38, no. 1, pp. 386–397, 2012.

[13] C. Alvial-Palavicino, N. Garrido-Echeverría, G. Jiménez-Estévez, L. Reyes, and R. Palma-Behnke, "A methodology for community engagement in the introduction of renewable based smart microgrid," *Energy Sustain. Dev.*, vol. 15, no. 3, pp. 314–323, 2011.

[14] K. Ubilla *et al.*, "Smart Microgrids as a Solution for Rural Electrification: Ensuring Long-Term Sustainability Through Cadastre and Business Models," *IEEE Transactions on Sustainable Energy*, vol. 5, no. 4. pp. 1310–1318, 2014.

[15] P. Cook, "Infrastructure, rural electrification and development," *Energy Sustain. Dev.*, vol. 15, no. 3, pp. 304–313, 2011.

[16] J. Llanos *et al.*, "Load estimation for microgrid planning based on a self-organizing map methodology," *Appl. Soft Comput.*, vol. 53, pp. 323–335, 2017.

[17] H. M. Al-Hamadi and S. A. Soliman, "Fuzzy short-term electric load forecasting using Kalman filter," *IEE Proceedings - Generation, Transmission and Distribution*, vol. 153, no. 2. pp. 217–227, 2006.

[18] R. Morales, D. Sáez, L. G. Marín, and A. Nuñez, "Microgrid planning based on fuzzy interval models of renewable resources," *2016 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)*. pp. 336–343, 2016.

[19] D. Palit and A. Chaurey, "Off-grid rural electrification experiences from South Asia: Status and best practices," *Energy Sustain. Dev.*, vol. 15, no. 3, pp. 266–276, 2011.

[20] F. van der Vleuten, N. Stam, and R. van der Plas, "Putting solar home system programmes into perspective: What lessons are relevant?," *Energy Policy*, vol. 35, no. 3, pp. 1439–1451, 2007.

[21] L. Ferrer-Martí *et al.*, "Evaluating and comparing three community small-scale wind electrification projects," *Renew. Sustain. Energy Rev.*, vol. 16, no. 7, pp. 5379–5390, 2012.