Minigrids for Electrification:
Policies to Promote Industry Growth

By

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Submitted to the Institute for Data, Systems, and Society in
Partial Fulfillment of the Requirements for the Degree of

Master of Science in Technology and Policy

at the

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Abstract

The International Energy Agency estimates $331 billion dollars will be invested over the next 12 years to provide energy access to the 1.1 billion people who currently lack access to reliable electricity service. Of the $331 billion, the IEA estimates that 34% of this capital will be directed towards minigrid systems.

In line with these capital estimates, governments in many countries with low levels of electricity service are undertaking significant capital expenditures in order to expand the existing electricity infrastructure. However, this capital is limited and will not be sufficient to provide universal access. One proposed solution to overcome limited government budgets and capacity is to allow off-grid and minigrid services in areas which will not be reached by government-led programs.

This thesis utilizes a computer-based simulation model to explore how minigrid developers respond to commercial, industrial, and residential customers and the type of service these minigrid developers may choose to provide to these customers. The effect of government policies and subsidies is incorporated into the developed simulation model to judge the effect of these policies on firm behavior. The simulation results find that if governments are to prioritize universal access to rural households, specific policy measures must be put in place to encourage minigrid developers to provide service to low-income consumers.

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If You Only Have 5 Minutes to Read This Thesis

It can be difficult to find the key figures or central tenet of an argument when first opening a master's thesis. For the sake of the reader and their precious time, I will suggest a few selected sections depending on background knowledge and desired time commitment. Perhaps these suggestions will assist any reader struggling with the question of "What's the point?"

For the 5 Minute Reader

If the reader is already familiar with the challenges of rural electrification and the proposed solutions, I recommend skipping the introduction, literature review, and methodology section. The most significant graphs are contained within the three case studies. I suggest beginning with Figure 8, Figure 26, and Figure 36. These figures clearly show the marginal cost for connecting additional consumers to a minigrid and assist the reader with understanding why entrepreneurs may be so hesitant to extend a minigrid to residential households.

Figure 4, Figure 21, and Figure 31 show the potential profitability of a minigrid, further emphasizing the rather narrow market available to minigrid firms.

For the 15 Minute Reader

After perusing the recommend figures above, I recommend the reader briefly skim the explanation of the research question to gain an understanding of why the policy-maker, investor, or minigrid developer may be interested in the marginal cost of connecting consumers to a minigrid.

It is then valuable to review the case studies, with particular attention to the willingness to pay (WTP) of each consumer and the profound effect of WTP on the profitability of a given minigrid.

This re-reading of the case studies will lead the reader back to Table 2, Table 4, and Table 6, which attempt to estimate the subsidy necessary for each minigrid. The key nuances of these tables can be teased out by asking which stakeholders are providing funds/revenue, how much each of these stakeholders are paying, and what alternative energy options are available for consumers?

I then suggest reading the recommendations for policy-makers to understand the advantages and pitfalls of various pricing approaches and government policies.

If You are Reading This Entire Thesis

After following the recommendations for the 5 minute and 15 minute reader, feel free to read this thesis from start to finish. While reading, remember that the perspective in this thesis is from the viewpoint of the private minigrid operator delivering energy services. Other structures for ownership and operation of energy infrastructure exist, and these structures can significantly change the formulation and methodology for approaching problems. A government may choose a different objective function such as cost minimization or maximizing energy service. In the end, it is a partnership of governments, private operators, and consumers which will enable energy access. Only by considering the perspective of each can a holistic and sustainable energy policy be formulated.

Acknowledgements

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Contents:

Introduction

The Unmet Need For Energy Services

Providing energy access to the world is a wickedly difficult problem. Despite the tremendous investment of time and capital to date, 1.1 billion people remain without adequate energy service. On the continent of Africa, the population growth is outpacing the growth in energy infrastructure [1].

Countries such as the United States electrified throughout the late 1800s and 1900s entirely through grid-extension. Although this approach was effective in wealthy countries with an appetite for energy, it cannot be transplanted to countries which still have electrification rates below 20%.

Recent efforts in electrification have adopted alternative approaches from both a structural and technological perspective. Private capital is moving into the electricity distribution industry at a significant rate as companies begin to see a market opportunity to provide energy service where the government cannot [2]. These privatized approaches can take the form of firms operating in a free, unregulated market, or as public-private partnerships, which have been seen in utilities throughout Africa and India.

In addition to the structural changes in the industry, the technological advancements in solar photovoltaics, energy storage, and mobile communication networks have enabled new technologies for providing energy service. The solar home system market is growing rapidly, and minigrid developers are scattered throughout sub-Saharan African and India.

Projected Investment Through 2030

The International Energy Agency estimates that $334 billion will be required to increase the worldwide energy access level to 92% by 2030. Due to population growth, this will still leave 602 million people in African without access, but will increase the energy access rate from 34% to 64% [1].

