Chapter

Flexible Demand for Optimzed Microgrid Design and Cost

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Abstract

Although access to energy has been a major enabler for the development of our civilization, more than a billion people remain without access to electricity. Recent improvements in solar technology offer a unique opportunity to achieve global electrification. However, field studies have reported number of project failures. This chapter is dedicated to project developers, engineers, academicians and policymakers, who wish to contribute to rural development. In the first part, it recalls some important features of a well-thought rural electrification project, while proposing to involve students to liaise with local population. In a second part, it presents an original approach for achieving lowest cost solar microgrid design considering the random nature of solar energy and the users' willingness to be flexible in their consumption. The inconvenience (loss of utility) for users has been modeled and the results suggest that rural users are likely to adapt their consumption to the availability of solar energy to reduce their electricity bill. Such a conclusion is likely to apply to interconnected power grid as renewable energy becomes more and more prominent in the energy mix and energy storage remains a costly challenge.

Keywords: microgrid, design, demand side management, Solar, rural electrification

1. Introduction

Access to energy has been a critical factor for our civilization in the achievement of immense progress in the last century. Sadly, a large fraction of the world's population remains without electricity. Recent improvements in affordable, renewable energy generation technology, offer a unique opportunity to achieve global electrification. In fact, there is a global energy transition towards large-scale integration of renewable energy into power systems [1]. Nevertheless, venturing into deployment of solar technology in rural areas may be challenging.

Although this paper does not address the topic of financing microgrids, it is one of the main barriers to their development, as many rural families have little expendable capital and lack access to credit on one hand and entrepreneurs face challenges due to the small size and risky nature of the projects arising from their remoteness, limited demand and poor consumer base on the other [2]. The first part of this paper is a reminder of few important points presented in the literature and that one must keep in mind while venturing into a rural electrification project: a) defining a clear goal for the community; b) having an inclusive approach to possibly involving students in projects; and c) comparing different technical electrification strategies.

The second part presents a novel technical design approach with a sensitivity analysis depending on users' willingness to be flexible in their consumption. The proposed method is then illustrated through simulations. The results are then analyzed and completed with a model for the loss of utility (inconvenience) that users experience due to their adjustment in electricity consumption.

2. Important points discussed in the literature

2.1 Defining rural electrification goals for the community

The main development goals to be achieved by an electrification project influence the strategy of electrification. The goals must be clearly defined before the study of any technical solution. Depending on the stage of development of a village, development goals may focus more on improving the standard of life in rural families, improving public services or supporting the development of income generating activities. Nevertheless, rural electrification is more important when socioeconomic development takes place simultaneously: the creation of employment, entrepreneurs and the middle class, are crucial to achieve global progress [3]. It is important to evaluate what the most pressing needs of the population are and to consider how different electricity usages can impact development goals [4]. Understanding this relationship will guarantee that the solar electrification effort will produce the expected results. **Table 1** summarizes and classifies the main possible utilization of electricity and their domain of application. For example, in many villages no toilette is available in or near the house and people practice open defecation in the vicinity of their house. Without light, women have thus to restrain themselves to avoid the risk of being abused in the dark [5]. Outdoor light contributes to establishing a general sense of safety. Outdoor light can also keep wild animals away from habitations [6]. Other key usages are solar pumping to provide access to water [7] and income generating activities.

	Light (indoor and outdoor)	Other appliances	Community applications
Economic progress	Increased working hours for shops	Smart irrigation with pumps; Improved productivity with electrical tools	Income generation (e.g. charging station, repair station…)
Social progress	Social/active life at night	Women empowerment; Internet access	Improved education; Access to information with community e-learning and computers
Environmental and health improvements	Better indoor air quality (replaces Kerosene)	Refrigeration for food (conservation)	Health care centre with refrigeration
Livelihood and safety	Better safety at night (women)	Easy and quick access to water for daily use (women) Appliances for cooking	Access to entertainment with computers

Table 1.
Different usages of electricity and their impact on development.

2.2 An inclusive approach

In the literature, there is a plethora of papers about rural electrification using solar energy. Many discuss technical design and methodology. Some point out that human factors play an important role to guarantee a long-term impact of the electrification project [8]. It has been observed that user's involvement has a disproportionate impact on the chances of success of a rural electrification project [9, 10]. Nevertheless, there are several levels of involvement that can be differentiated. Local population can be involved in the definition of the development objectives, in the design of the technical solution; they can be trained on solar photovoltaic (PV) installation and operation practices; finally, they can participate actively in the management of available solar energy and in the payment collection [11, 12]. It is also important to be aware of the gendered aspects of electricity access; not all types of electrification reach and benefit all groups in the same manner [13]. In this context, electrification generates more positive impacts when complementary activities take place (e.g. capacity building, awareness campaigns, access to credit for entrepreneurs, etc.), and when electrification is supported by proper infrastructures and local institutions [14].

It is essential to have a clear vision and values for the project, to have a broad picture of the local situation (social, political and economic), and to identify trusted individuals to be ambassadors of the solar electrification project locally.

2.3 Choice of technical solution

When specific objectives are clearly defined, a technical expert has to translate them into technical requirements. The amount of electricity requested and information regarding geographical and social constraints will inform future decisions regarding the most suitable electrification solution: centralized with or without grid, individually owned systems or a hybrid solution with decentralized solutions. Stakeholders can compare the different viable, technical solutions and write a detailed technical proposal. The proposal must also include implementation, maintenance and monitoring details. The environmental impact of different solutions and technologies has also to be considered, in particular, battery replacement and recycling. The expected reliability of the electrical supply can be a major issue and must be discussed early. Trained manpower may be lacking, yet one must guarantee the regular maintenance of the system. A simple solution may be to train local manpower. However, maintenance of PV systems by users is rarely successful and spare parts and technical assistance should be readily available. Although this issue has been identified more than 20 years ago [15] it remains one of the main challenges for the long-term operation of microgrids today. Fortunately, technology comes to help with a new range of remote control and supervision tools [16].

