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# FutureGrid: Use of Microgrids in Underserved Communities

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## Abstract

Rural electrification in developing countries—especially Sub-Saharan Africa—has trailed urban development drastically. The extreme costs associated with expanding traditional grid networks, and the relatively few people they serve, have proved to be a serious economic barrier. Being able to generate and distribute electricity at an affordable rate is crucial in order to effectively power homes, schools, health clinics, and private business. Through this continued cycle and lack of access to electricity, poverty only continues. If given access, quality of life increases through more educated, longer, and healthier lives as well as through developed entrepreneurship and business growth. Unfortunately, because of the remoteness of many communities they are often dismissed as unreachable. Furthermore, microgrids help address another global need: increased renewable energy penetration. Small-scale energy production lends itself to solar installations, but depending on the location and available resources, wind and hydropower can also play an important role.

**Keywords:** microgrids, distributed generation, energy storage, grid extension, rural communities

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## 1. Introduction

Often when we look at how technology has changed since its inception, it is difficult to imagine how the creators would react to the relentless progress and improvements on their original idea. Over a hundred years after Alexander Graham Bell invented the telephone, today's smartphones are infinitely more complex, contain thousands of features, and possess processing power, Bell could never have imagined. Once luxury, cell phones

are now found in every corner of the globe including the most remote villages in the developing world. If Thomas Edison and Nikola Tesla could see the state of electrification today, it is safe to assume they would be sorely disappointed. While electrification has certainly improved, it has severely lagged behind the growth of other technology. The generation and transmission of electricity looks much the same as it did over 130 years ago when the Vulcan Street Hydroelectric Plant in Appleton, Wisconsin began producing 12.5 kW of DC power. Over the next few years, more plants were constructed in both AC and DC, mostly powered by water or coal. While access to this electricity increased—as did the quality and economic viability—electricity never experienced the gigantic expansion in both availability and technology that other sectors did. Since its creation and original spurt of distribution, electricity has been slow to advance to a significant portion of the global population.

Unlike cell phones, electricity cannot be manufactured and shipped in discrete units. Because it is not a physical device, the infrastructure required to produce and distribute it is entirely unique. Due to the immense capital costs associated with electrification, individual business (and thus competition and natural advancement) have not developed in the same manner. As a result, electric utilities are slow to develop or expand, leaving no need for innovation.

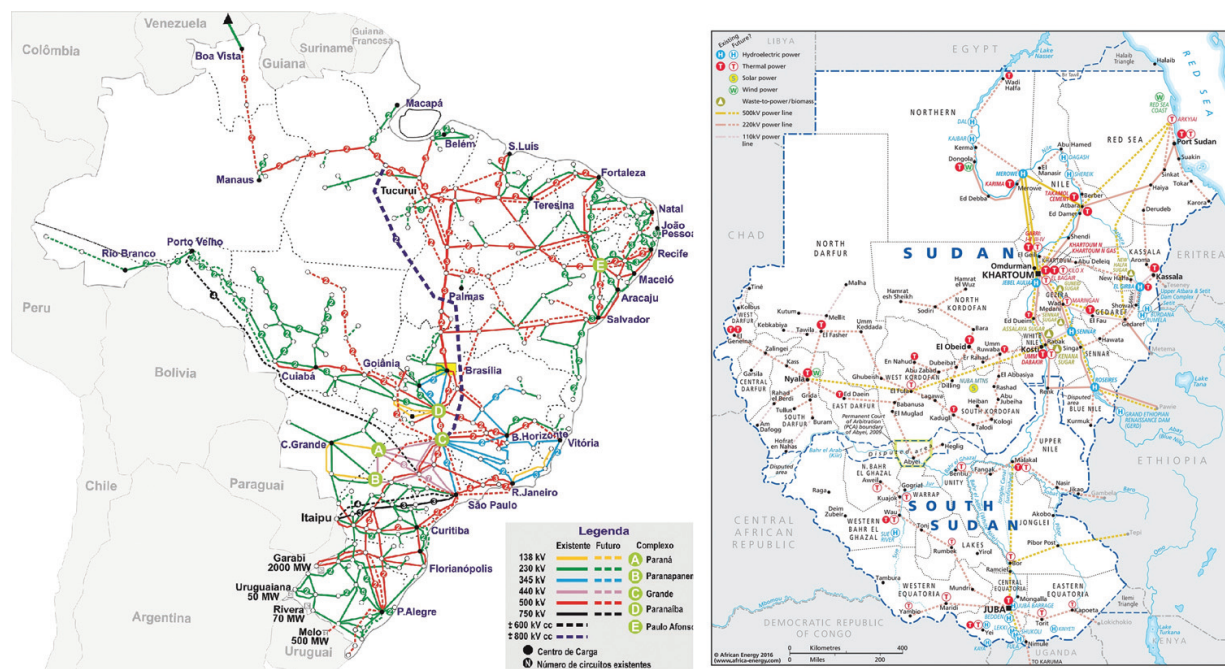
Nowadays, power production finds its way into the public view as we battle the negative effects of climate change. Instead of the natural pressure in the industry to improve and out-compete other companies, utilities are now being pressured externally via the government and general public. While a shift to renewable energy is undoubtedly important, it does not represent the only problem in this area. Access to any form of electricity in developing and rural areas is severely limited. At face value, it may seem that this is not an immediate problem, but there are innumerable secondary effects all stemming from a chronic lack of access.

Imagine a rural town in a developing country. There are 300 homes, a few grocery stores, a pharmacy, a general store, a school, a carpentry workshop, and a coffee milling station. What they do not have is electricity. While the government and utility are aware that the town exists, plans to offer electrification have never gone further than a Master Plan written years ago and shelved. Extending transmission lines are expensive, and if the utility thinks that there is not sufficient demand, they will not invest the money. The utility may also be unaware of the current size of the town, and thus the potential customers. Even if they did extend the grid, there are production shortages. Blackouts lasting hours or even days. This is not an unreasonable scenario, and is an accurate descriptor of a large portion of the unelectrified developing world. This lack of electricity means that at night families burn candles or kerosene lanterns which have harmful effects on the respiratory system when used in enclosed spaces; refrigeration is impossible, and food cannot be saved for long; water is pumped manually from boreholes, or carried from the nearest stream. All these activities which have to be done manually take an immense amount of time. Frequently, children are required to help their families in these tasks, and their studies suffer. By expending all this energy on the day-to-day tasks, it is difficult to develop and remove oneself from this cycle. Lacking access to electricity keeps people impoverished and uneducated.

## 2. Rural electrification and national grid distribution

Often microgrids are seen as solutions creating a more stable and reliable interconnected grid in urban settings [1–3], however, they need not be limited to these uses. Electrification in developing countries has trailed industrialized nations drastically and even more so in rural settings [4]. The vast majority of those without an electrical connection live in rural developing settings, where their access to resources in general is scarce. The eradication of poverty is on nearly every government agenda around the globe, and while on the surface, the undertaking is targeted and defined, in reality it is not. Access to reliable electricity is one large step in the correct direction and can no longer be considered a luxury. Lack of electrification contributes to the continued cycle of poverty, child mortality, chronic but otherwise treatable health issues, as well as suppressing education. Electricity is necessary for providing lighting without risking unnecessary smoke inhalation, for pumping water on anything other than an individual scale, and for refrigeration—which allows families to reduce food waste. Providing reliable and affordable electricity should be the top priority in tackling poverty eradication.

Unfortunately, the extreme costs associated with electrifying rural developing areas, as well as the relatively few people served, have caused some countries to exclude entire regions from their electrification schemes. With transmission lines costing up to \$20,000 per km [5] in rough and rural terrain, shortening the transmission distances through the use of distributed generation and microgrids brings down the cost of rural electrification significantly. To understand the scope of the problem, transmission line coverage can best be depicted through utility maps. In **Figure 1**, large portions of Brazil, Sudan, and South Sudan are not currently serviced by existing transmission lines. In order to electrify these regions, millions of dollars would



**Figure 1.** Brazil's, Sudan's, and South Sudan's existing electrical networks.

be required in infrastructure development. Fortunately, distributed generation microgrids can be utilized instead.

Immediately, it becomes apparent that a more economical solution skips the long transmission lines and produces power closer to the users. The lower capital investment and varying sizes of communities present a wide array of customizable solutions, and as a result, there exists no uniform microgrid design which is applicable to all or even most potential microgrid sites. Despite this microgrids still hold a place in the global electrification scheme. This chapter aims to demonstrate that not only are microgrids closer to wide scale deployment in rural developing areas than may be commonly believed, but that there exist methods and technology making microgrids uniquely suitable for rural electrification.

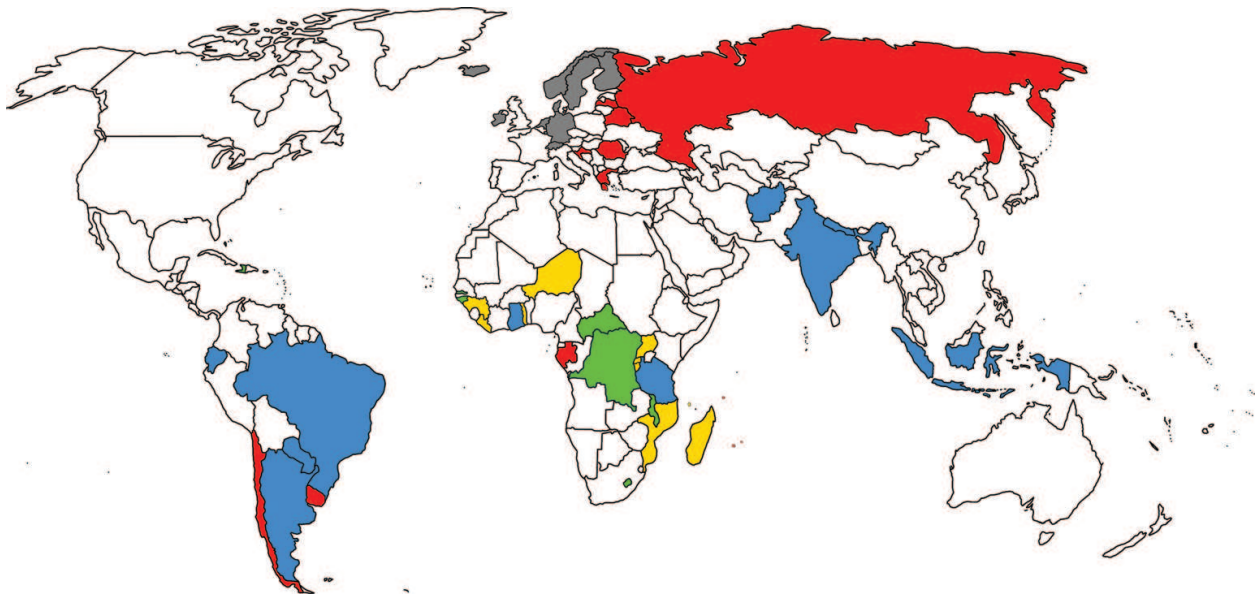
### 3. Economic feasibility of microgrid breakeven distances

Traditionally, there has been a singular approach to electrification: extend the national grid. When the utility considers this option for remote areas, little or no math goes into the determination. They are simply too far from the grid, and their demand is too low to justify the immense cost. With extension costs as high as \$15,000 per km [6, 7] in rough terrain, the cost per kilowatt-hour to achieve any kind of payback would have to be prohibitively expensive. As an alternative, residents of these rural areas can sometimes afford a few solar panels and batteries—especially if the cost is shared. This simple setup can sustain a little lighting and offer a place to charge cell phones, but stops well short of an acceptable solution. Instead, there exists a medium between these two solutions. Something, larger and more robust than a few panels linked together, but less expensive than grid extension: the microgrid. The microgrid can be sized and built according to demand and expanded with usage. The costs can be kept in check because the electricity is produced and consumed in the same area—no need for the expensive transmission lines. As a solution to rural electrification, the microgrid is new on the scene, and being largely untested requires some analysis to determine its feasibility.