Of the $334 billion in investment, over 34% is estimated to for minigrid development and 29% in other off-grid products. This represents an investment of $114 billion in minigrids, or an average of $8.1 billion per year between 2016 and 2030.

Although the split of public and private investment is not delineated in the report from the IEA, there is considerable discussion regarding the business models and regulation for private investment. This discussion suggests that the banks and international agencies believe private investment will comprise a significant portion of the financing.

In the State of Electricity Access Report published by the World Bank, a number of measures are proposed to facilitate the developing minigrid markets. Of particular note are the recommendations to establish clear rules for scaling the central grid, risk-guarantees, and light-handed regulation [2].

The Existing Investment Situation in Rural Africa and India

Through a combination of reports, internet searches, and industry interviews, it was possible to compile a list of approximately 38 minigrid firms which are operating throughout sub-Saharan Africa and India. Most of these firms are small with only a few minigrids. The largest providers are Husk Power, which operates primarily in Bihar and Uttar Pradesh, India, and PowerGen, which operates in East Africa [2].

The investment in the minigrid industry is not growing at the same pace as solar home systems. The World Bank report identifies $160 million in capital raised by pay-as-you go SHS providers in 2015 [1]. This is contrasted with the minigrid industry, which has seen one serious equity investment of only $20 million [3]. The majority of the minigrid operators have fewer than 20 sites.

Motivation for the Research Question

When this research began in 2016, there were significant amounts of investment flowing into the market for Solar Home Systems, but a stagnation of funding for minigrids (a notable exception being Husk Power in January of 2018). Despite the abundant literature on the benefits of minigrid systems and the techno-economic analysis pointing to minigrids as the least-cost approach to electrification in many scenarios, the industry appeared stagnant.

The literature often cites risk, unfavorable regulation, and lack of anchor customers as barriers to minigrid industry growth. Much of the work in this thesis attempts to explore these barriers, but with a secondary question of determining which customers are most likely to be served by minigrids. Particularly, this thesis asks, if minigrids were to be constructed at scale would certain customers still be left behind? Anecdotal evidence suggests that in the solar home industry, the customers with the least ability-to-pay are still not being served by the market. Would the same situation occur in the minigrid market?

Statement of the Research Question

In many cases, especially sparse, rural areas, minigrids operated by private firms are the lowest cost solution. However, without adequate government regulation, few of these systems will be built and solar home systems will fill the market need. This thesis explores how minigrid developers respond in a market free of regulation, and subsequently, in a market with various forms of government regulation and incentives.

This thesis first attempts to answer questions related to service quality and reliability of minigrid systems. Anecdotal evidence suggests that high reliability is provided to ensure customer satisfaction, but lower reliability would in fact be more profitable. If higher reliability is indeed more expensive, regulation from the government may be necessary to ensure that consumers are receiving adequate service quality.

The second question addressed by this thesis is related to the desirability of various customers as seen through the lens of a private developer. Minigrid customers range from anchor customers such as mobile phone towers, to residential customers requiring only lighting and mobile phone charging. The literature suggest that anchor customers are necessary to the viability of minigrid projects, but does not answer the question of how large these customers need to be, how many are required, and how much benefit they provide.

The thesis recognizes that anchor customers do indeed provide benefits to the minigrid operator, but a customer threshold exists at which the minigrid operator would no longer be willing to connect additional customers, similar to the behavior of the national electricity grids which are not under a universal service obligation. The model and framework attempts to identify the threshold at which a minigrid provider would no longer be incentivized to add customers to the minigrid distribution network.

Literature Review

Brief History of the Electricity Sector in India

Prior to Indian Independence in 1947, 80 percent of generation capacity was privately owned or managed by local authorities in India. Vertically integrated state electricity boards were created in each state after independence, and by 1991, owned approximately 70% of generation. This was a generally successful practice, with electricity growth of 9.2% year over year, faster than the economic growth rate of India.

However, the state electricity boards began to accumulate debts due to low tariff rates for farmers, increasing amounts of theft, and an industrial customer base which was switching to private generation.

Starting in 1991, due to untenable state electricity board debt and a clear shift in consensus on electricity policy, the government began enacting reform. This paralleled the larger economic reforms throughout the country designed to liberalize and open the economy.

The World Bank encouraged India to begin privatizing the electricity industry to encourage private investment. This private investment was meant to help revitalize a failing industry. The State Electricity Boards were generally bankrupt and servicing large amounts of debt, and were generally deemed incapable of building the needed infrastructure. Encouraging private investment was seen as a potential solution to building needed infrastructure, but required political reforms in order to ensure investors that their investments would remain secure and free from politics.

This began with the Electricity Law Amendment Act in 1991, which allowed for Independent Power Producers to own, operate, and maintain generation. A number of fast track generation projects were created, and although the private power producers were generally disgruntled with the bureaucracy of India, private investment did occur [4].