Extending the main power grid to a village is a simple solution, yet, not always the most reliable and cost-effective. The cost-effectiveness of grid extension can be evaluated by comparing it with the most cost-effective off-grid electrification solution [17, 18]. However, field studies report poor reliability and voltages issues in rural grids [19, 20]. Communication with official utilities is often cited as non-existent, which affects the feeling of trust and ownership of the population. With generation units situated far away from remote villages grid extension also implies a large amount of Transport and Distribution (T&D) losses paid by utility companies. The average T&D loss in developing countries is often very high (37% in Venezuela, 27% in Niger and 19% in India.) (source: World Bank online database). A mixed approach to rural electrification has recently been suggested where renewable energy generation is installed at strategic locations to reduce T&D losses [21], and where villages can also benefit from local battery back-up to improve reliability of supply [22–24]. Though a mixed approach may be the best from the technical and financial standpoint, such an approach requires convincing local utilities about the viability of the project for them to actually perform the grid extension while allowing the village to function in an autonomous mode during power interruptions.

Autonomous solutions require less support from official bodies. They range from a microgrid powered by a single source of energy to solar lanterns, dispatched in each house. Solar lanterns are the cheapest and quickest way of providing light in a village. However, solar home systems require well prepared awareness campaigns to be sustainable and successful [25].

Figure 1 illustrates the main topologies possible. An example of a comparison of different types of solutions is provided in **Table 2**; such a comparison table is project-specific. Solutions were given a grade from 1 to 4 for different criteria, '4' being the best grade and '1' the lowest. This comparison is provided as an example with grades given merely as a general indicator; each project represents a particular situation, and each solution must be evaluated within its context.

Certain solutions can be implemented with alternative current (AC) and direct current (DC). The main advantages of using DC solutions are 1) savings in cost;

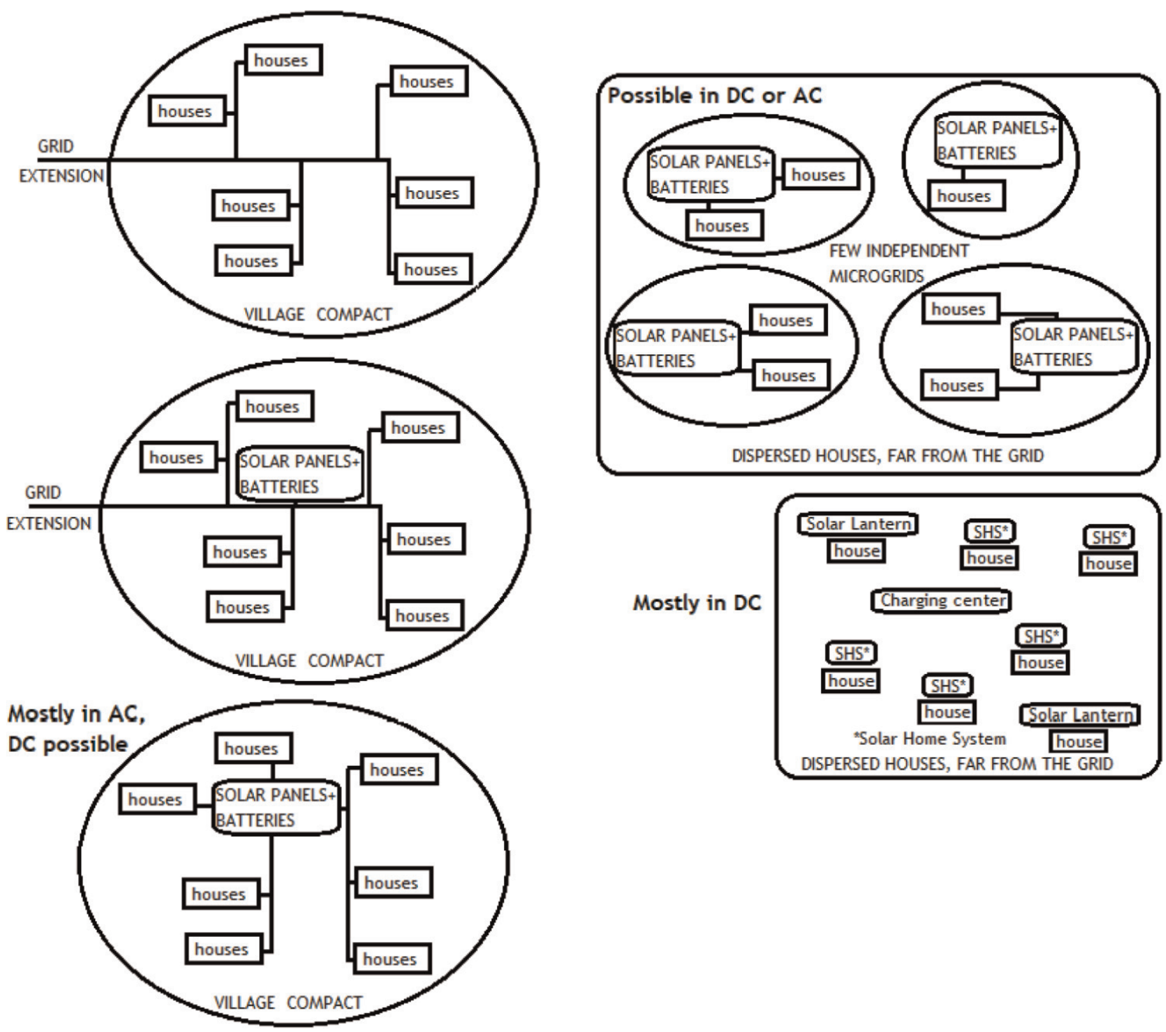

Figure 1.
Different topologies for rural electrification.

	Grid extension	**Single microgrid**	**Grid extension +microgrid**	**Multiple microgrids**	**Solar Home System (SHS)**	**Solar lanterns**
Feeling of ownership	1	1–3	2–3	2–4	3–4	2–4
Ease of maintenance	2 (often not reliable)	2	1–2(more complex)	2–3 (Direct Current and modular systems are preferred)	3	3–4 (identical material)
Range of services	4 Can include community services	3	4	3	2 (mostly for individuals)	1
Security of installation	2 (weather)	1 to 3 (theft, and damage)	1 to 3	2 to 3	2 to 4 (misuse)	2 to 4 (misuse)
Social integration	1	2 to 3	2 to 3	2 to 4	2 to 4	3 to 4 (low tech easily assimilated)
Ease implementation	2 to 4	2 to 4 (depends on local support)	1 to 2	2 to 3	3 (rooftop)	4
Affordability	1 to 3 (various distances)	1 to 3 (distance between houses)	2 to 3 (most economical for full service)	2 to 3 (savings on power lines +loss)	1 to 2 (requires more batteries)	4

1 = No/Very little; 4 = Yes/Very much.