The first step in determining if a microgrid is suited to a particular rural site is to compare the cost of the stand-alone microgrid to the cost of extending the existing grid structure. The cost of a stand-alone system is dependent on the load generated from the community, but is also dependent on the available resources. Wind and solar are obvious options because of their availability in remote areas, but diesel for generators should also be considered due to its widespread availability and capacity for consistent energy generation. These three options, plus battery storage, are at the heart of the microgrid solutions examined here. While options like geothermal and hydroelectric are completely viable, they have been intentionally omitted due to their geographical restrictions.

A study of 200 fictitious communities was performed in 50 unique locations with varying load profiles. For simplicity, and to ensure a variety of locations, one location was chosen over each of the 50 countries. The countries are shown in **Figure 2**. The countries were furthermore subdivided into five categories based on their economic standing. The countries presented in **Table 1** rank the selected countries based on estimates of annual income generated by the





**Figure 2.** Selected countries.

poorest 10% of the population. This is calculated by taking the GDP produced by the poorest 10% [8] and dividing it by a tenth of the population. Class 1 countries generate less than \$100 of income per year, whereas class 5 earns more than \$10,000 per year. **Figure 2** highlights the countries chosen.

This distribution of communities better captures the purchasing power of lower income households. The World Bank currently draws the international poverty line at \$1.90 per day [9]. This boundary encompasses all of Classes 1 and 2, as well as half of Class 3 in **Table 1**—in all, 46% of the communities listed can be considered to fall under the poverty classification.

In each of the simulations, four load profiles were constructed from two Rwandan villages. Rwamiko and Nyakabanda [10, 11] are used as representative load profiles and are shown in **Figure 3**. From these two profiles, two more were generated to increase the robustness of the model. The first was a combination of both original profiles into a fictitious village called Nyakamiko. This profile is simply the sum of the hourly originals. The final profile, titled Small Rwamiko, is a scaled down version of the Rwamiko profile. The four profiles weigh in at 164, 248, 433, and 74 kWh per day, respectively.

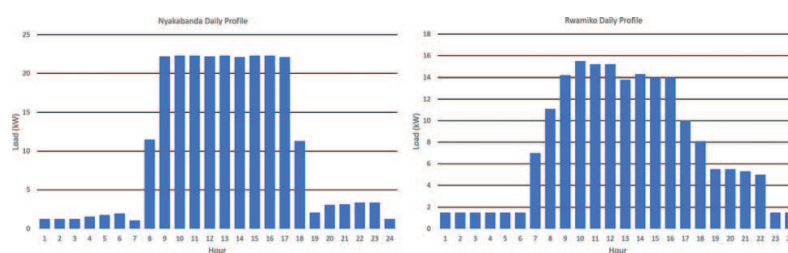
These load profiles are atypical of traditional profiles where the peak occurs in the evening. The first distinction to recognize is that these are not home-level systems where occupants are away during much of the daylight hours. These systems account for the entire village including 200 households, 4 small grocers, 2 restaurants, 2 small shops, 1 dispensary, 1 office building, and 2 water pumps in Rwamiko; and 200 households, 1 coffee milling station and 1 restaurant in Nyakabanda. While daytime operations tower above the early morning and evening, it can be seen that the evening still carry a relative peak.

These profiles can then be loaded into HOMER—a microgrid optimization tool—to determine the best course of action for electrification. The microgrid design considers photovoltaic, wind,

Country	Poorest 10%	Class	Country	Poorest 10%	Class
Central African Republic	43.02	Class 1	Brazil*	1138.44	Class 3
Haiti	49.45		Indonesia*	1187.26	
Malawi	56.11		Argentina*	2001.52	
The Gambia	84.37	Class 2	Chile	2469.82	Class 4
Guinea-Bissau	90.85		Gabon	2477.57	
Dem. Rep. Congo*	92.89		Russia	2975.52	
Lesotho*	93.08		Mauritius	3004.99	
Liberia	109.89		Uruguay*	3193.29	
Mozambique	111.27		Belarus	3296.42	
Burundi	114.40		Croatia	3368.81	
Madagascar	116.84		Latvia	3458.23	
Togo	120.66		Greece	3654.73	
Comoros	121.51		Romania	3698.77	
Rwanda*	146.09	Class 3	Seychelles	3730.37	
Fed. Sts. Micronesia	152.85		Singapore*	12,945.45	Class 5
Guinea	161.88		Germany	16,259.45	
Niger	162.40		Ireland	16,856.05	
Uganda	171.50		Denmark	16,998.03	
Afghanistan*	240.76		The Netherlands	17,738.54	
Nepal*	245.59		Sweden	18,860.41	
Ghana*	273.91		Iceland	19,241.66	
Tanzania*	287.47		Finland	19,431.24	
India*	553.53		Switzerland	28,246.13	
Paraguay*	706.92		Luxembourg	31,499.45	
Ecuador*	1015.33		Norway	35,030.67	

\*Countries were part of a previous study and not selected based on the same criteria discussed in the text.

**Table 1.** Rural GDP distribution.

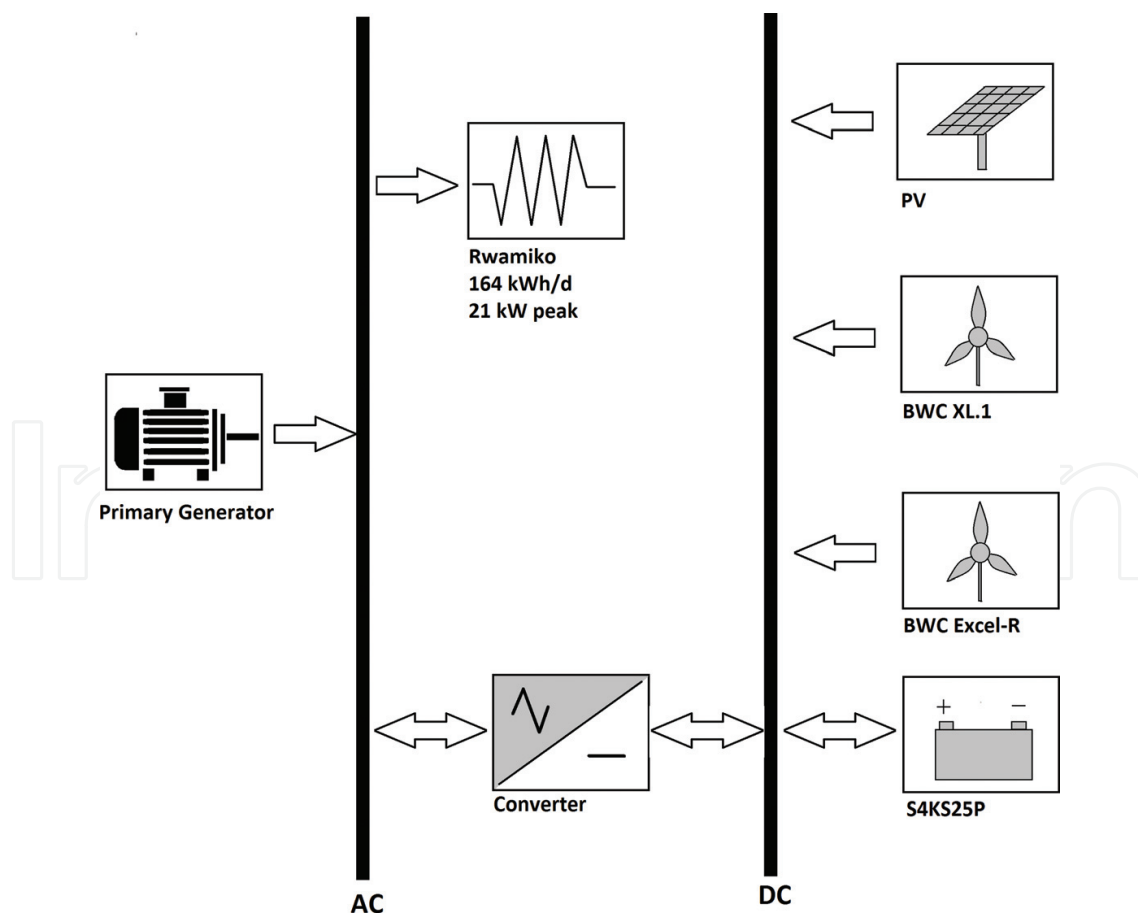


**Figure 3.** Nyakabanda (left) and Rwamiko (right) load profiles.

and diesel generation with battery storage. **Figure 4** illustrates this setup. It is important to note that the DC line carries two BWC turbine options. This allows for economies of scale to evolve by providing large-scale turbines (7.5 kW) for areas with high wind or smaller versions (1 kW) for low wind.

Besides the varying load profiles, the difference from site-to-site hinges on resource availability. The three resource factors are wind, diesel prices, and solar irradiation, which are based on longitude and latitude and can be obtained through HOMER [12, 13]. The alternative—grid extension—was priced at \$15,000 per km and an exceedingly reasonable electricity price of \$0.10 per kWh (it is not uncommon to see electricity prices more than double this figure).

The resultant optimization by HOMER reveals a wide spread of solutions. In **Table 2**, the solutions for three sites are shown, Ireland with its high renewable availability and diesel prices, Russia for its low diesel prices and poor renewable availability, and Guinea-Bissau for being a balance of the two. It is important to stress again that the communities named after their countries do not represent the renewable availability of the entire country, just at the coordinates selected for the rural site. A different site could have been selected for Russia which favored renewables more; this is the reason for choosing 50 countries to gain a diverse spread.