In 1998, the Central Electricity Regulatory Commission was established as well as the state level commissions. Throughout 2000-2002, the Electricity Act of 2003 was introduced and slowly worked through parliament [4]. The federal government passed the Electricity Act of 2003 in an effort to encourage private generation, establish independent regulatory bodies, and revitalize the industry. A departure from the previous policies of India, the reform during the 1990s did not have an explicit consideration of universal access included. The World Bank supported the argument that better fiscal management would lead to improved social benefits. However, the recommended policies did not address the known fact that many in India could not afford electricity at the market rate, and total subsidies would increase if an even larger segment of the population was provided electricity [4].

In an effort to address low electrification rates, the government has implemented a number of programs to expand existing infrastructure. The Deen Dayal Upadhyaya Gram Jyoti Yojana (DDUGJY) scheme aims to improve the existing electricity infrastructure with feeder separation, as well as proving new distribution lines to villages and households. Under this scheme, a village is considered electrified if electricity infrastructure is present and public buildings as well as 10% of households are electrified. The scheme only requires 6-8 hours of power to be provided each day [5]. The Rural Electrification Corporation (REC) is also presently charged with providing loan assistance and capital for generation projects and rural electrification projects [6].

Recently, a number of Solar Home System and Minigrid providers have been operating in India, primarily in the states of Uttar Pradesh and Bihar, were access rates are lowest.

Planning Methodologies and Tools for Rural Electrification

Proper planning and technical assessment tools are required to understand the cost structures of off-grid electrification and the feasibility of certain technology choices. Planning tools can take a variety of forms in the rural energy space, but can be distinctly characterized by their methodology and purpose. A number of literature reviews of the minigrid space have been performed which attempt to categorize the types of minigrid planning tools [7]–[9].

S. Mandelli et al. define a number of categories for minigrid research, although for the purposes of this review, two categories are important: models and methods for simulation and sizing, and techno-economic feasibility analysis [7].

Bhattacharyya does not distinguish between these categories, instead identifying this combination of activity as "methodology" for off-grid projects. The use of the term methodology implies that these research studies are focused on best practices for minigrid projects. He breaks down the methodologies into four categories: indicator-based approaches, optimization techniques, multi-criteria approaches, and systems analysis [8].

Indicator based approaches depend on minimizing a common metric, which could be levelized cost of energy, weighted scoring technique, or sustainability indicators. Among these strategies, levelized cost of energy appears to give the most objective metric for quality of design. However, despite the appearance of objectivity, use of levelized cost of energy can contain certain assumptions and values established somewhat subjectively, such as cost of non-served energy [8].

The most technically complex models used for simulation and sizing seek to optimize a mathematical formulation (typically cost or net present value) subject to technical constraints. Many of these models might be considered combinations of simulation and feasibility analysis according to S Mandelli et al., while they would be identified as optimization techniques according to Bhattacharyya. These models typically minimize cost, but a variety of objectives are possible. Erdinc and Uzunoglu identify a number of algorithms used for hybrid renewable energy systems, citing studies using each method. They evaluate HOMER, Genetic Algorithms, Particle Swarm Optimization, Simulated Annealing, Linear Programming, Evolutionary Algorithm, Neural Networks, Simplex Algorithms, Stochastic approaches, and Design Space based approaches.[9]

Although the number of tools used for minigrid simulation is numerous, it is worthwhile to identify the most popular tools and methods. Sinha and Chandel focus not on minigrid planning processes and techniques, but review specific minigrid software tools. They identify 19 software tools developed for hybrid minigrid system design. The most prevalent tools appear to be HOMER, HYBRID2, RETScreen, iHOGA, and TRNSYS, but of these, HOMER is the most popular due to the number of energy sources included and the ease of use [10]. Erdinc notes that HOMER is widely used in numerous studies, and it is common to find the software used in a variety of literature case studies [9].

HOMER is an interactive visual software tool which optimizes minigrid design for lowest Net Present Cost. The software includes detailed technical models for a variety of generation sources and allows for sensitivity analysis to assist with risk assessment. The software provides some functionality for demand profile creation, although this is done at an aggregated level, not at the individual appliance or end-user level. HOMER does not include any features for network design. The optimization techniques for HOMER are rigid, and not openly published. The HOMER website claims the use of a derivative free optimization technique, likely an iterative direct search method. [11]

Network Planner is a decision support tool developed at Columbia University. The aim of network planner is not to simulate the specific designs and network layouts of minigrids, but to optimize electrification efforts given economic profiles, costs, and the layout of the existing grids. Although this tool is not designed to plan technical details of minigrids, the cost-benefit analysis and decision support in rural electrification is similar to other tools [12].