Table 2.
Example of comparison of different types of electrification.

2) simplicity; and 3) gain in efficiency. Indeed, DC systems do not require inverters and are most suited for an individual system with small loads. DC is also less dangerous for humans than AC for the same voltage. The main drawback of DC systems is the high losses over long distances and their lack of compatibility with the main grid and standard appliances. However, more and more efficient DC appliances are available.

2.4 The opportunity to involve youth and students

The many years of experience in rural electrification and international development have taught us that fostering the right environment for growth and community development is even more important than having the right technological design. A holistic approach is more complex but allows for a more durable and sustainable impact [26, 27].

In many developing countries, youth constitute a large part of the population in the age of working (in Arica: 37%) but is also largely affected by unemployment (more than 60% of all unemployed people in Africa). It is therefore essential to promote youth leadership and involvement in decision-making to participate in energy access projects [28]. Involving local and international students in such projects has many benefits. Several institutions are now offering their students the opportunity to contribute to rural electrification and more generally, rural development projects.

One of such initiatives is the millennium village project that brings together Columbia University, the United Nations, and industrial partners [29, 30]. Another initiative, on a much larger scale, is proposed in India: Live-in-LabsTM. It was launched by Amrita Vishwa Vidyapeetham, (Amrita University) in 2014 and follows a similar holistic approach aiming at rural development while exposing youth to the lifestyle and problems of the rural population [31]. In Live-in-Labs projects, students get an opportunity to use their skills to contribute to society, thus fulfilling one of the main objectives of education: inculcating ethical values and giving exposure to students. Partnering with an NGO, more than 1000 students, faculty and staff, from Amrita Vishwa Vidyapeetham (Amrita University) have already had the opportunity to serve these villages, living among villagers and experiencing their life. Among the many students' feedbacks, three points are to be highlighted [6]:

- Many students have reported that such projects were a platform for the utilization of their skills, and for experiencing the practical challenges of teamwork.

- There is a new awareness among students about the living conditions of the underprivileged and the challenges they face.

- Most students reported that it was gratifying for them to participate in the design and implementation of a practical solution. Many have stated their wish to continue contributing to similar causes.

The opportunity offered to student to be part of a real project that includes technical and socio-cultural components and associated with a budget and deadlines plays an essential role in preparing them to the active life and completes their education.

3. Methodology for the design of technical solutions

3.1 Overall approach and main parameters

A common approach in the field has been to estimate electricity demand and availability of local resources to design an approximate solution. Nowadays algorithms and software have been developed to optimize the design of autonomous solutions [32, 33]. In general, the design is based on the estimation of a non-flexible electricity requirement that can vary from day to day around an average demand. The load is then modeled with possible time steps ranging from 1 minute to 1 hour. The different technical and economic parameters and weather data that describe the local situation are then added to the simulation software. Possible designs with different combinations of renewable energy sources, diesel generators, grid extension solutions and energy storage possibilities can then be simulated and compared to find the least cost design. Algorithms can perform complex optimizations with multiple objectives [33]; when a professional simulation software is used, the inbuilt algorithm selects the most economical design for a certain level of reliability of supply. In this case, the environmental and social impacts of different solutions can be evaluated and compared manually, by project engineers. **Figure 2** illustrates the general process.

The number of parameters required to perform one simulation or optimization can be excessively high. For example, load can be modeled by a fixed load profile, or by a

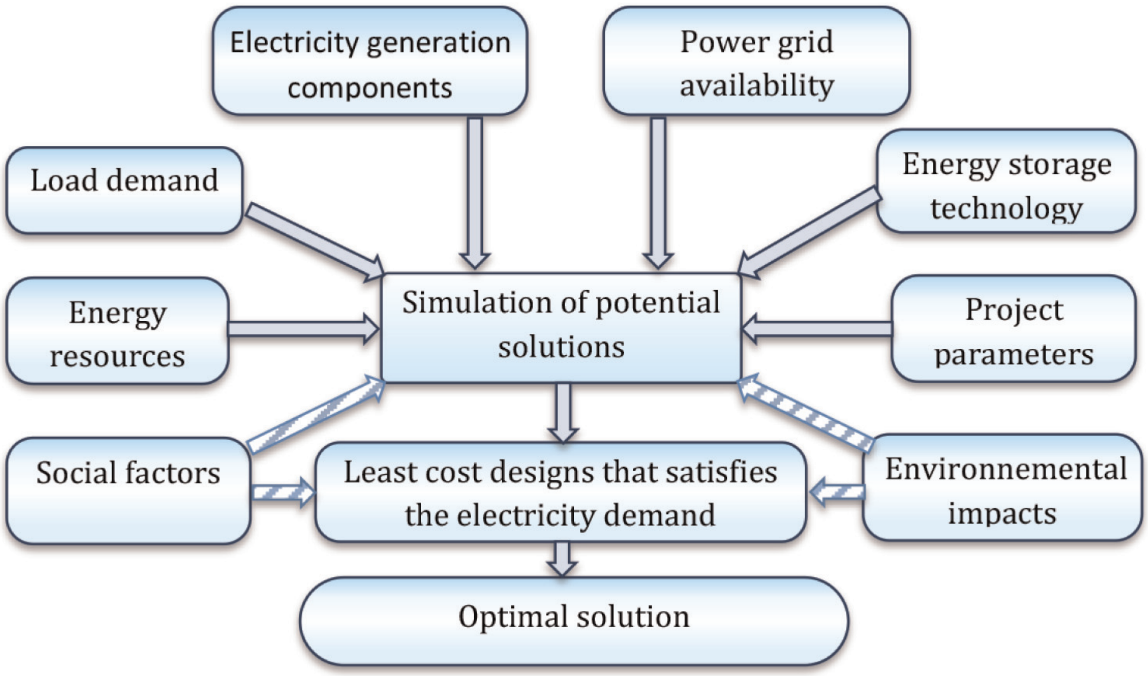

Figure 2.
Rural electrification process to determine the optimal technical solution.

profile with random variation around it. Numerous other parameters are necessary to model energy resources, environmental factors, technical characteristics and costs of energy generation and storage systems, as well as project parameters. A brief summary of the major parameters that influence the design of an autonomous electrification solution is presented in **Table 3**.