**Figure 4.** HOMER microgrid diagram.



Country	PV Array (kW)	Wind Turbines (kW)	Batteries* (Strings)	Diesel Generator (kW)
Ireland (Small Rwamiko)	5	7.5	3	0
Guinea-Bissau (Small Rwamiko)	30	1	4	0
Russian Federation (Small Rwamiko)	15	0	2	5
Ireland (Rwamiko)	30	15	2	0
Guinea-Bissau (Rwamiko)	60	0	6	0
Russian Federation (Rwamiko)	30	0	2	7
Ireland (Nyakabanda)	40	22.5	3	0
Guinea-Bissau (Nyakabanda)	90	2	3	1
Russian Federation (Nyakabanda)	40	0	3	10
Ireland (Nyakamiko)	90	30	4	0
Guinea-Bissau (Nyakamiko)	180	0	5	0
Russian Federation (Nyakamiko)	100	15	4	15

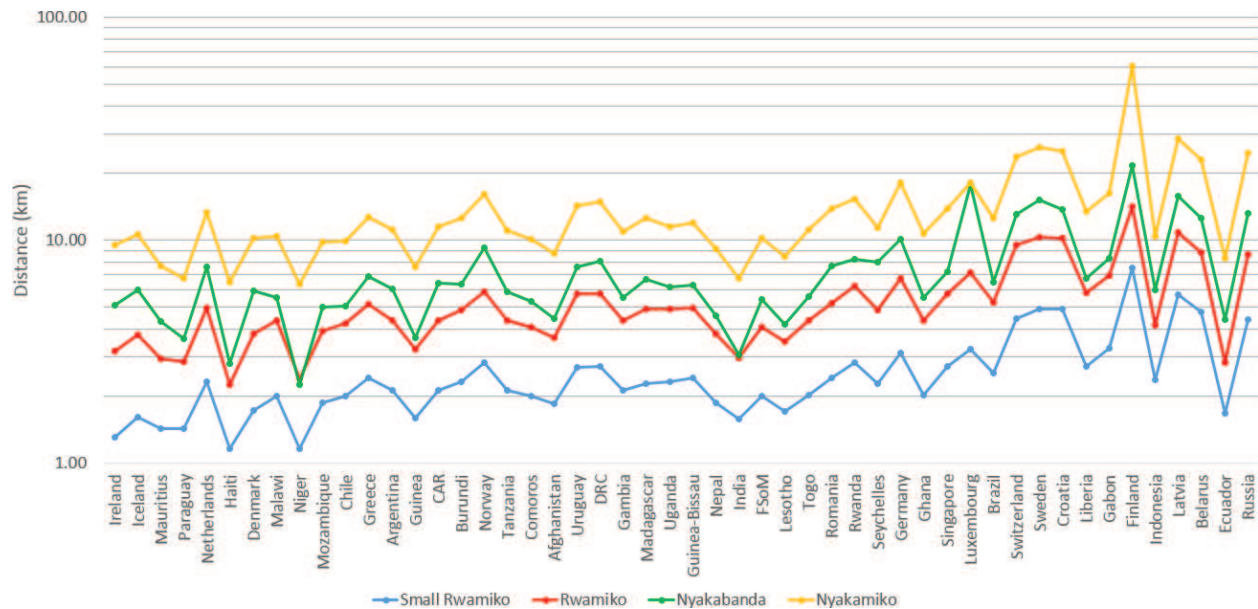
\*Strings contain 3, 6, 9, and 12 batteries, respectively. Each battery with 1900 Ah or 7.6 kWh capacity.

**Table 2.** HOMER optimization solutions.

Some obvious and unsurprising patterns begin to emerge. With its high wind speeds and decent solar activity, the Ireland site favors turbines and panels in place of diesel generation. However, it becomes apparent that Guinea-Bissau and Russia sometimes have more installed capacity than Ireland. This is indicative of Ireland having a greater renewable efficiency. Guinea-Bissau and Russia require spending more money to achieve the same level of electrification, and as a result they are less well adapted to utilizing their renewable resources.

Now that a microgrid solution has been obtained for each of the sites, these optimized microgrids need to be compared to the alternative: the national grid. The easiest method in this case is to compare the capital costs and maintenance plus the electricity which would be purchased—in this case—over a 20-year period. The location of the community does not matter to the microgrid because the microgrid is built in the community. Its proximity to other communities or the national grid is irrelevant. However, a large cost associated with electrifying through the national grid is the capital required to bring that electricity to the community. By comparing these two options, the breakeven distance is born. If the community is very close to a national grid tie-in point, then the cost to electrify through the national grid is low, and is thus the better option. At some distance, this flips. Eventually, the cost to extend the national grid outweighs the cost of the microgrid, and the microgrid becomes the better option. These breakeven distances are shown in **Figure 5**.

Each country on the  $x$ -axis corresponds to the four load profiles. As the load profile increases in size, so too does the breakeven distance. This is unsurprising since a larger microgrid would



**Figure 5.** Breakeven distances for different load profiles.

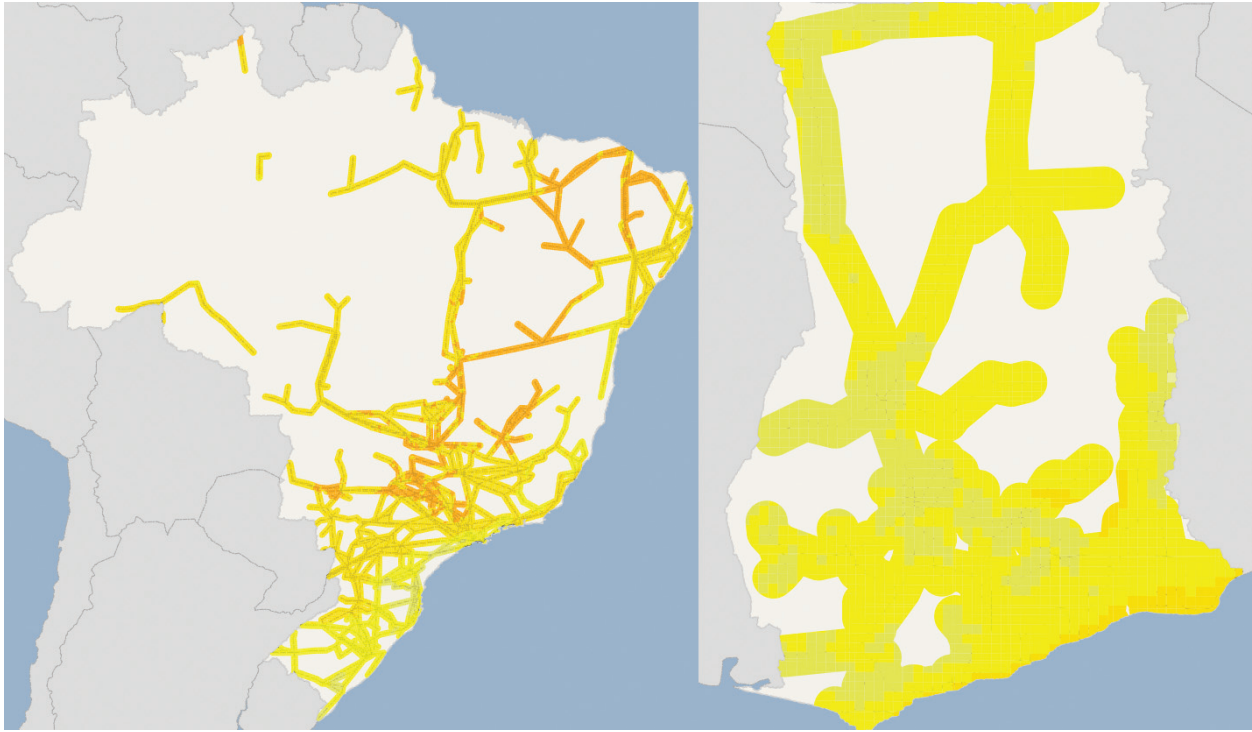
be required to meet the demand, driving up costs. Many sites with the largest demand do not even exceed 20 km, a surprisingly low value. Additionally, the smaller loads can have breakeven distances in the 1–3-km range, rendering grid extension all but completely unreasonable. Those sites that do have unusually high breakeven distances, such as Finland, can be explained by a combination of high diesel prices and poor renewables, making it costly to build the microgrid no matter the combination.

To comprehend what proportion of a country this area may constitute, **Figure 6** highlights in yellow the areas of Brazil and Ghana within 20 km of the national grid. Communities similar to the Nyakamiko load profile in the white space of these figures are more likely to be better off with a stand-alone microgrid than with grid extension. Furthermore, the coverage map is realistically less than that depicted here. Distance to the grid and distance to a grid tie-in point are two separate ideas. The highlighted areas represent the corridor around the grid, but the grid cannot be tapped into anywhere. The voltage must be stepped down through a transformer, often requiring a complete substation to be erected.

When planning potential microgrid sites, this breakeven distance information can be translated into something more useful. The average breakeven distance from the above results can be estimated using Eq. (1). Since this is an average estimation, the equation and its constants were simply derived from a line of best fit through the case data in this work.

$$\text{Breakeven distance (km)} = 0.0316 \cdot \left( \frac{\text{kWh}}{\text{day}} \right) + 0.0565 \quad (1)$$

The average load in kWh per day of the proposed site can be plugged into the equation and an estimate of the breakeven distance can be obtained. If the community is closer to a grid tie-in point than the value returned by this equation, then grid extension is more likely viable. To



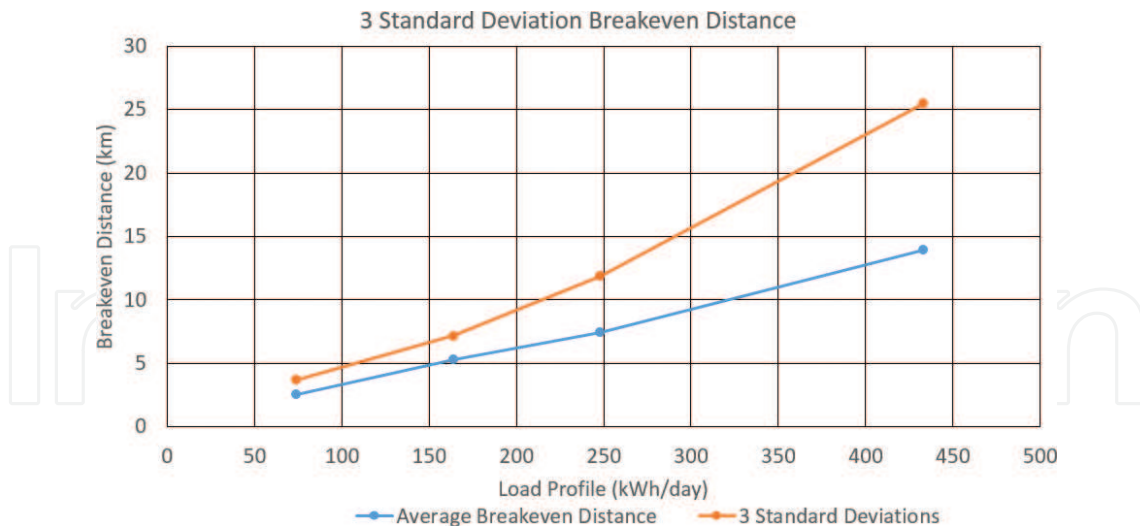
**Figure 6.** A 40-km wide corridor around existing transmission lines in Brazil (left) and Ghana (right).

increase the certainty, but decrease the range of this equation, another version incorporating the third standard deviation can be generated. If the breakeven distance returned by Eq. (2) is less than the actual distance from grid to community, then it is extremely likely that a microgrid is the more viable option. Eq. (2) is derived through similar methods as Eq. (1), only including the third standard deviation as well. As a result, the larger the demand, the greater the uncertainty, hence the estimate becomes quadratic.

$$\text{Breakeven distance (km)} = 8.0 \times 10^{-5} \cdot \left( \frac{\text{kWh}}{\text{day}} \right)^2 + 0.0215 \cdot \left( \frac{\text{kWh}}{\text{day}} \right) + 1.6629 \quad (2)$$

The two equations are presented graphically in **Figure 7** become clear. Sites that fall below the orange line should be studied further to determine if they should be stand-alone microgrid systems. Sites above the orange line are highly likely to be better off as stand-alone microgrid systems.

These relatively short breakeven distances highlight the microgrid viability when compared directly to the national grid. Additionally, the parameters chosen in this setup are fairly conservative. This breakeven distance only decreases further when a more typical electricity price is considered, or when new generation to meet the demand is factored in. At a high level, the microgrid is clearly a viable option for areas that are not already being serviced by the national grid. Furthermore, this microgrid versus national grid decisions can be streamlined through the use of the breakeven distance prediction equations. Determining what type of



**Figure 7.** Average and three standard deviations breakeven distance.

electricity and where it comes from is the first step in rural electrification. The remainder of this chapter takes a closer look at several real-world examples, with a focus on how to identify potential sites, as well as what technology and process improvements can be made to better the reliability and decrease the cost of a microgrid.