GEOSIM is a commercially available tool "dedicated to decision support for planning rural electrification aimed at decision-makers and planners." GEOSIM uses geospatial and socioeconomic data to prioritize rural electrification efforts in the most cost-effective manner. GEOSIM has the ability to forecast demand data and select from a number of different electrification technologies, including both grid connection and distributed generation [13].

The Universal Energy Access Group at MIT has developed two models to assist with rural electrification planning. The Reference Electrification Model (REM) is a large-scale planning model which assists in electrification planning efforts over a large region. Using geospatial coordinates for consumers and the characteristics of existing electricity infrastructure, REM selects the appropriate electrification methodology in the considered area: grid extension, minigrid, or solar home system [14].

Stemming from the research efforts in REM, the UA group has developed a second model, the Local Reference Electrification Model (LREM), which serves as a decision support tool for rural minigrid developers. This tool stands out among others due to its breadth of features. LREM provides features for the entire design process including individual consumer demand profiles, generation sizing, and network design. The tool typically employs a hybrid minigrid design consisting of solar PV, battery storage, and diesel generation [15].

LREM utilizes an objective function which seeks to find the lowest available annuity. The optimization algorithm does not use traditional mathematical programming due to the highly non-linear model, instead utilizing a nested, direct-search approach. The master optimization problem varies the minigrid generator design while performing a sub-optimization of PV and battery size [15].

LREM is used extensively throughout this thesis to estimate the cost of providing minigrid service for a number of village types and geographies. To understand the investment decisions of private firms however, the capital investment and ongoing expenses of a minigrid must also be combined with the anticipated revenues from customers and subsidies from the government.

Customer Willingness-to-pay and Expectations of Reliability

The willingness-to-pay of consumers is a crucial component for minigrid developers in the private sector. Equally important is an accurate estimation of expectations regarding reliability and service quality. Fortunately, within India, there have been numerous studies conducted to determine the willingness-to-pay of consumers and their expectations regarding service. These studies generally focus on a specific service, either grid-supplied electricity, minigrids, or solar home systems, but given the similarity in service between minigrids and grid-supplied electricity, review of these studies still provides important insights.

In rural areas where lighting is a primary use of electricity, the trade-offs between kerosene usage and electric lighting are a key component in understanding potential revenue from customers. In a rural survey of 1576 rural residents in Barabanki district of Uttar Pradesh, four-fifths responded that they were unsatisfied with their lighting. Only 11% of participants believed that solar powered lighting would be more difficult to use than kerosene. 65% of respondents were willing to pay INR

50 per week for two lights and mobile phone charging. 45% were in favor of solar power, 30% favored grid electrification, and 25% considered both approaches [16].

In the Unnao district of Uttar Pradesh, surveys found mean willingness-to-pay for a 40 Watt Solar Home System with mobile phone charging and 3-4 lights was 4209.3 INR ($67 USD). The mean willingness-to-pay for a monthly lease of a similar system was 152.3 INR ($2.43 USD) [17].

In a more recent survey focusing exclusively on solar lanterns with mobile phone charging, willingness-to-pay was on average 134 INR for a single lamp. However, the researchers found that learning has a powerful effect on willingness-to-pay for simple household technologies, and those who received the treatment through a passive network were willing to pay INR 120 more, and those who witnessed a demonstration from peers on the benefits of the solar lantern were willing to pay INR 195 more [18]. This hints that if village has few early adopters at a high price, as residents witness the benefits of a particular service, their willingness-to-pay may increase.

When surveying usage among Mera Gao Power customers (fees of INR 100 per month), users were generally happy with the service, but were unwilling to accept increased charges. When asked about additional services, 56% said they would not pay for a fan, 82% said they would not pay extra for a TV [19].

Although many of these studies focus on products and basic lighting services, they do not address the customer perceptions on reliability and quality of service.

Surveys of households in rural Madhya Pradesh found that for a bill of 200 INR / month, 75% of high income households would be willing to accept improved service. However, only 45% of poor households would be willing to pay 200 INR / month, even with improvements in service. [20].

Sagebiel and Rommel find that in the city of Hyperbad, residents are generally unwilling to pay for improvements in quality of service and additional use of renewable energy. This highlights that although quality of service may be important to some customers, there may be diminishing returns given that the residents of Hyperbad are unwilling to provide the additional revenue necessary for improvements. [21]

Surveys in urban areas concerning electricity expenditure found that the percent of monthly income spent on electricity is 6.5% for legally connected households and 3.5% for illegally connected households. Average monthly expenditure range from 290 to 610 Rs for illegal and legal connections, with mean consumption between 70 to 80 kWh / month. [22]

One final point of concern regarding the willingness-to-pay for electricity service is customer perception of government provided services and privately operated enterprises. Given that most minigrids and distributed generation technologies would be privately operated, either through profit-making companies or NGOs, customer perception will have an impact on viability.