Load demand is thus an input parameter among many others that is fed into an algorithm which calculates the 'optimal' combination of technology and energy storage able to satisfy the load at least cost. Design algorithms are compared based on their precision (i.e. their ability to find the best design), computational time and if they can achieve multi-objective optimization. Nevertheless, the precision of the calculated design is limited by the precision of input parameters fed into the algorithm. The two most imprecise parameters are renewable energy resources [23, 34] and load demand. Long-term weather forecast can help optimize the microgrid design while short-term forecast can help better manage the available energy [35, 36]. The accuracy of the load profile immensely influences optimization results [33, 37]. However, with most standalone hybrid energy systems being used in remote and rural areas, load profile data are still scarcely available.

Many field reports highlight that affordability and reliability of supply are critical for the sustainability of isolated solutions used for electrification [8, 38]. Cost of battery storage can be compared to the cost of power outages that can be avoided [39]. Nevertheless, providing high reliability of supply necessitates high investment and thus impacts negatively 'affordability'. On the one hand, low reliability of electrical supply is an obstacle for rural development and on the other hand, affordability is critical for a good portion of rural households. Until now, reliability has been considered to be a firm loss of load. In an isolated microgrid powered by renewable energy, it happens due to a lack of available energy to satisfy firm electricity demand. The proposed method is to introduce flexibility in load demand as a novel parameter for the design of an autonomous solution powered by solar energy. Previous research showed that having sufficient load during daytime reduces the requirement of

Load	Average demand	Load profile	Statistical distribution (variability)	Seasonal variation	Cost of outage	**Flexibility** NEW
Energy resources	Type of source: solar, wind hydro, biomass	Annual Average energy	Distribution of energy throughout the year	Variation around the profile	Environmental parameters: Temperature, air density, humidity,	Derating factors: shading, dust, and surface roughness
Electricity generation components	Power curve, efficiency	Cost (capital, replacement and fuel cost)	Maintenance schedule and cost	Lifetime	Lifecycle environmental impact	Technical settings (site specific): angle of inclination for solar PV, hub height for wind turbine…
Energy storage technology	Max. rate of charge/ discharge and energy content	Efficiency	Lifetime in years and energy throughput Vs. utilization pattern	Environmental impact: CO2, metal depletion, and other risk of pollution.	Range of utilization: Depth of Discharge	Condition of operation and derating factors: Temperature coefficient
Project parameters	Project lifetime	Reliability	Inflation	Discount rate	T&D Losses	
Power grid	Distance from specified location	Cost of extension	Grid capacity	Reliability	Environmental impact of electricity produced from the grid	Cost of electricity, and selling price for electricity excess

Table 3.
Major parameters influencing the design of a rural electrical solution.

batteries for an autonomous solution powered by solar (+wind) energy [40–42]. Suitable energy tariffs could be developed to attract such entrepreneurs that consume electricity mostly during the daytime [43]. Once such a microgrid is deployed, shifting load during daytime reduces the probability of loss of load and increases the lifetime of batteries [44].

Mandelli et al. [45], began to detail the different aspects of reliability, energy wastage and their actual costs, when designing a stand-alone microgrid. It is possible to go one step further by evaluating how diverse degrees of flexibility in electricity consumption affect the technical design of an autonomous system powered by solar energy. In other words, the proposed method evaluates the possible savings, on microgrid design, when users agree to adapt their needs to the availability of solar energy (see **Figure 3**).

The flexibility of users was quantified according to three criteria: 1) seasonal: users reduce their consumption during the month with less solar resources; 2) load shifting during daytime: users are invited to shift a portion of their load during sunshine hours; and 3) quick adaptability: users accept that a portion of their needs is adjusted (postponed) according to the real-time availability of solar energy. The savings are evaluated in terms of 1) cost over the project lifetime; 2) reduction in percentage of unused energy (energy in surplus which could not be stored in batteries and was wasted); 3) number of batteries required in the design; and 4) number of solar panels required.

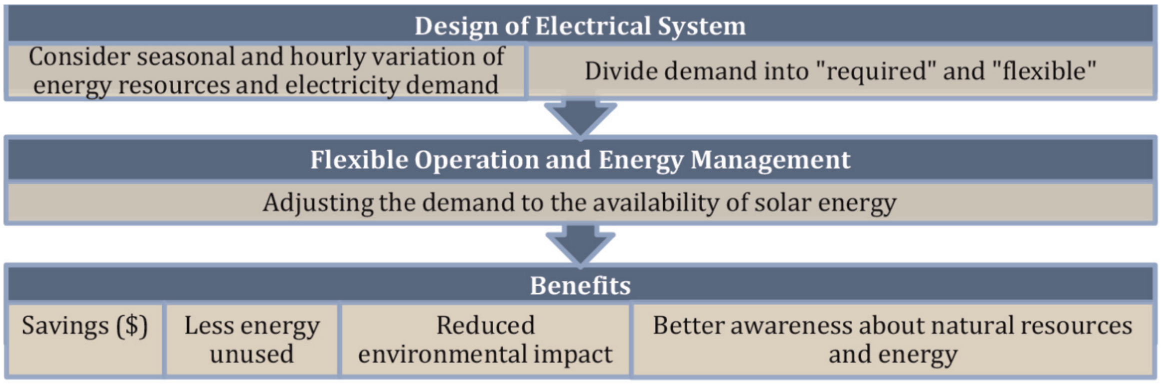

Figure 3.
Proposed approach and its benefits.

The repercussion of the proposed approach, is financial, social and environmental. Such an approach to microgrid design encourages conservation of resource and promotes awareness about the availability of natural resources. It also encourages the development of professional activities that use locally available resources, at the time when they are most available. Here, the notion of degree in flexibility in electricity demand replaces the former notion of reliability. In this context, reliability referred to the occurrence of power interruption due to lack of renewable energy. Flexibility in consumption is rewarded in the form of economic benefits for users. The economic savings comes from two factors: 1) better utilization of renewable energy, with a reduction of unused electricity, previously produced in surplus; and 2) a reduction in the size of energy storage and solar panels. In addition, the environmental footprint of the electricity generation system is minimized.