#### 4. Analysis of identification schemes for electrification in rural communities

Determining whether or not a community should be electrified with a microgrid or the national grid connection is only part of the problem. One of the larger issues is finding communities, measuring their load potential, and categorizing their current level of electrification, if any. The largest factor in determining the payback period for an investment is a substantial understanding of how much true demand exists. It is easy to ask someone if they want electricity, and they will most likely say yes. Since the individual does not front the capital costs, there is little risk to them. But the entity funding the project needs to calculate an electricity price based on supply and demand. If the price is too high, no one will use the electricity, and if it is too low, then the microgrid or extension will not pay for itself and thus continued electrification is dissuaded.

Since the data on rural electrification is sporadic, the United Nations developed the global tracking framework “United Nations Sustainable Energy for All” (UNSE4ALL). This allows for different levels of electrification to be compared directly independent of location. Traditionally, electrification has been measured solely by the number of people connected to a national grid. While this data is relatively easy to access and measure, it is not entirely accurate [14, 15]. Numerous other metrics already exist, such as measurement of minimum energy consumption thresholds [16], tracking of income-variant energy demand [17], the



“Multidimensional Energy Poverty Index” (MEPI) [18], and the “Total Energy Access” (TEA) [19]. These types of metrics treat electricity as an output of the system, instead of an outcome, and fail to truly capture the whole picture.

Before the use of the multidimensional approach, electrification was categorized into levels. Communities fell into one of eight steps based on the scope and source of electricity (if any) [20]. These steps are shown in **Table 3**.

While this method provides multiple levels of classification, it does not account well for emerging or combined technologies. If a system does not fit neatly into one of these categories, it must be either misrepresented or reported as an exception. In contrast, UNSE4ALL classifies electrification by usage instead of categorizing it by production. By defining electrification by attributes, similar technologies, which provide the same or similar effects, can be distinguished by quality of energy produced.

UNSE4ALL classifies electrification by the service provided (lighting, refrigeration, etc.) as well as peak capacity, duration, evening supply, affordability, formality, and quality [21]. These tiers are shown in **Table 4**.

What remains are five different tiers of electrification. Tier 0 not corresponding to any particular type, while tiers 1–5 evaluate on the criteria above. Tiers 4 and 5 constitute either a grid connection or a reliable but independent mini-grid with national grid backup. Power here can be used in the home for the majority of the day, and the capacity exists to run most appliances found in the home. Tiers 1–3 represent varying electricity access through power available, and duration of availability as detailed in **Table 4**.

The nonbinary nature of metrics like the UNSE4ALL electrification ranking system offers a substantial basis on which to define energy access. An alternative to the UNSE4ALL method is the Energy Sector Management Assistance Program (ESMAP) that also provides a multitiered approach to defining electrification. Unlike UNSE4ALL, ESMAP measures electrification independently of technology and seeks to measure the quality of access. ESMAP measures seven criteria: capacity, duration, reliability, (technical) quality, affordability, legality, and health/safety. **Table 5** outlines the tiers and criteria [22].

With this method, the performance for each criterion is evaluated and is then assigned the electrification classification tier based on the lowest performing attribute. The tier rating for each household is calculated by applying the lowest tier rating across all the criteria [21]. The effect of this classification is presented in Eq. (3).

$$\text{Index of access to energy} = 20 \times \sum_{k=0}^5 P_i \times k \quad (3)$$

where  $P_i$  is the rate of households in the  $k$ th tier. This method allows for a level of customization whereby the organization employing this tool can easily set targets to be tracked. This multitiered framework is a significant shift from past binary systems and more accurately assesses the level of electrification in rural communities. There are limits to this approach as well; the information gathered does not directly segue into a solution for the best course of



action. While further research is required to optimize these methods and formulate a transition into electrification solutions, UNSE4ALL, ESMAP, and other multitiered frameworks are the best course of action in identification.

Steps	Energy Source	Uses
Step 0	Candles, Kerosene	Lighting
Step 1	Battery powered torches	Lighting, mobile phone charging and radio
Step 2	Car and motorcycle batteries	Step 1 + small TVs and low wattage appliances
Step 3	PV lanterns/torches	Same as Step 2
Step 4	Solar home systems	Step 3 + small refrigerators
Step 5	Isolated Minigrids	Step 4 + fans, air conditioning, full size refrigerators, motors/electric pumps
Step 6	Grid-connected Minigrids	Same as Step 5
Step 7	Grid-based power	Same as Step 5

**Table 3.** Classic electrification rankings.

Energy Access According to UNSE4ALL	No	Basic	Advanced			
Attributes	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Services		Task light and phone charging	General lighting, television, and fans	Tier 2 and any low power appliances	Tier 3 and any medium power appliances	Tier 4 and any higher power appliances
Peak Available Capacity (Watts)	–	>1	>20/50	>200/500	>2000	>2000
Duration (hours)	–	>4	>4	>8	>16	>22
Evening Supply (hours)	–	>2	>2	>2	>4	>4
Affordability	–		✓	✓	✓	✓
Formality (Legality)	–			✓	✓	✓
Quality (Voltage)	–			✓	✓	✓
Indicated Minimum Technology		Nano-grids/ Micro-grids, Pico-PV/Solar lantern	Micro-grids/Mini-grids, Rechargeable batteries, Solar home systems	Micro-grids, Mini-grids, Home systems	Mini-grids, And grid	Mini-grids, And grid

**Table 4.** UNSE4ALL global tracking framework tiers.

		Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
1. Capacity	Power*		Very low power ≥3 W	low power ≥ 50 W	Medium power ≥ 200 W	High power ≥ 800 W	Very high power ≥ 2 kW
	AND Daily Capacity		≥12 Wh	≥200 Wh	≥1 kWh	≥3.4 kWh	≥8.2 kWh
	OR Services		Lighting of 1000 lm-hrs per day and phone charging	Electrical lighting, air circulation, television, and phone charging are possible			
2. Duration	Hours per Day		≥4 hrs	≥4 hrs	≥8 hrs	≥16 hrs	≥23 hrs
	Hours per Evening		≥1 hrs	≥2 hrs	≥2 hrs	≥4 hrs	≥4 hrs
3. Reliability						≤14 disruptions per week	≤3 disruptions per week. Total ≤ 2 hrs
4. Quality							Voltage problems do not affect the use of desired appliances.
5. Affordability							Cost of a standard consumption package of 365 kWh per annum is less than 5% of household income.
6. Legality							Bill is paid to the utility, prepaid card seller, or authorized representative.
7. Health and Safety							Absence of past accidents and perception of high risk in the future.

\*The minimum power capacity ratings in watts are indicative, particularly for Tier 1 and Tier 2, as the efficiency of end-user appliances is critical to the real level of capacity, and thus the type of electricity services that can be performed.

**Table 5.** ESMAP electrification tracking framework tiers.

Once communities lacking sufficient access to electricity have been identified, work can then progress to rectify the problem. Knowing which areas are in need of electricity and devising an electrification method are two incredibly independent functions. The next section delves deeper into two case studies—one in Brazil and the other in Rwanda—in order to ascertain what a customized solution for these might look like.

## 5. Case studies on rural loading in Brazil and Rwanda

With the understanding that microgrids are a viable option, and armed with the tools to identify communities and classify them based on their access to electricity, we turn our

attention to two specific case studies. First, Brazil's Amazonian region contains an abundance of natural resources, but due to its expanse and remoteness, it remains largely underdeveloped. Providing access to electricity is one critical step in the direction of eradicating poverty in the area.

A population of more than 5.6 million people in the Brazil's Amazonian region are living outside of city centers, and approximately 155,000 rural households are unelectrified [23]. Access to many of these communities is not possible by road; the rainforest is too thick. Instead, inhabitants move via waterways or, when possible, air. Grid infrastructure improvements are severely limited to areas with road access, making expansion to these sites extremely difficult. A common solution in rural areas desperate for electrification is to use diesel generation. Typically, 10–100 kVA generators are sourced for this kind of application, but the high price of diesel and an unreliable supply make for a bad combination. Apart from the cost and access, diesel is a pollutant fossil fuel, whose affects are compounded by poor generator efficiencies from ill-maintained equipment. However, if properly tapped, there are an abundance of renewable energy sources (RESs) including solar, wind, hydroelectric, and biomass. These RESs can offset or completely replace the diesel fossil fuels currently utilized.

Brazil is in the midst of a push to offer electrification for these rural areas, which makes it an excellent case study. The program Brazil has adopted is called "Luz Para Todos" or "Lights for All" (LFA). Currently, LFA has provided electrification for 2.9 million households or 14.4 million people [24]. Unfortunately, while this scheme has been successful, it lacks the ability to penetrate into the more remote and rural areas. The initial phase of the plan was a national grid extension network through relatively populated areas. This equated to a large number of people benefited through a relatively short distance of grid extension. As the distances increase and population density decreases, this tactic becomes increasingly less effective.

Previously, **Figure 1** illustrates Brazil's transmission network—both existing and planned. In the figure, the solid lines represent existing power connections, whereas the dashed lines are proposed extensions [25]. This interconnected system is capable of generating and distributing 138 GW of installed power. Despite this there are still a large number of people lacking access in the dispersed settlements. In contrast to the integrated grid network, there are numerous independent isolated systems of both diesel generation and thermoelectric in the North-West region of Brazil, where the interconnected systems do not penetrate [26].

Brazil has a unique and widely varying electrification rate. The rural electrification rate of Brazil is approximately 97%, whereas specifically in the Amazonian region, rural electrification drops to 61.5% [4]. This drop illustrates the extent to which this region has been isolated and ignored. **Figure 8** presents this unequal distribution into focus by shading areas with less access a darker color. Immediately it becomes obvious the Amazonian region is seriously underelectrified [27].