Aklin finds residents are willing to support reform of the electricity sector when presented the benefits or reform. However, they did not find that residents support privatization of the industry, regardless of the benefits of privatization [23]. Urpelainen has similar findings in a survey of rural residents. Of those surveyed, 65% were in favor of government leadership for electricity supply, while only 26% preferred private companies [16]. Although these studies do not provide quantifiable inputs for a techno-economic model such as LREM, they provide import insights when considering the model formation and policy implications.

Methodology

The Private Investment Framework for Minigrid Design

Successful electrification is dependent on the active participation of all stakeholders, including the government, electricity service provider, investors, and most importantly, the consumers.

Although it is possible to examine the minigrid project from the lens of the government, consumers, or even national utility, the research questions laid out by this thesis concern the behavior of private firms in the minigrid industry. The appropriate viewpoint for answering these questions is from the perspective of the private firm, which requires a specific framework and methodology when evaluating investment and design decisions.

Valuation of Minigrid Projects

Investment decisions typically have three elements as laid out by Asquith and Weiss: The Strategy Element, the Valuation Analysis, and the Execution [24]. In examining the role of private firms in building minigrid projects, this thesis focuses on the second of the three elements, the Valuation Analysis.

A number of options exist for performing valuation analysis, ranging from discounted cash flows, adjustment present values, multiples, or comparable. For the purposes of valuing minigrid projects, this model uses a discounted free cash flow analysis. This thesis follows the Net Present Value Rule: if the project has a positive net present value (NPV), the firm will undertake the project [25].

Present Value Based on Free Cash Flow

Private investors have incentive to maximize returns, and thus seek projects with positive net present value. In encouraging private investment in the minigrid market, these individuals seek to provide assets which provide electricity service, but in exchange, seek a return on these investments. Returns on investment can take many forms, but for the minigrid project, revenue from electricity sales is the primary source of cash flow. If the investor believes they will receive sufficient revenue from the investment, the minigrid project may be considered feasible.

Brealey, Myers, and Allen list a four-step procedure for Capital Investment: Forecast after-tax cash flows, assess the project risk, estimate the opportunity cost of capital, then calculate the Net Present Value [25]. The discussion below first centers on the assessment of risk and the opportunity cost of capital before moving on to the methods for estimating the after-tax cash flows.

Valuation Methods

Assessment of Risk

Throughout the literature on minigrids and investments, there is ample discussion of project risk and expected return. Discerning between the two is not only a difficult problem, but in reality, impossible. Modern Finance theory teaches that the rate of return demanded by an investor is directly linked to the risk. Common examples are U.S. Treasuries, which are typically considered zero risk, and often have the lowest expected rates of return. Alternative examples include common stocks with high betas, which demand a higher rate of return than the prevailing market portfolio.

In typical infrastructure projects such as a rural minigrids, financing is often provided through a combination of debt and equity. Debt for these projects typically receives a lower interest rate due to the seniority of the debt-holders in the case of financial distress.

With multiple types of debt and equity on the balance sheet, a method is required to select a single rate of return at which to discount future cash flows and value a potential minigrid project. The Weighted Average Cost of Capital approach attempts to overcome this difficulty by providing a method to estimate an appropriate interest rate as a combination of equity and debt.

Weighted Average Cost of Capital

The most common approach to finding the appropriate discount rate for a project is through the Weighted Average Cost of Capital (WACC). The WACC formula (Eq. 1) is a weighted average of the interest rate for equity and debt, each being weighted in proportion to the amount of investment in the project. The interest rate for debt is typically discounted further due to the tax shield provided by debt [25].

$$\text{Eq. 1} \quad \text{WACC}=r_D(1-T_C)\frac{D}{V}+r_E\frac{E}{V}$$

Determination of the appropriate discount rates for debt and equity is dependent on the risk of the project and is discussed further in the section on interest rates and perceived risk.

Adjusted Present Value

The weighted average cost of capital approach is often used for valuing projects within firms that have relatively constant debt and equity ratios. The WACC methodology assumes that the leverage ratio of the firm will remain constant over the life of the projects.

With infrastructure projects such as minigrids, the leverage ratio of the project may be changing significantly over time, especially if early cash flows are used to pay down significant amounts of debt. In these scenarios, it is more appropriate to use the Adjusted Present Value (APV) method [26].

The Adjusted Present Value Method determines the value of the project as the sum of the unlevered project value combined with the value of the interest tax shield. Any cost of financial distress can then be subtracted from the total project value if necessary. This approach lends itself to project financing due to the ease at which various levels of debt and changing capital structure can be incorporated into the valuation.

$$\text{Eq. 2} \quad V_L=APV=V^U+PV(Interest\ Tax\ Shield)-PV(Financial\ Distress)$$

Although the Adjusted Present Value method presents some advantages over the WACC method, due to the popularity of use, the WACC method will be used for minigrid valuations in the case studies.