3.2 Proposed design method and assumptions

3.2.1 Test scenario for the proposed approach

As mentioned earlier, the novel approach is to design an autonomous solution while performing a sensitivity analysis for different degrees of flexibility in electricity demand. A base electricity consumption pattern was assumed to illustrate the method with an average daily load of 50 kWh. The load profile used is shown in **Figure 4**. It corresponds to the profile of a rural settlement of 30 households with 80% of

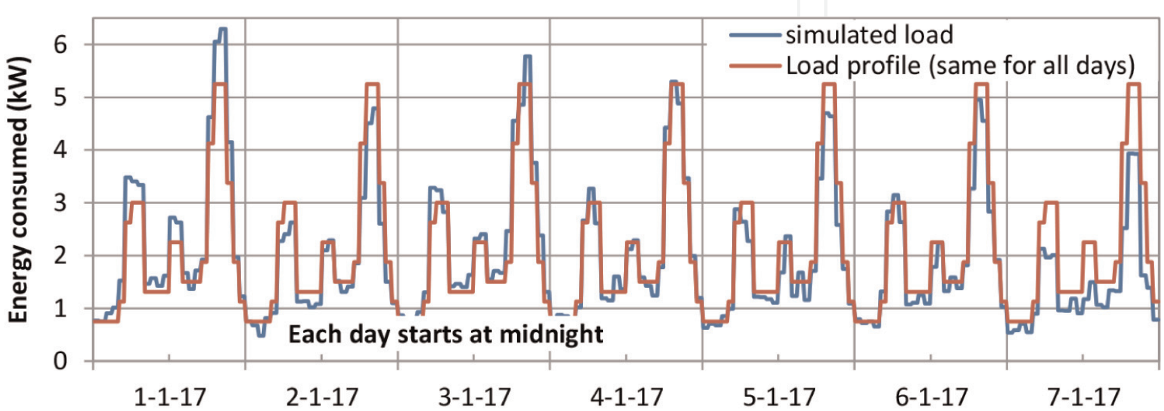

Figure 4.
Chosen load profile and variability over 1 week.

energy consumed by households– mostly in the morning and early at night– and the remaining 20%, consumed by home businesses, enterprises or schools, throughout the day [42].

HOMER Pro, is a well-recognized professional software that compares the cost-effectiveness of different microgrid designs. It can compare different technologies among each other (solar, wind, hydro, biomass.) and suggests the most economical combination of generation units and storage to meet the predefined electricity demand (more details in [46]). The total cost of the microgrid project, called the Net Present Cost, is minimized over its chosen lifetime. Here it is assumed to be 25 years, the lifetime of the solar panels. To account for the remaining lifetime of batteries, a portion of their replacement cost proportional to their remaining lifetime at the end of 25 years, is added to the project. Thus, two designs, one with batteries near their end of life after 25 years, and one with brand new batteries at the end of the 25 years, can be compared fairly.

In HOMER Pro software, loads are represented by a load profile. When a power grid is available, certain loads can be backed-up by the microgrid energy storage while other can be programmed to be interrupted. There are more parameters such as seasonal variation, a difference between weekdays and weekends, flexible loads … The software assumes that the load in each time step varies around the set profile according to a *time step perturbation value* and a *daily perturbation value*. The mechanism for adding day-to-day and time-step-to-time-step variability is simple. First, HOMER assembles the year-long array of load data from the daily profiles specified. Then, in each time step, it multiplies the value in that time step by a perturbation factor α:

$$\alpha = 1 + \delta_d + \delta_{ts} \qquad (1)$$

Where, δ_d is the daily perturbation value and δ_{ts} is the time step perturbation value. HOMER Pro randomly draws the daily perturbation value once per day from a normal distribution with a mean of zero and a standard deviation equal to the daily variability input. It randomly draws the time step perturbation value every time step from a normal distribution with a mean of zero and a standard deviation equal to the time-step-to-time-step variability input value. **Figure 4** illustrates the profile chosen for the simulation as well as one-week consumption data with a day-to-day variability and a time-step-to-time-step variability of 10% each, the chosen variability factors for this simulation.

Lead-acid batteries were used for backup as they have the cheapest capital cost though Li-ion batteries are surely becoming an interesting option. The technical characteristics of Lead-acid battery chosen for the simulation are shown in **Table 4**. The lifetime is defined as the maximal length of time or maximum energy throughput for a battery. As soon as one of these values is reached during a simulation, the battery bank

Energy capacity (kWh)	Cost			Lifetime		Maximal depth of discharge (%)
	Capital (€)	Replacement (€)	O&M (€/a)	(kWh)	(a)	
1	83	75	1.5	800	8	60

Table 4.
Battery characteristics.

is replaced by the software. The cost of solar panels, inverters, and batteries is the benchmark cost provided by the government of India [47]. The actual solar production of the 31.5 kW solar installation installed on the roof of Amrita University, Amritapuri campus, has been used. The data were measured using a commercial smart meter placed just before the inverter, on the DC cables coming from the solar panels. The software assumes different numbers of solar panels by scaling up or down the measured values. For the microgrid simulations, the inverter and rectifier were both modeled as 95% efficient.

The real-discount rate was assumed to be 7.5% in all simulations [48, 49].

3.2.2 Flexibility criteria

Three flexibility criteria have been introduced and tested. The first parameter tested is the willingness to shift a portion of the load during sunshine hours (8 am to 5 pm). The portion of this flexible load was 0%, 5% or 10%.

The second parameter is seasonal, with a shift of consumption from the month with the least solar energy resource, to other months with maximal solar irradiance. The reduction of load was 0%, 10% or 20% for 1 month, and was compensated by an increased consumption spread over 2 months with higher solar irradiance.

The third parameter proposed is the flexibility to adjust one's consumption throughout the year depending on the availability of solar resources. The portion of load adjusted represents 0%, 5% or 10% of the total electricity consumption.

3.2.3 Test cases

The test cases are summarized in **Table 5**. For a fair comparison, the annual average consumption is the same in all cases. The flexibility of consumption in relation to the availability of the solar resources is thus the only parameter that influences a change in cost for the overall project.

The parameters describing electricity demand and its flexibility have been fed to the software, which calculated the cheapest design able to feed the associated load. A total of eight sets of simulations have been performed. Cases 1A, 2A and 3A are identical, with non-flexible loads (i.e. the software assumes that if a certain microgrid design is not able to feed 100% of the load demand, it is rejected).

Case N° → ↓		A	B	C
1	Flexible load between 8:00 am and 5:00 pm (% of total load)	0	5%	10%
2	Seasonal variation of demand	0	−10% June and +5% Feb. and March	−20% in June and +10% in Feb. and March
3	Adjusted (reduced) consumption (% of energy shortage in a year)	0	5	10
4	Max. flexibility	Case 1C + 2C + 3C combined		

Table 5.
Test cases with different flexibility criteria and associated parameters.