Eirunepe city, located 1160 km from the region's capital Manaus, is an excellent example of an Amazonian electrification problem. While Eirunepe city has electricity through diesel generation, the surrounding communities do not. This is because the diesel comes from Manaus by boat. The journey is approximately 2400 km along the river. Because of these massive distances involved, the cost of electricity is increased, and thus expansion becomes difficult. Torre de

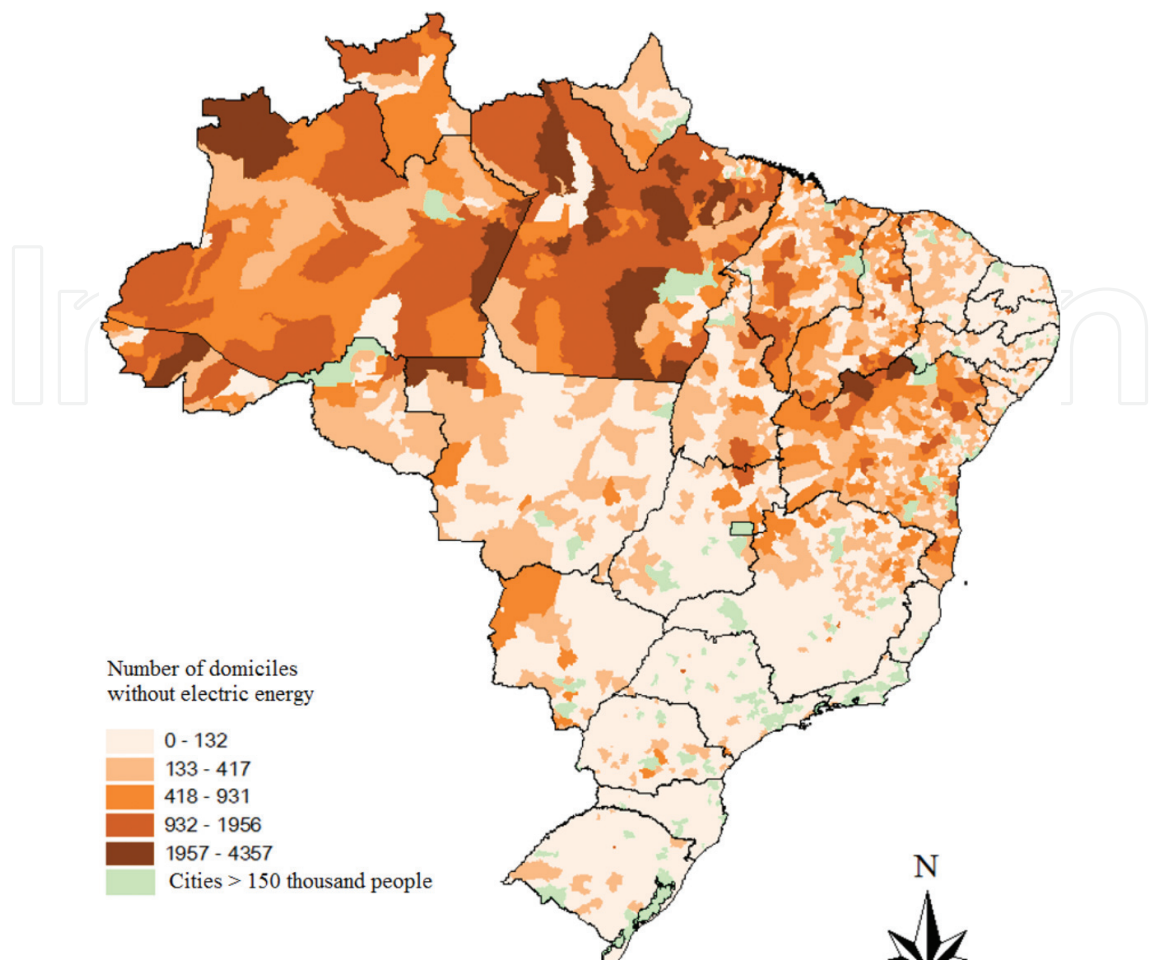
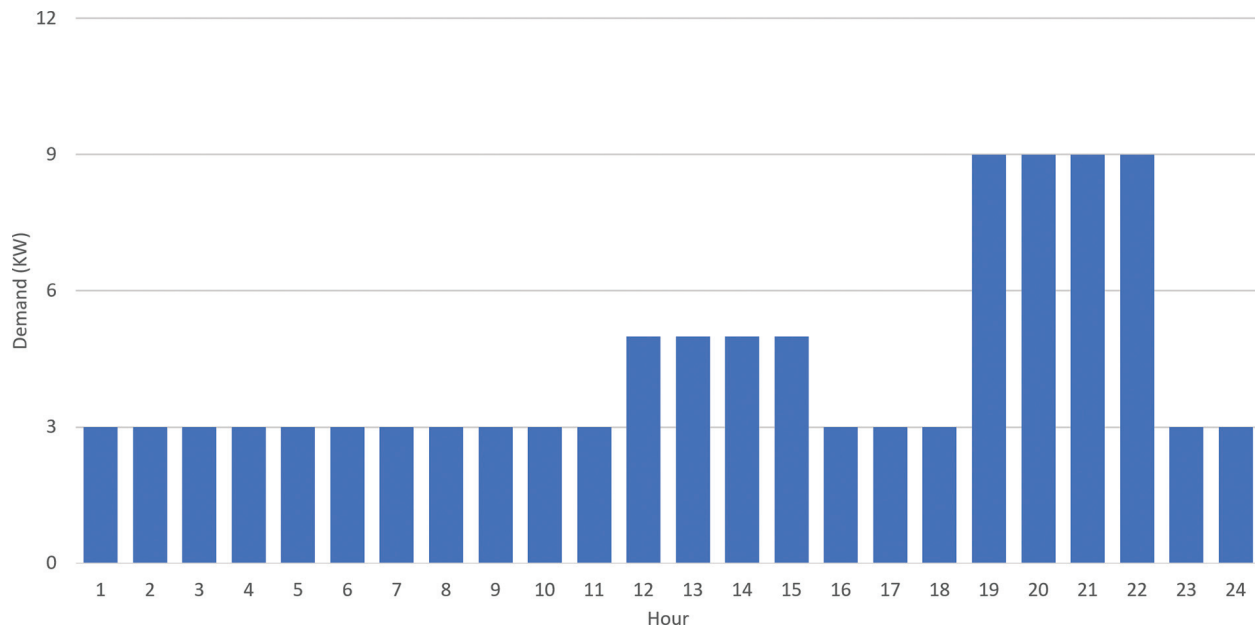


Figure 8. Areas lacking household access to electricity.

Lua, a community near Eirunepe city, consists of approximately 25 households near the river. The purpose of the remainder of this section is to determine the specific viability of a renewable energy-based microgrid system including solar and hydropower. Because the community is unelectrified, there exists no real-world data to base usage on. Instead, with the size and population of the community, and expected load profile can be estimated. **Table 6** shows the breaks down the power requirements for a community like Torre de Lua, and **Figure 9** shows the aggregated demand for the entire community.

Loads	Power consumption (W)	Number of items	Demand (W)	Hours per Day
LED Lights	9	5	45	4
Refrigerator	100	1	100	24
Radio	50	1	50	4
Television	100	1	100	4
Fan	120	1	120	4

Table 6. Single household load in Torre de Lua.



**Figure 9.** Torre de Lua community load profile.

Once a load profile has been established for the community, an optimization can be run using HOMER to determine the appropriate makeup of generation and storage. **Figure 10** shows the proposed generation and storage in connection with the demand. A converter is used to move power from the AC and DC buses as the batteries or solar generation power the load, or as the hydropower recharges the batteries.

The calculations for the available solar power are based on the NASA radiance database for Eirunepe city, which come from longitude and latitude. **Figure 11** illustrates the radiation expected on the monthly bases, which is directly translated into kWh per m<sup>2</sup> per day, which when coupled with the efficiency of solar panels, an exact power can be calculated.

The second resource—hydropower—can similarly be predicted based on location. The Water National Agency (ANA) in Brazil tracks flow rates of various rivers. The Taruaca River, on which Torre de Lua sites, has a station known as Envira (Station Code 12680000) which is the closest to Torre de Lua. **Figure 12** shows the average stream flows in the area, peaking in June [28]. This is complimentary to the solar resource, as July through October are the highest solar times, whereas there is a drastic dip in flow rates for these months.

The remaining inputs are cost and sizing options. Inputting a price list for HOMER and giving a range of options for sizing to be compared (e.g., solar sizing options: 0, 5, 10, and 15 kW), HOMER then optimizes the generation and storage solution. **Table 7** shows the cash flow expected for a solar-hydro system to be able to supply the energy required.

HOMER's optimal solution returns a PV-Hydro-Battery mix which proves to be revenue neutral by charging \$0.091 per kWh. Compared to the price of electricity from the Amazonas Electrobras utility of \$0.090 per kWh, this is a highly competitive solution.



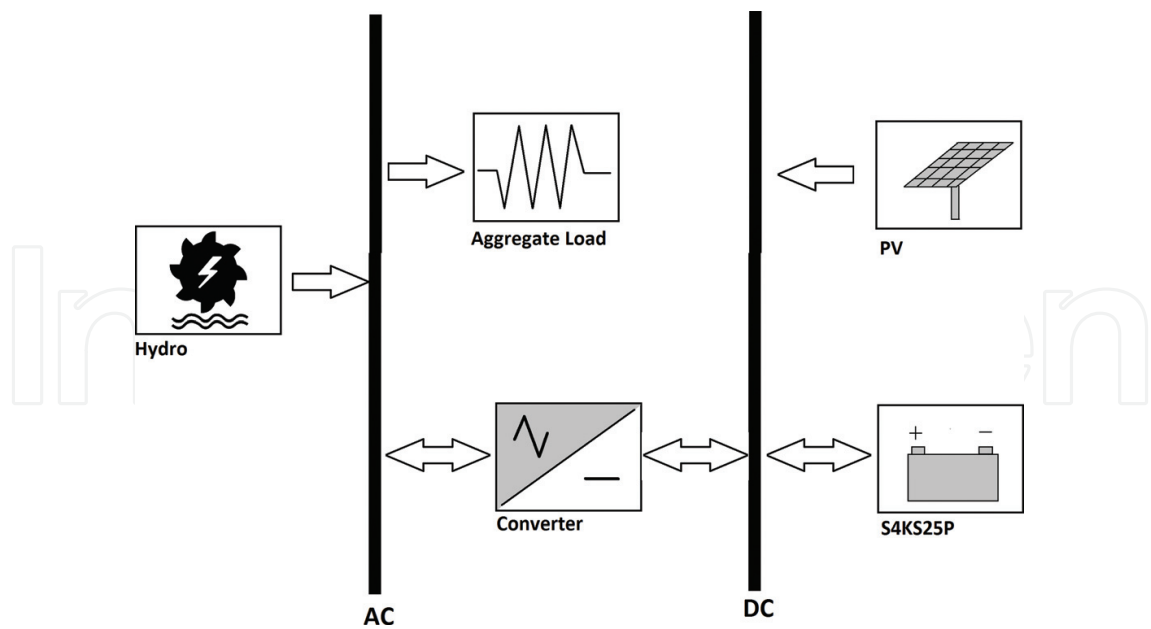


Figure 10. Torre de Lua HOMER microgrid schematic.

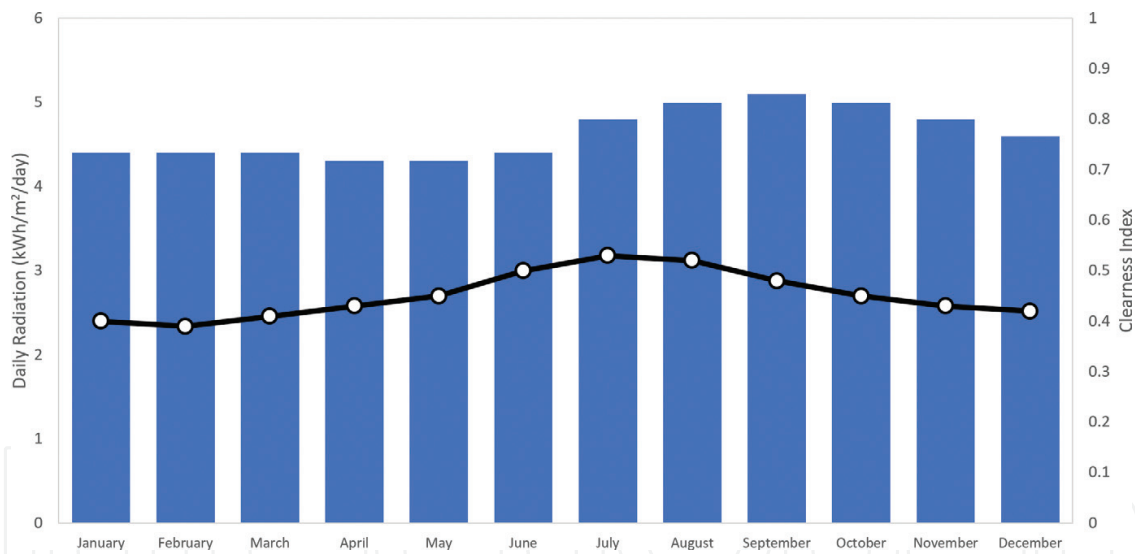
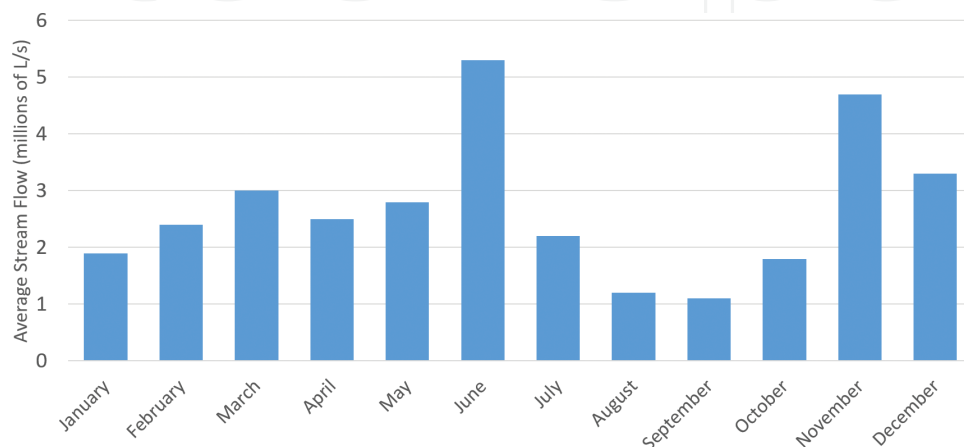


Figure 11. Torre de Lua solar radiance.