International Risk, Capital Structure, and Interest Rates

Minigrid projects in emerging economies often have some degree of international investment. Foreign-own firms may see the minigrid industry as an emerging market with growth potential. Impact investors may desire to contribute equity to socially impactful projects. In many cases, the World Bank may provide credit guarantees to the project in order to mitigate risk.

In the case of these cross-boundary investments, the debt and equity holders often perceive an increased risk due to currency exchange, political risk, and regulatory risk. Although these risks can be mitigated through various financial products and portfolio diversification, others must be appropriately assessed.

Selecting the Appropriate Discount Rate for Equity

For minigrid projects, assessing the risk becomes increasingly difficult due to revenue generation in a local currency but possible debt payments due in a foreign currency. This can be further complicated by the political risk associated with international investments.

If the minigrid project has domestic financing with revenue generation in domestic currency, the interest rates should be based on the local risk free rate, with a market premium appropriate for the local economy. This can be done with the Capital Asset Pricing Model (CAPM) shown in Eq. 3

Eq. 3 $$r_e = r_f + \beta \cdot (r_m - r_f)$$

In the case of a foreign investor, currency can be hedged using a swap or forward, although in many cases this becomes nearly impossible in developing economies. The foreign investor must also determine the appropriate risk-free rate, project beta, and market premium.

Brealey et. al suggest that the beta for the project be determined based on the returns of the local market compared to the returns on the home market. The home market risk free rate should be used as the risk-free rate, and the home market premium used as the market premium. [25] The home market required return can then be converted to the foreign market required return using the risk-free interest rates of the two countries, which should be linked to the inflation rates of the two countries.

This approach should give relatively modest discount rates for minigrid projects, specifically if the investor views these projects similar to energy distribution companies. For reference, companies such as Southern Company, Duke Energy, and American Electric Power have betas between -0.03 and 0.02 (As of August 2018). Even with conversion due to relatively high inflation rates in the foreign markets, the required returns should remain modest. However, if investors view minigrids firms similar to firms distributing Solar Home Systems, which could be considered riskier technology companies, the beta would be much higher.

Assessing Country Risk

Although regulatory risk is often cited as a barrier to the development of minigrid firms, the financial models tend to imply that this risk could be diversified. If investors view regulatory risk as a country risk which requires a premium on the discount rate, investors may not be appropriately diversifying their portfolios. Sabal states, "Nevertheless, there are a number of reasons to believe that adding some kind of country risk premium to the CAPM is not the best way to account for country (i.e., political) risk." He goes on to argue that country risk is often viewed as systematic risk, but in many cases, it can be diversified, which happens naturally in a diversified portfolio of publically traded stocks [27].

Sabal suggests that the Ross Arbitrage Pricing Model may be well-suited to international investments, but acknowledges that it may be difficult to identify all the appropriate factors for the international market [27]. A Local CAPM could also be applied to the country of interest, similar to the recommendation of [25], but this would only apply to investors who are diversified in the country of interest. Additionally, it may be difficult to compute the appropriate betas if the markets are illiquid [27].

Alternative approaches for calculating the appropriate discount rate are proposed by Lessard, who recommends adjusting the offshore project beta by multiplying the home market industry by a country beta for the associated project [28].

The Godfrey and Espinosa model is a CAPM based model, but adds an additional term for country risk [29]. Sabal argues that proper diversification should allow the investor to completely eliminate the necessity for an additional risk premium [27].

Alternative Methods to Mitigating Country Risk

Brealey, Myers, and Allen recommend the involvement of international banks when the perceived risk from foreign governments is high. Capital can be borrowed from the international banks with guarantees written on the loan requiring the foreign government to honor the agreements or regulation. In the instance that the foreign government does not honor the agreements, the government must assume the loan and potentially harm their reputation with the international banks. In many cases, having an institution such as the World Bank provide the loan is powerful due to the reluctance of the government to impact their reputation with such a large institution [25].

The Effect of Discount Rates on Minigrid Projects

Selection of the appropriate discount rate for minigrid projects could be the topic of an entire thesis, but the short review of the literature on both minigrids and international investment reveals an important insight. The minigrid industry perceives high interest rates and risk as a barrier to project development, but applied finance theory suggests than many of these risks are diversifiable, and interest rates may be overpriced.

For the purposes of this thesis, the Nigerian Minigrid Case Study will be used as a template for exploring questions related to discount rate. Examining the project with a range of discount rates will illuminate the effect of financing cost on the minigrid industry and the potential benefit of lower discount rates for these projects.

Maximization of the Project Net Present Value

Understanding Firm Behavior

In order to understand how minigrid firms respond to various market and regulatory conditions, we model the minigrid firm as a profit-seeking firm attempting to maximize shareholder value. This approach leads to vastly different outcomes than a minigrid company which seeks to maximize social impact or a government entity which may have a universal service obligation.