3.3 Results and analyses

Due to the variable nature of solar resources and electricity consumption, battery storage is required to ensure that electricity is available when users want to consume it. However, batteries are expensive; in the simulation, they represent 70% of the overall project cost in case 1A, and 50% in case 4. Thus, it is sometimes more economical to purchase additional solar panels and let a portion of electricity be wasted (unused) due to a lack of storage capacity. The results of the simulations show the most economical design in all cases. **Figure 5A–D** show respectively, total cost, percentage of electricity unused, (i.e. produced in excess while batteries were full), number of batteries, and number of solar panels. Capital cost is also an important parameter since it often requires the help of donors or subsidies, whereas replacement costs and maintenance costs can more easily be paid by users [2, 8]. **Table 6** illustrates the number of solar panels, number of batteries, total cost and capital cost for the most economical design in each set of simulations.

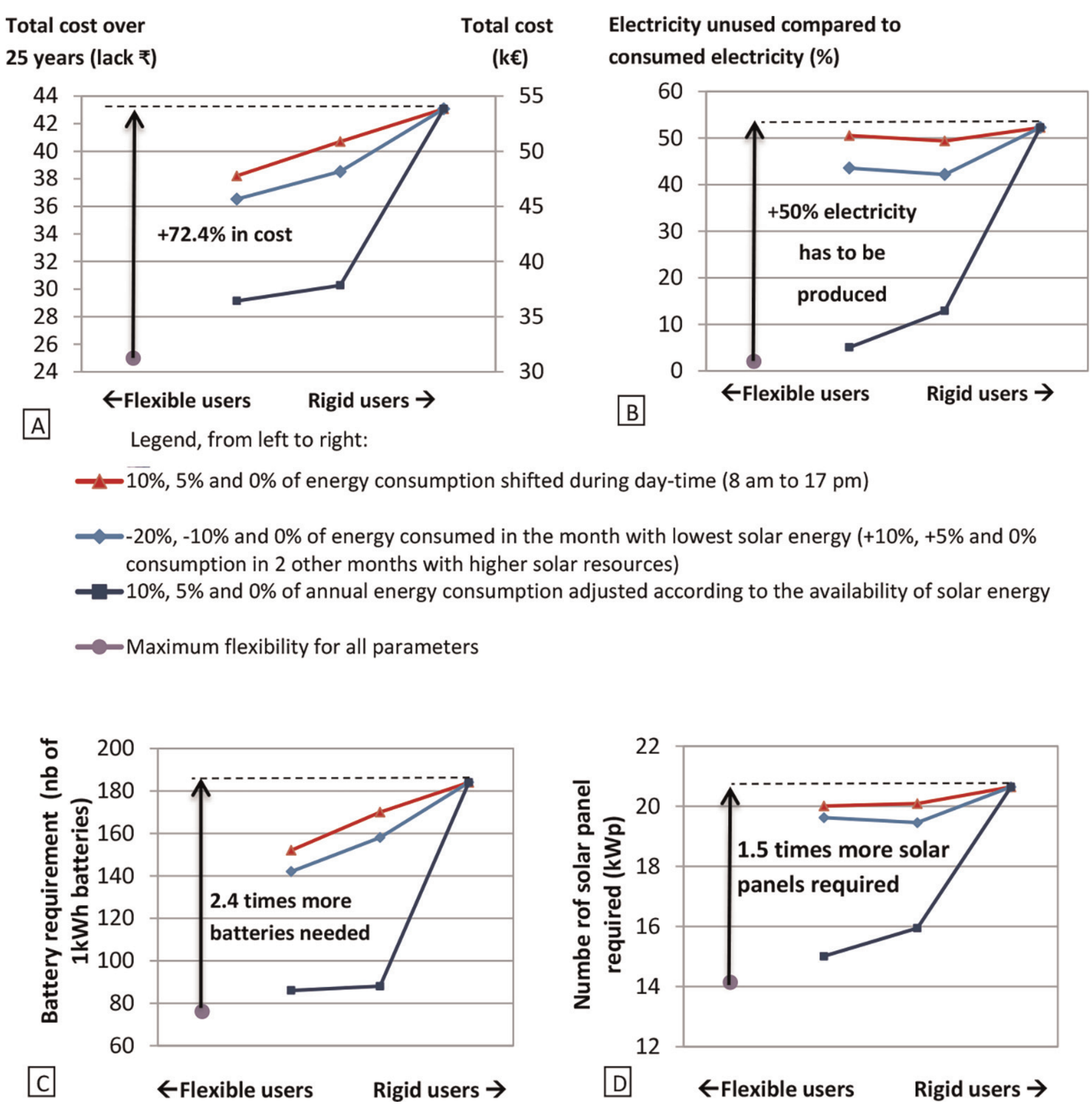

Figure 5.
Microgrid design and total costs depending on users' flexibility. Influence of willingness of users to be flexible on optimized microgrid: total cost (A), unused/surplus electricity (B), KWh of battery (C) and kWp of solar panels (D).

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Figure 5 illustrates that the more flexible users are, the less expensive is the overall cost of microgrid.

Summary of key findings

- If users accept to shift 10% of their load during daytime compared to their preferred load pattern, the overall project cost is reduced by 11%.
- If users agree to reduce their load by 20% during the month with the least solar resource (June in this case), the saving on project cost are of 15%, and users have the possibility of consuming 10% electricity more than usual in the two months with the most solar resources.
- If users agree that over a whole year, 10% of their electrical need may not be met, due to lack of solar resources, the savings are of 32% on the overall project cost.
- When users are the most flexible, with 10% of their load shifted during daytime, -20% of load during the month with the least solar resources, and 10% of the remaining load demand to be adjusted as per solar resource availability, the microgrid can be designed at the lowest cost. Comparatively, non flexible users must pay 72% more for their electricity. Indeed, 1.5 times more solar panels are required and 2.5 times more batteries are required for non-flexible users. To meet a none-flexible demand, 50% of energy would be produced in excess of the demand and would remain unused against 2% for fully flexible users.

Shifting load during sunshine hours reduces overall project cost, mostly because it reduces the number of batteries required. When 10% of consumption shifted during daytime, the optimal number of 1kWh battery recommended by the software (to minimize cost), was 153 compared to 184 (21% more) when no load was shifted. When 10% load is shifted during daytime, solar electricity can be directly consumed and the round-trip losses that happen during the storage process are avoided. The savings in round-trip losses also helped reduce the number of solar panels slightly.