The first of the two case studies proves to be feasible, but this is one isolated view. For the second community, we travel thousands of miles and a continent away to Rwanda. Rwanda provides an excellent case study. It is a highly populated land-locked resource-poor country where 75% of the population lives in rural areas [29]. Similar to Brazil, Rwanda has also rolled out a version of LFA called the Electricity Access Roll-out Program (EARP); and again, the aim is to provide a higher rate of electrification for the rural population; however, the total installed capacity for Rwanda’s 12 million people was 115 MW as of 2014 [30]. This shortage in supply means that simple grid extension will be grossly insufficient, as there is not enough power

Component	Capital	Replacements	O&M	Fuel	Salvage	Total
Generic Flat Plate PV	\$18,000.00	\$0.00	\$0.00	\$0.00	\$0.00	\$18,000.00
Hydro	\$15,500.00	\$0.00	\$646.38	\$0.00	\$0.00	\$16,146.00
Discover 12VRE-3000TF-L	\$2200.00	\$629.05	\$2895.80	\$0.00	(\$257.66)	\$5467.20
Converter	\$2750.00	\$986.44	\$0.00	\$0.00	(\$185.66)	\$3550.80
System	\$38,450.00	\$1615.50	\$3542.10	\$0.00	(\$443.31)	\$43,164.00

**Table 7.** Cash flow for RES system.



**Figure 12.** Torre de Lua river flow rates.

currently generated. Coupled with the fact that Rwanda has no ocean access for importing petroleum or other fossil fuels cheaply (Rwanda does not have natural reserves, with the exception of some methane production on Lake Kivu), a greater emphasis must be placed on the role of renewable energy.

A community called Nyakabanda is located 40 km west of the capital. Nyakabanda is an unelectrified community a little over 11 km away from the national grid, as shown in **Figure 13** [31]. Similar to the Brazilian case, the first step is to determine a load profile.

Because the region in which Nyakabanda is located is known for growing coffee, two milling stations are included in the load profile, along with household lighting shown in **Table 8**.

This may appear to be a very conservative, bare-bones electrical demand, however, because of its unavailability, current electricity usage is limited to running lights off of car batteries (if any electricity is used at all). This proposed system would be to run industrial equipment brought in by the government or private business (in the event electricity was available) and lighting. There is no economic room to account for larger loads, such as refrigerators or washing machines because the community would not immediately buy these appliances due to the high capital cost. Instead, the microgrid must be allowed to grow naturally.

Similar to the Brazilian case, a HOMER grid is generated. However, in this case, wind is considered along with solar and hydro, as shown in **Figure 14**. When the simulation is run,

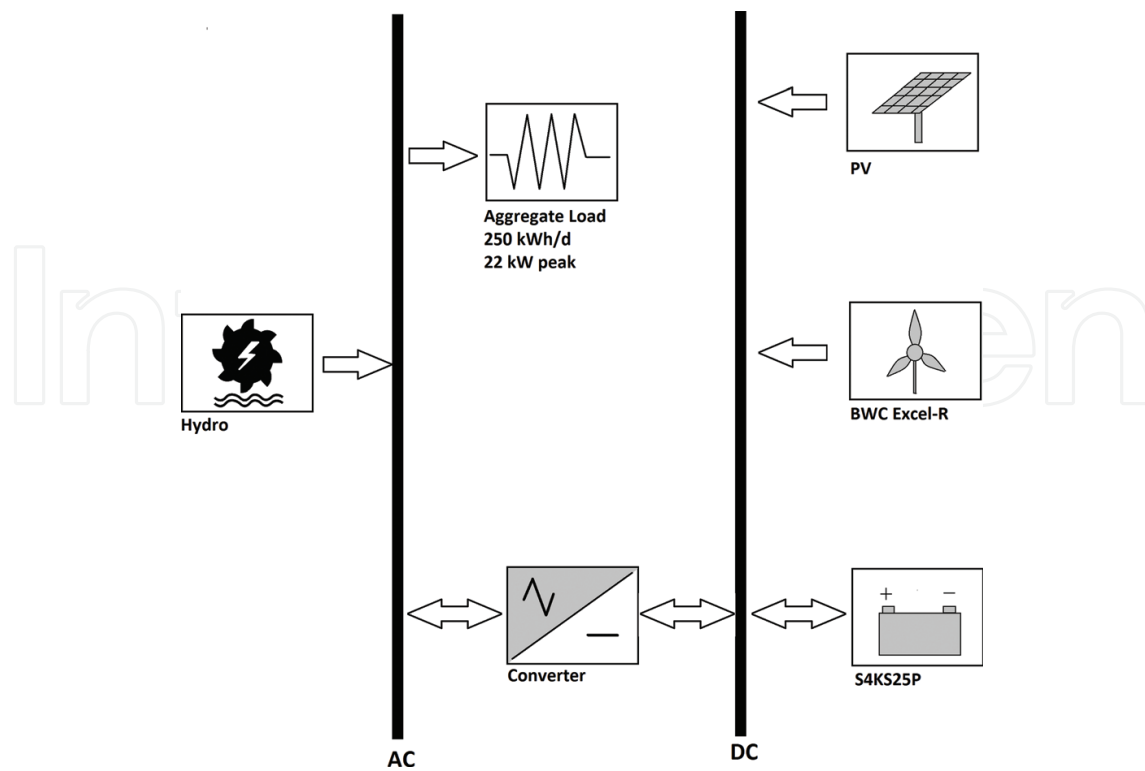


Figure 13. Relationship between Nyakabanda community and closest grid access point.

	Load	Power
Household	LED Lights (2)	5-Watts Each
	Phone Charger (2)	3-Watts Each
200 households		
Coffee milling station	Milling Machines (1)	11-kW Each
	Outdoor LEDs (2)	5-Watts Each
2 Milling Stations		
Restaurant	Indoor LEDs (3)	5
	Outdoor LEDs (1)	5
1 Restaurant		

Table 8. Estimated Nyakabanda loads.

the optimal solution contains 5 kW of solar, 11 kW of microhydro, and 16 kW of battery storage. The wind in this location was neither strong nor constant enough to financially justify a wind turbine at this scale. Compared to the grid price of approximately \$0.26 per kWh, the levelized cost of energy for this system is approximately \$0.24 per kWh. The breakeven distance for this system was approximately 1 km. Since the community is 11 km



**Figure 14.** Nyakabanda community HOMER microgrid setup.

from the existing grid infrastructure, it stands to reason that the microgrid option is more economical.

Both the Rwandan and Brazilian case studies have shown that isolated microgrids are economically feasible. These are rough snapshots of what is required for electrification, but they highlight the major aspects. Thus far we have seen the viability of microgrids compared to grid extension, and the actual “per kWh” costs of implementing the microgrid. But these solutions represent an out-of-the-box electrification scheme not tailored to rural life. Because the way electricity is consumed in the West and in rural developing locations differs drastically, new technology, process improvements, and innovative uses can drastically reduce wasted energy and thus further bring down the costs. The next section in this chapter delves into these changes and analyzes how much of an impact they can have on a microgrid.

## 6. Innovative enhancements for microgrid optimization

So far the microgrid has been treated as a response to a static load profile. Generally, this is acceptable because the electrical loads receive no feedback from the supply as to the amount of over/under production. If a new load is added to an already saturated system, voltage drops or blackouts may occur. Since these microgrids are designed and built from scratch, extra measures can be taken to reduce peak loads and distribute power consumption—easing the burden on the microgrid.

Batteries are often used in microgrids as a means of load shifting. When renewable energy generation is producing power in excess, the batteries can be charged and when the load outweighs the supply, the power stored in the batteries is used. Unfortunately, traditional batteries can be expensive and have limited cycle use before they need to be replaced. Alternative power storage methods are available—such as pumped hydro or flywheels—but a more grassroots solution reshapes the problem. Rather than store energy to match supply to meet demand change the nonessential demand to match supply.

6.1. Smart energy management for health Centers

Examples of how loads can be rearranged are readily available. One system, known as “smart energy management for health centers” (SEMHCs) clearly analyzes how this process works [32]. Rural health centers in particular are more prone to suffer from chronic power outages because of the nature of their loading. Clinics often have high-power equipment that is only run for a short period of time. If many of these devices are powered simultaneously, it can overload the individual PV systems the run off. Since sufficient battery banks can be cost prohibitive at this scale, the clinics are at the mercy of whatever their arrays can produce. Alternatively, when the system is not being overloaded, energy that is not being used is lost. Instead, low-tech scheduling systems can organize and shift loads to use the electricity more wisely.

**Figure 15** illustrates this point further. The dotted line represents the power curve generated by a PV array throughout the course of a day, and the gray shaded blocks represent the loads. From  $t_0$  to  $t_1$  and between  $t_4$  and  $t_5$  the demand exceeds the generation, while the white space between them represents energy generated by the array that is lost.