The view of the profit maximizing firm is chosen due to the inherent desire to identify minigrid projects which can encourage private investment. The IEA new policies scenario estimates that $110 billion will be invested in minigrids over the next ten years [1]. If a portion of this investment will occur through international capital, investors will demand reasonable rates of return. This results in a firm which will make management decisions to protect investments of both debt-holders and equity-holders while maximizing the returns for equity-holders.

This thesis focuses on only a few management decisions available to the minigrid firm: System design, customer selection, and reliability. Each of these decisions will be modeled through the lens of a manager seeking to maximize shareholder value for the equity-holders.

Customer Selection

In expanding services in rural areas, minigrid operators spend a considerable resouces on site selection [30]. A significant component for site selection is based on customer demand for electricity service and the expected revenues for the minigrid. Li identified over 10 different customer types for a single minigrid, ranging from residential households, health centers, and banks

[15]. Recent work by the Universal Access Group at MIT has commonly modeled minigrids with up to 28 customer types.

Through targeting villages with specific mixes of customers, minigrid operators can not only diversify their revenue stream, but potentially increase the profitability of projects through the proper selection of customers. Additionally, within a single village, minigrid operators may choose to connect certain profitable customers, but bypass other customers with low ability to pay or low service levels. This would mimic the current ad-hoc diesel minigrids that are active in many parts of rural sub-Saharan African and India.

Realistic modeling of minigrid firm behavior will incorporate this active decision making process in the customer connection policy of the firm. Adequate policy in the minigrid realm must address issues that might arise when a private firm decides not to connect a certain customer group.

Reliability

Throughout many emerging economies, unreliable electricity not only promotes substantial usage of diesel generation as back-up power, but encourages distrust between the customer and the energy supplier. In India, almost all utilities are seen as mismanaged and corrupt [31]. Nigeria faces similar problems, with 60 million Nigerians owning back-up diesel generation due to unreliable electricity supply [32].

In determining the appropriate level of reliability for minigrid systems, firms must weigh the benefits of reliability against the increase in cost. This analysis become especially difficult as increases in reliability typically correspond to higher willingness to pay from consumers [33]. At some point, the increased cost for improved reliability will not be offset by the increased customer willingness-to-pay, and the firm will have little incentive to improve reliability beyond this point. The cut-off for reliability is often set based on past experience for operators in the field, but has not been explored in detail.

Option to Abandon Project

Minigrid operators often cite weak regulation and unclear planning as a major risk for minigrid investment [34]–[36]. Unclear planning exacerbates a key concern for minigrid developers that the main grid will expand into the operational area of the minigrid [30].

With uncertain revenue streams that may be disrupted by new regulation or grid expansion, investment is often deferred. However, even with deployment of a minigrid in a particular site, managers still retain the option to abandon the project if revenue streams drop below a sustainable level. Abandonment may involve stranding the asset, or salvaging the generation equipment and assets for use at another site.

In properly addressing the value of a minigrid investment, developers must account for some probability that the central grid will arrive and revenue will decrease significantly. This can have considerable effects on design, motivating developers to choose technologies such as diesel, which have low investment cost / high operational cost, over other technologies which have high investment cost / low operational cost. Analyzing the effect of this uncertainty on system design and investment decision is not thoroughly discussed in the case studies below, but the abandonment option has real value which should be explored in future research. The value of this option, which may be exercised at any point during the life of the project, is significant and should be incorporated into any project valuation and investment decision.

Maximizing Firm Value through Optimization

The decision to maximize minigrid firm value is modeled as an optimization problem with free parameters of customer selection and reliability level. The model assumes the minigrid firm operates in a relatively competitive market. Consumers in this market have numerous options for energy service, ranging from kerosene lanterns, solar home systems, solar appliances, and diesel generators. This gives the firm the ability to decide how much energy is sold, but not the price consumers are willing to pay for this energy.

A common definition for the profit maximization function is given below as Eq. 1 [37], where TR represents Total Revenue and TC represents Total Cost

$$\text{Eq. 4} \quad \pi = TR - TC$$

This profit maximization function is often reformulated to be dependent on quantity, with a specific value, $q*$, which presents the units of output where profit is maximized. In the general case, the profits are maximized when the price equals the marginal cost of production [37].

$$\text{Eq. 5} \quad \pi(q) = pq - c(q)$$

Problem Statement

Eq. 4 can be modified to include the Net Present Value of the firm, broken into components of cost and revenue:

$$\text{Eq. 6} \quad NPV_{firm} = NPV_{Revenue} - NPV_{Cost}$$

This profit maximization function is then reformulated as the objective function for the optimization problem with the assumption that firms will choose to maximize firm value when given a range of investment decisions.