Shifting load away from the month with lowest solar resources reduces overall cost because some of the batteries and solar panels are otherwise purchased only to

Case	Solar panels (kWp)	1kWh battery	Total cost		Initial capital	
			(k€)	Savings (%)	(k€)	Savings (%)
1A-2A-3A	20.6	184	53.8	0	33.9	0
1B	20.1	170	50.9	5.4	32.2	5
1C	20.0	152	47.8	11.2	30.6	9.7
2B	19.5	158	48.2	10.4	30.6	9.7
2C	19.6	142	45.7	15.1	29.4	13.3
3B	15.9	88	37.8	29.7	21.7	36
3C	15.0	86	36.4	32.3	20.6	39.2
4	14.1	76	31.2	42	19.0	44

Table 6.
Most economical microgrid design and cost for different flexibility levels of users.

supply the full load during the month with lowest resource (monsoon in India). This equipment may not be useful for the rest of the year, resulting in electricity produced, but unused.

Adjusting ones consumption throughout the year according to the availability of solar resources has the most impact on overall cost. This is due to the unpredictable nature of renewable energy. Indeed, the software has to plan for sufficient solar panels and batteries to supply the full load even when a few days of bad weather occur in a row. When users agree to adjust their consumption based on the availability of solar energy, the design can be optimized. For the same amount of electricity delivered, a microgrid designed to supply an average of 90% of a load of 55kWh requires only 86 batteries and 15kWp solar panels, while a microgrid designed to supply 100% of a load with a daily average of 50kWh, requires 184 batteries and 20.6kWp solar panels. Though both designs supply an average load of 50 kWh/day, in the case where 10% electricity demand is adjusted (shifted), almost all the electricity produced can be consumed. On the opposite, when users are none-flexible, the additional solar panels produce 50% of electricity in excess of the demand, which remains unused.

3.4 Modeling discomfort of users when their demand is not met

Users experience discomfort when part of their demand is not met due to a lack of solar energy resources and a low level of stored energy. This discomfort can be simplistically modeled as the loss of opportunity compared to the utility users would have benefited if their full electricity demand would have been met by the microgrid. In the literature, the benefit that users get from consuming electricity (i.e. the utility) is modeled as a second-order polynomial function [50]. Thus, for the same amount of energy curtailed the distribution of energy shortage in a year can impact the discomfort felt by users. A simple example clarifies this principle in **Figure 6**. The curve illustrates a typical utility function that represents the benefits that users get from consuming different amounts of electricity. The first few kilowatt-hours provide the most benefits, while the marginal utility (i.e. the benefits users get from an additional unit of electricity) reduces and even saturates. At the point of saturation, users do not get any additional benefits from

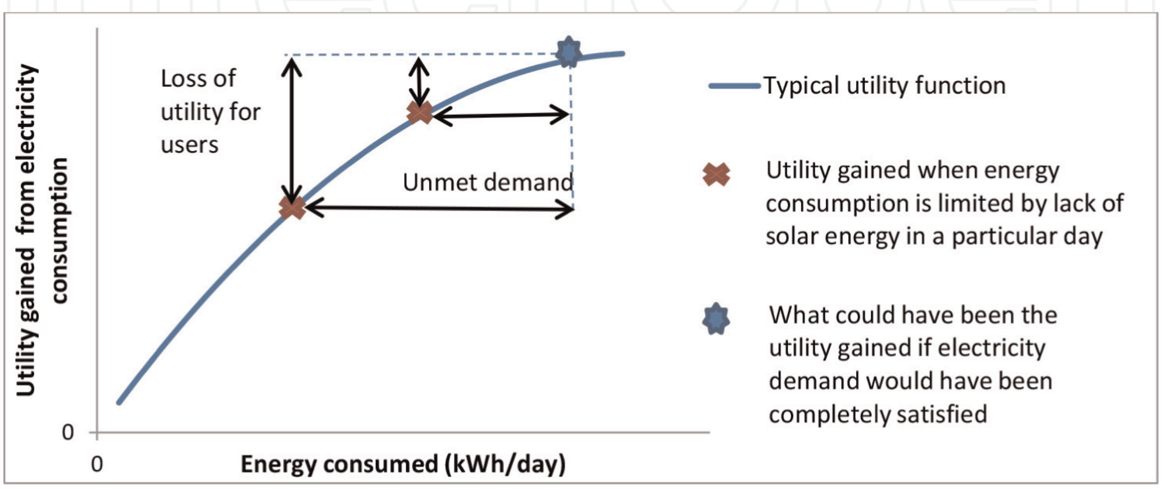

Figure 6.
Example of utility function and loss of utility due to electricity shortage.

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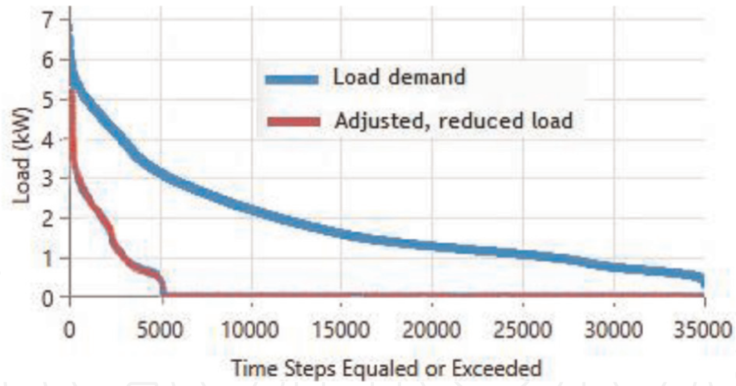

Figure 7.
Satisfied load vs. distribution of adjusted load by time step for an average of 10% adjusted load over a year.

consuming more electricity. From **Figure 6**, one can understand that for the same amount of energy curtailed over a year, users experience less discomfort from having their load curtailed from a few per cent quite often, rather than heavily curtailed but rarely.

A few days of complete black-out may be very detrimental for a workshop or a small business, while limiting the electricity consumption by 30% over a day may lead to a marginal loss. Thus, before agreeing on a certain percentage of flexibility over a year, users must be informed about the expected distribution of energy curtailed. This will allow them to evaluate the loss of comfort or loss of revenue due to adjustments in their electricity consumption. Making the comparison between loss of utility and overall savings on cost of electricity, users can choose the option of flexibility most appropriate to them.