Scheduling patients’ services without the knowledge of power available ultimately hinder the services provided. Traditionally, clinics operate on a first-come, first-served basis, and if overloaded, the power will cut out with waiting patients. With the already low density of health centers in rural developing areas, patients sometimes have to travel large distances in

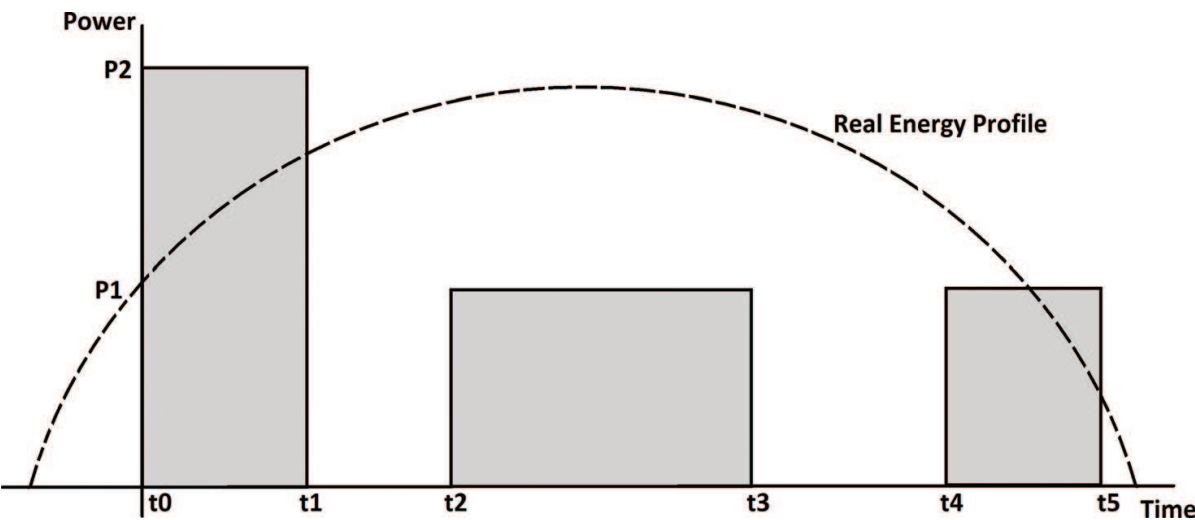


Figure 15. Unused energy in storage-less systems.



order to arrive at the clinic. When the clinic then does not operate due to power issues, access to health services is essentially nonexistent.

SEMHC addresses this issue by scheduling services based on available energy and the priority of the service. The program starts by assessing the solar power production available, defined in Eq. (4) where  $s$  is the surface of the PV array,  $k$  is a constant for in-line energy loss due to increased temperature, incident angle of radiation on the array, shading, and panel degradation, and  $R(t)$  is the average solar radiation on the PV panels over a specific period of time  $t$ . The values for  $R(t)$  can be pulled from satellite data from organizations such as NASA.

$$E(\Delta t) = s \cdot k \cdot R(T) \cdot \Delta t \quad (4)$$

Next, the algorithm assigns a value  $C_i$  to the service required, where  $C$  represents the power rating and  $i$  is the device ranking or priority. The device is expected to operate for a closed time interval  $d_i$ . The process is optimized mathematically with Eq. (5).

$$\max_{n \in \mathbb{N}} \left( \int_{t_d}^{t_d + \min(d_i)} s \cdot k \cdot R(t) \cdot \Delta t - \sum_{i=1}^n C_i d_i - A \right) \quad (5)$$

The constant  $A$  represents the base load of the clinic—devices that are always on and consuming power.  $t_d$  represents the lowest time for which the generation power exceeds the nominal power of the devices. The final assurance is to guarantee that the demand does not exceed the power produced  $P_n$  by the panels, eliminating the possibility of overloading the system. Condition Eq. (6) then must be true at all times.

$$\sum_{i=1}^n C_i d_i \leq P_n \quad (6)$$

Since this is a priority-driven system, any excess power not used by critical loads can be used low low-priority low-power demands. The system is shown in **Figure 16** graphically. At the onset of the program,  $t_{\min}$ , there are five loads already scheduled and running. Since the power available exceeds the demand, a new load NL3 is moved from standby to operating. NL3 is used because the higher priority loads would render condition (6) false.

After the completion of any load, the system reevaluates which waiting loads can be fit into the unused capacity. With this low-cost, low-tech solution to power management, unnecessary outages can be avoided and wasted energy can be minimized. This is only one specific case of a computer-based microgrid improvement. With the advent of smart meters, control at a household level can be more than binary (on/off) as seen with the health clinic example. With built-in wireless communication hardware, individual loads inside a household can be monitored and controlled.

## 6.2. The load attenuating stochastic simulator

The load attenuating stochastic simulator (LASS) utilizes the abilities of networked smart meters to control loads at a fine granularity, delivering or cutting power at the appliance level

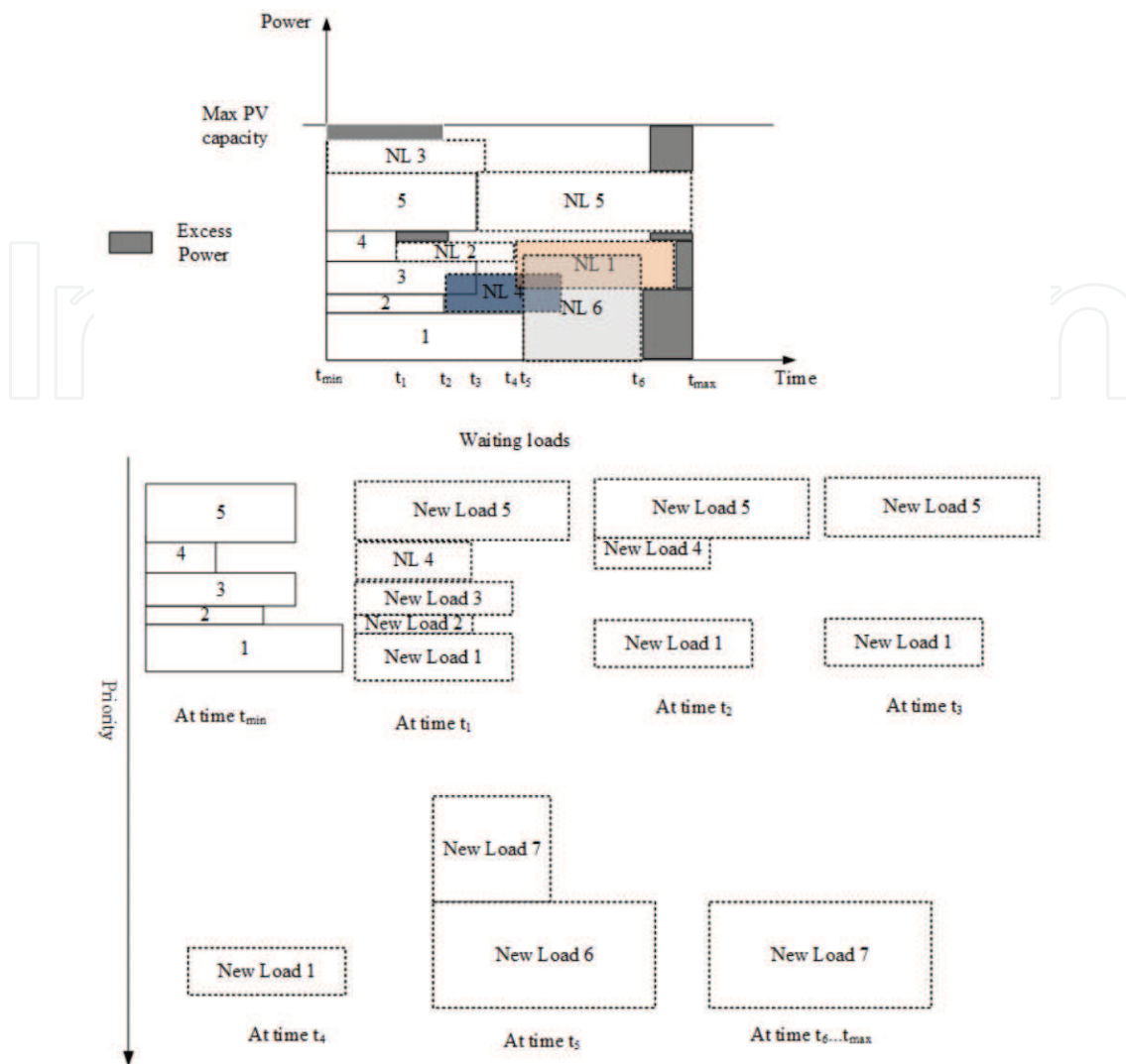


Figure 16. Rearrangement of loads to match SEMHC scheduling.

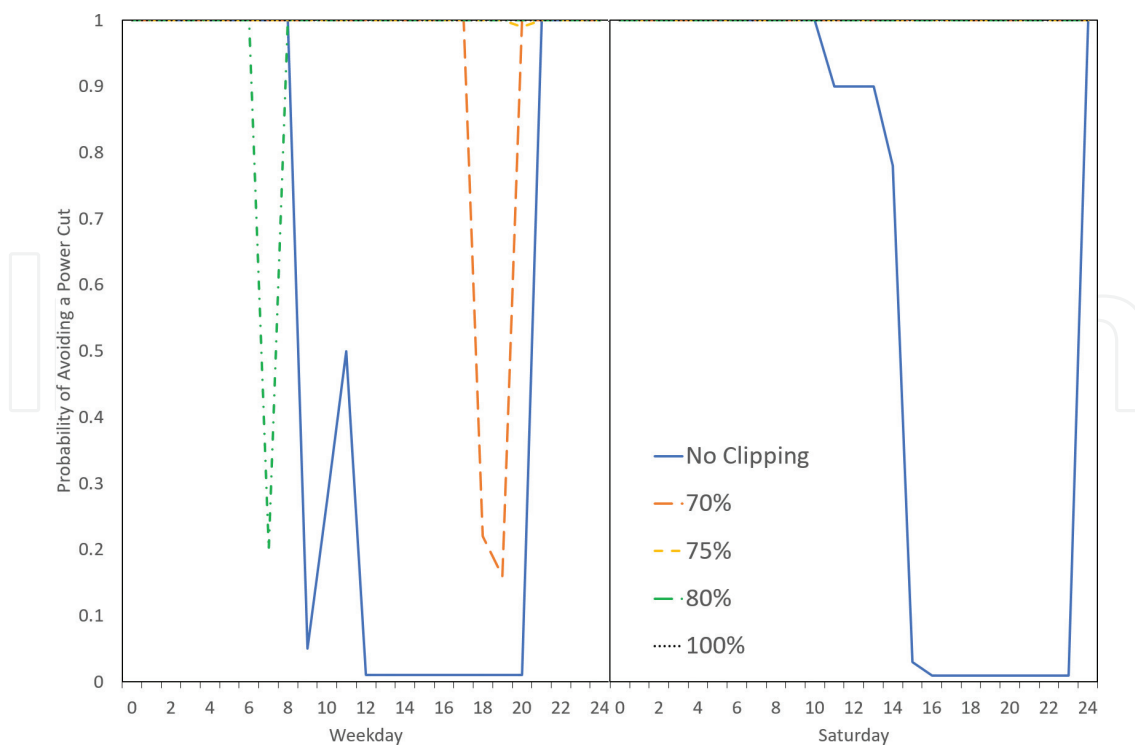
depending on the customer's desires or requirements. This creates a tiered electrification scheme in which customers can pay a reduced rate under the condition that their power may be throttled first in the event, the demand exceeds generation [33]. While the results in this field suggest that the most economical solution is to provide sufficient capacity to meet all demand, once there is a limitation in supply, customers are best served by having their loads clipped versus having the entire system overload and experience blackouts. This works in much the same way as SEMHC, except it is applied over an entire microgrid, not an individual consumer.

To prove that load clipping increases overall electricity distribution, a simulation is used whereby LASS uses a Probability Mass Function (PMF) as an input over each time step for the possible loads and generation over a microgrid system for a traditional weekday and Saturday [33]. The simulator generates demand and loads for each time step based on a fictional microgrid setup. Inside this simulation, there exist two tiers of customers: customers

whose power can be clipped and customers whose power cannot be clipped. The goal is to reduce the probability of power outages by determining what percentage of customers must be in the clipped category.

The base case (where no customers are clipped) and four other scenarios where 70, 75, 80, and 100% of homes can be clipped are examined. In the control case with no clipping, there are instances where power will have to be cut for multiple hours per day for both weekday and weekend profiles. The severity of this can be seen in **Figure 17**. The reverse is obviously true as well. If you cut power to 100% of homes, then the probability that there will be an outage is essentially nonexistent, since instead of overloading the microgrid, it has just been shut down completely.

Whether or not power has been clipped, a power outage that has been avoided is only part of the problem. For any form of electricity distribution system to be viable, the maximum amount of electricity needs to be sold without shutting down the entire system. Protecting the grid by turning power off to everyone means that the utility (or distribution owner) loses income. Instead, there exists a balance between providing electricity to the maximum amount of people without increasing the risk of an outage. **Figure 18** highlights the amount of power consumed (or sold) respective to each clipping scheme. No clipping is still the worst performing, since without clipping an outage is nearly guaranteed, and therefore no power is consumed by anyone. Again, the inverse is not ideal. If you cut power to everyone, then again, no power is sold or consumed. When 75% of customers' power is clipped, the probability of an outage is less than 1%—nearly the same as any of the higher schemes. However, clipping only 75% of homes compared to 80% generates more revenue through more distributed power.



**Figure 17.** Probability of sufficient power for multiple clipping tiers.

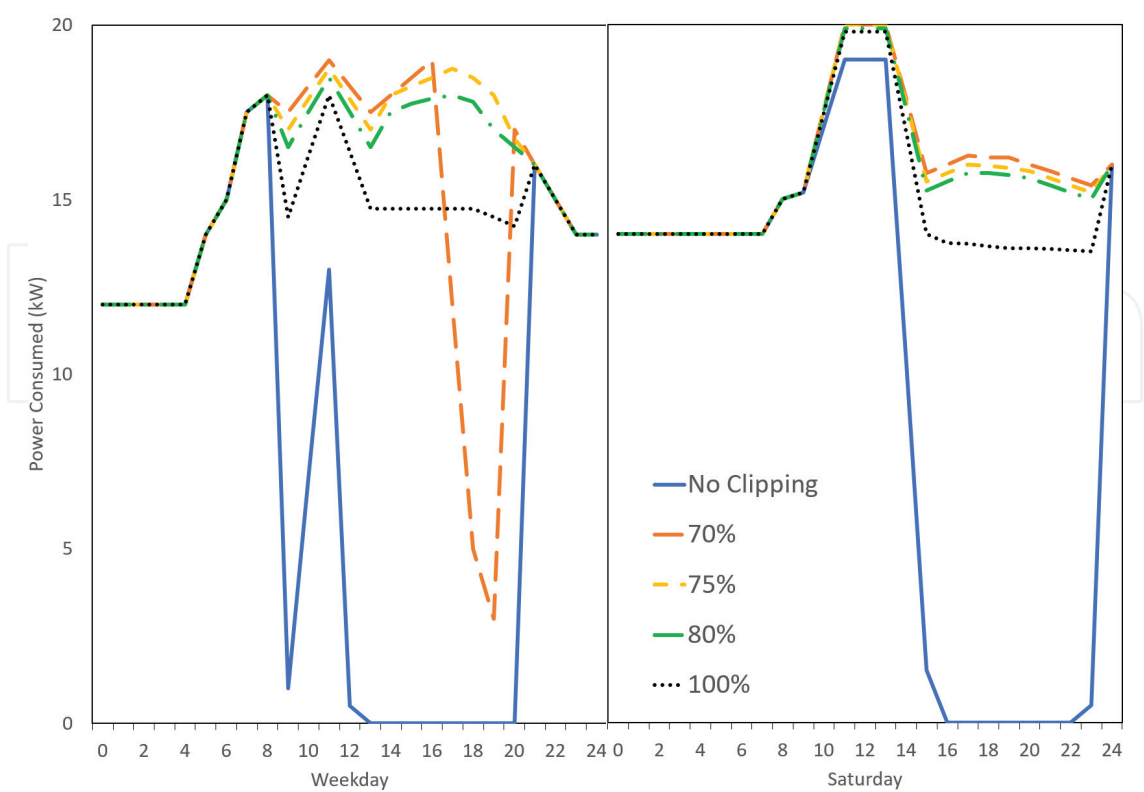


Figure 18. Power consumed based on an amount of home clipped.

The figures provide excellent visuals for hour-by-hour outage probability, but the root of the issue focuses on the total time, or overall percent chance of an outage. Table 9 shows the solutions for the weekday and weekend times.

	Percentage of homes clipped	Expected total power cut duration (hours/day)	Expected energy sold (kWh/day)
Weekday	0 (No Clipping)	11.2303	197.17
	70%	1.9474	360.59
	75%	0.0137	392.31
	80%	0.0005	385.33
	100%	0.0005	356.29
Saturday	0 (No Clipping)	9.4835	240.20
	70%	0.0005	396.87
	75%	0.0005	392.89
	80%	0.0005	388.92
	100%	0.0005	373.13

Table 9. Optimum clipping rates.

Clipping to 75% on weekdays and 70% on Saturdays results in the highest amount of energy sold. While the power outages required for weekdays is higher than if more homes were clipped and the overzealous clipping actually leads to less power sold. This does not increase the robustness of the system, but instead takes an overly cautious approach and shuts down power unnecessarily.

Choosing the correct percentage of homes to clip is critical in the cost effectiveness and reliability of microgrids. While this study has provided an excellent starting point or generalization, each microgrid will have to be fine-tuned to its particular power generation and loading curves. The goal of this section was to demonstrate that demand-side changes can have a meaningful impact on both the reliability and affordability of microgrid setups.

## 7. Agricultural and biomass generation for baseloading and critical demands

The final section of this chapter explores a rural-specific energy source not often considered in microgrids: agriculture. About 78% of the world's poor lives in rural areas and relies on agriculture for both food security as well as household income [34]. Biomass is a large and often untapped rural resource that can provide a significant portion of on-demand power.

Burning agricultural waste in small steam furnaces allows for localized generation utilizing an abundant and proximal resource. Generation units 10 and 50 kW are already in production for exactly this kind of use [35]. Village industrial power (VIP) operates in East Africa and offers an off-the-shelf 10 kW unit, which can be transported in the back of a small pickup truck. Agricultural waste is burned directly and the self-contained unit can generate electricity. Used in tandem with solar or wind generation, a biomass unit can act in the same way that a diesel generator traditionally assists microgrids. Biomass can be stored and the unit brought online when demand is high.

The viability of biomass as a generation source primarily hinges on its availability, which is what makes this option suitable for rural and not urban use. Case studies have been carried out which are generally geographically limited. Specifically, the Punjab region of India was analyzed and it was determined to house vast untapped biomass resources. If the Punjab example is followed, the first step is determining what types of biomass are available. The six major biomass options from crops grown in the region are outlined in **Table 10**, and are categorized into four sections [36].

The A1–A4 category ratings simply separate the styles of biomass, where A1 represents generic unused dry biomass and A2 represents woody biomass. It is important to note that the energy reserves of biomass do not come directly from the sum of biomass itself, rather, the



Category	Type of biomass	Name of crop
A1	Straw	Wheat
		Barley
		Paddy
		Seasum
		Pulses
A2	Stalk	Cotton
		Maize
		Arhar
		Rapeseed and Mustard
A3	Bagasse*	Sugar Cane
	Tops and Leaves	Sugar Cane
A4	Cobs*	Maize
	Husks*	Paddy
	Shells*	Groundnuts

\*Indicates processing residue.

**Table 10.** Identification of available biomass [36].

actual unused biomass represented here accounts for the subtraction of biomass used for domestic purposes, animal fodder, heating, etc. These values here represent biomass burned by farmers in the field. This biomass is truly unused and serves no other purposes.

The amount of energy available comes from the product of the present supply and the lower heating value (LHV). This is taken through the amount of cultivated land with each of the above-described crops, as well as the reduction due to moisture. The final available amounts are shown in **Table 11**.

With tens of millions of tonnes of unused biomass going to waste, the potential for on-demand electricity generation is immense. In total, there exists over 200 TJ of unused energy from all the biomass over the entire Punjab region. Obviously, this is only one specific instance, and many other areas may come in well below this, but even at a fraction of the potential, the remaining energy is immense. From this point, the major hurdles become collection and storage. Fortunately, at the microgrid scale, the volumes required are not overwhelming.

The capital costs and operation can be handled in a similar way to renewables or diesel generation, but with a few caveats. Whereas diesel would be purchased, stored, and used by the microgrid operator, the biomass is locally sourced. Two prominent incentives exist for engaging the community and collecting the biomass required to operate the generation unit. Either cash can be directly paid out per kilogram of biomass collected by farmers, or discounts/ vouchers for electricity can be distributed.

Category	Type of biomass	Name of crop	Cultivated area (km <sup>2</sup> )	Moisture content (%)	Total biomass (dry basis) (kt)	Used (%)	Unused biomass (dry basis) (kt)
A1	Straw	Wheat	34,765	9.2	14,317.30	80	2863.45
		Barley	70	–	45.28	20	36.22
		Paddy	35,406	10.6	8774.14	16.45	7417.70
		Seasum	206	–	19.35	20	15.48
		Pulses	274	–	31.92	80	6.88
Total					23,187.99	–	10,339.73
A2	Stalk	Cotton	6043	12	707.47	31.3	486.03
		Maize	1649	11.5	800.44	24.2	598.70
		Arhar	91	–	39.00	70	11.70
		Rapeseed and Mustard	498	–	142.49	70	42.75
Total					1689.43	–	1139.18
A3	Bagasse*	Sugar Cane	1441	15	1154.14	40-50	577.07
	Tops and Leaves	Sugar Cane		59.2	940.99	60	376.40
Total					2095.13	–	953.47
A4	Cobs*	Maize	1649	8.6	207.78	24.2	154.70
	Husks*	Paddy	25,406	9.6	2417.18	49	1152.76
	Shells*	Groundnuts	37	9.87	0.92	36	0.49
Total					2625.88	–	1307.95

\*Indicates processing residue.

**Table 11.** Available energy stores derived from unused biomass [36].

## 8. Conclusions

It is often said that no single renewable energy source will be able to entirely replace our dependence on fossil fuels, but instead it will take a combination of solar, wind, hydro, biomass, and others to wean our dependence on pollution-heavy and unsustainable fuels. The idea of a multipart solution is not a new one, and it is certainly not limited to power production. Much in the same way that our energy needs must come from multiple sources, there are multiple levers to pull in order to reduce the cost of rural electrification and bring it within the reach of developing countries.

Just like solar, wind, hydro, and biomass come together to offer a solution to our power production needs, microgrids equally rely not only on multiple generation sources, but also on multiple consumption strategies to increase viability. The microgrid by itself is expensive and clunky and does not utilize new technological developments or advancements to improve on itself. At its core, it is a scaled-down technology that has not changed in over 100 years.

However, when combined with the techniques and technologies discussed in this chapter, the microgrid takes on a new form. It is no longer wasteful—carrying extra capacity which cannot be used—or allowing itself to be stretched and overloaded leading to total failure. This smart microgrid recognizes its own capacity, stores as much excess energy as possible, and recommends the shifting or clipping of noncritical loads for the benefit of the entire community. Tightening down and preventing electrical waste directly translates to a less expensive, more efficient distribution of energy. Cheaper electricity opens the door to rural electrification where it was once too costly to distribute power, and direct access to inexpensive power provides a boost in quality of life unimaginable to those who have been fortunate enough to have access to a near unlimited supply of inexpensive power.

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