One can evaluate how the electricity curtailment is expected to be distributed over a year. **Figure 7** shows the incremental distribution of the load curtailed when 10% of the overall demand is unmet (case 3C). The blue curve represents the incremental distribution of the full load demand. The simulation was performed with 15 min time steps so 35,040-time steps in a year. The figure shows that users have to reduce their load 5000-time steps over 35,000 and thus can consume as planned 85% of the time (20 h30/24 h in average). While the peak load observed was above 6 kW, the unmet demand (due to lack of renewable energy) was less than 1 kW for 5% of the time (small reduction in load required for ~1h10min per day on average). The unmet load was between 1 and 3 kW for 10% of the time (fair reduction in load required for ~2 h20 per day on average). The unmet load was above 3 kW for 100 h in a year (important shift of load is required for ~30 min per day on average). With this information, users may prefer to be more or less flexible to spare on cost.

It can be noted that this 'adjusted load distribution' was obtained without considering any energy management algorithm. In practice, users could reduce their load in anticipation of energy shortage to avoid large amounts of energy curtailment. For example, users may reduce their load during a rainy day even though batteries may be nearly full or use simple weather forecasting and thus, avoid power interruption later.

3.5 Main findings and limitations

The sensitivity analysis showed that flexibility of users has a strong impact on microgrid design and should therefore be taken into consideration at the design stage. However, the lack of reliability of the system is also a critical parameter that can lead to user dissatisfaction and non-payment of the electrical bill [8]. It is thus essential that users are aware of the possibility of lack of energy according to the pricing option and microgrid design chosen. When users are informed about the relation between microgrid design, cost, and reliability of supply, they can agree beforehand on a level of cost and flexibility. This approach encourages users to learn about the relationship between their consumption habits, technical equipment, and natural resources. Being aware that consumption habits must follow natural resources availability, can in turn inspire them to care for the system better: avoiding shading and dusting of solar panels. This method of design is also more ecological with less electricity going to waste.

When such an approach is implemented, three additional factors have to be addressed.

- First, users have to develop an ability to predict a shortage of electricity in advance to minimize the impact of energy shortage on their comfort level, or on their business. Thus, an appropriate demand response mechanism is required for users to anticipate energy shortage and reduce their consumption before a power interruption. The literature offers many different mechanisms [49]; an interesting approach consists in settling the demand response process based on a predefined alternative load pattern ranked by preference, 24 hours ahead [51]. Alternatively, a few days of weather forecast, and a simple battery energy level indicator could be broadcasted to all users. Such information will not only improve the usability of renewable energy but also strengthen the feeling of ownership, and responsibility of users towards the energy generating system.

- Second, in a community not all users may accept the same level of flexibility [52]. Poor households may prefer a reduced cost of electricity while entrepreneur, having less flexibility, may prefer a reliable supply, more independent of weather fluctuation. By equaling flexibility to a cost for users, a technical design can be obtained using a single objective/one dimension algorithm and provide a technical solution tailored to the preference of users. Different options are available to satisfy users' preferences. The first option is to design solar home system tailored to each user's requirement. Another option is to prefer small microgrids at different locations in the village, each connected to a group of users with a similar level of flexibility. Research has also shown that it is possible to connect users with a different level of flexibility into a single microgrid [38]. Thus, solutions exist, but they have to be implemented.

- Lastly, electricity demand is evolving over time and predicting its evolution is a real challenge for project with a life-time over 10 years. Existing literature shows that the electricity access-development domain is very complex, dynamic as well as context-and time-specific. Being able to understand and model the aspects and dynamics that determine rural electricity use, can lead to more robust energy planning solutions in rural areas [14].

4. Concluding remarks

This chapter discussed one of the main aspects of renewable energy: its variability, and how it impacts cost and reliability of supply for microgrid users who are not connected to the grid in the context of rural electrification. First, the various electrical usages were classified into categories to gain clarity on how rural electrification can impact the different axes of progress: economic, social, environmental, and related to health, livelihood and safety.. Second, the different rural electrification strategies were classified and rated against key parameters of success to support decision-making by developers. Considering the importance of involving the population early in the project, it was proposed to involve students to liaise more easily with the population; two successful large-scale programs were presented: a win-win approach for the long-term benefit of society: transforming both rural areas but also the students involved.

The full process of technical design was then detailed to achieve the optimal design in diverse scenarios, with key parameters and simulation procedure so far. Instead of considering the load as firm, like in other methodologies, a level of flexibility was introduced as an additional key parameter to achieve a low-cost microgrid design that satisfies users in the context of solar powered microgrid with variable power supply. The proposed method was tested using actual solar production data from the field. The willingness of users to adjust (curtail) 10% of their annual consumption depending on the availability of solar energy, led to 32% savings on the overall project cost. Shifting 10% of load during daytime and lowering consumption by 20% during the month with the lowest solar resources, were found to be effective sources of savings, respectively 11% and 15%. A model was presented to assess the inconvenience for users (loss of utility) to be flexible. This model shows that consenting to a small reduction of load often in the year, is preferred compared to a complete power cut, some of the time. This signals that the new developments in energy management tools such as weather forecast, and user involvement in managing their consumption, can play a decisive role in optimizing comfort of users in a low-cost microgrid powered with solar energy. Their active participation reinforces their feeling of ownership towards the system and transforms simple users into responsible consumers, aware of natural resources availability. On the contrary, an electrification project, aiming at supplying a fixed amount of electricity without considering its final usage and local situation leads to a) under usage of the system and over cost, or b) lack of energy in the microgrid, user dissatisfaction, lower payment recovery, and project failure. In the general context of fast development of renewable energy in the power mix of many countries, it is expected that the same conclusion will apply in interconnected power grids. It is thus expected that in the near future, utilities may offer a wider variety of tariff options to users in order to more accurately reflect the intermittency of power production and the associated cost of energy storage.

To conclude rural electrification: it is more than a technical project; it involves human development and empowerment of individuals. The complexity of interaction between different stakeholders, the various aspects of a project, and the numerous parameters involved makes it hazardous to venture into rural electrification without a proper method. This paper provided guidelines to support project development and academic research towards successful rural electrification using solar energy, with maximum short-term and long-term impacts on the population at the lowest cost.

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