Objective Function

The objective function defining the minigrid firm behavior is formulated as Eq. 7.

$$\text{Eq. 7} \quad \min\ -NPV_{firm} = NPV_{Cost} - NPV_{Revenue}$$

$$s.t.$$

$$70\% < Reliability < 99\%$$

$$0 < Customer\ Score < 100$$

NPV_{Cost} is a function of the minigrid design, customer selection, reliability, generation assets, and a number of other local factors that contribute to system cost. Given the numerous design variables available for meeting customer demand, this cost calculation is the result of a sub-optimization which determines the least-cost design given a required customer load, equipment cost, and local constraints.

This sub-optimization problem is explored in detail in the work of Li and Ellman [14], [15].

$$\text{Eq. 8} \quad \min NPV_{Cost} = f(Reliability, Customer\ Score)$$

$$s.t.$$

$$Relibility = x$$

$$Customer\ Score = y$$

In the sub-optimization, the reliability of the minigrid is a continuous variable which can be adjusted to change the quality of service for customers. Similarly, as the reliability is increased (or decreased), the overall system cost increases (or decreases).

Customer selection is incorporated into the model through the use of Customer Score Variable. In the available market for customers, the minigrid operator could theoretically provide service to every customer in a reasonable area. At some point, the marginal cost of an additional customer exceeds the marginal revenue of this customer. This model assumes that the shrewd operator would then choose not the connect these customers to the system.

The Customer Score variable in Eq. 7 and Eq. 8 dictates the threshold at which no additional customers are added to the minigrid. The model uses this variable to subselect the pool of customers available when optimizing the minigrid system design.

The customer score variable is conditioned to range from 0 to 100, and all customers are ranked based on a heuristic to define their "profitability". Each customer is assigned a rank from 1 to n. Customer 1 is deemed the least desirable and customer n is deemed the most desirable.

Customer rank is then normalized from 0 to 1 such that the variable Customer Score creates a threshold cutoff, which represents the percentile of customer. If Customer Score is set at 85, then only the top 15% of customers will be selected for the minigrid. If Customer Score is set at 10, the top 90% of customers will be selected for the minigrid.

The Customer Score is computed as an aggregation of the energy demand for the customers and the network cost for delivering the energy. This approach assumes that customers with higher levels of demand are more desirable due to the higher utilization of fixed assets. However, this must be balanced by geography; customers farther from the center of the minigrid require a higher network connection cost.

To account for the various geographic distributions and energy demand characteristics, the customer score for both generation and network cost is normalized between zero and one. The two score are then aggregated into a single customer score.

$$\text{Eq. 9} \quad Customer\ Score = 0.8 \cdot Demand_{Normalized} + 0.2 \cdot Network\ Cost_{Normalized}$$

Evaluating the Validity of the Customer Score Metric

The customer score metric is formulated with inherent bias towards high demand customers by weighting demand with a unitless factor of 0.8. Improvements to this scoring methodology might include metrics such as willingness-to-pay, or customer demand load shape, etc.

Evaluation of the effectiveness of this score can be judged based on the marginal cost curve of the minigrid as well as the profitability curve of the minigrid. In general, maximizing firm value assumes that the minigrid firm will pursue the most profitable customers first and then continue adding customers until the marginal cost of a consumer exceeds the marginal revenue. If the customer score has been properly formulated, the plot of net present value with respect to the addition of customers should have a decreasing slope (i.e. each additional customer adds less value than the previous customer). The weights of 0.8 and 0.2 have been chosen to create these characteristics. The effectiveness of the score will be discussed when evaluating the case studies.

Net Present Value of Revenue

The Net Present Value of the Revenue is based on the customers served by the minigrid (determined through Customer Score) and the reliability of service received by these customers. Customers are only billed for demand which is delivered, and thus as the reliability of the system increases, the total number of kilowatt-hours billed also increases. In the below equation, the $NPV_{Revenue}$ is the sum of revenue for each customer x and then summed for the entire pool of potential customers, n.

Eq. 10 $NPV_{Revenue} = \sum_{n=1}^{n} f_x(Reliability, Customer\ Score)$

$$f_x = \begin{cases} Annual\ Demand_x \cdot Reliability \cdot WTP_x, & Cust\ Score > Cust\ Score \\ 0, & otherwise \end{cases}$$

Optimization Technique

Sub-optimization

The NPV_{Cost} is modified through customer selection and reliability levels but involves a complex sub-optimization to determine the least-cost system for the given criteria.

Eq. 11 $\min NPV_{Cost} = f(Reliability, Customer\ Score, System\ Design)$

The sub-optimization for NPV_{Cost} simplifies to Eq. 12 shown below due to the fact that Net Present Value can be transformed to Annuity through a linear transformation.

Eq. 12 $\min NPV_{Cost} \rightarrow \min Annual\ Cost$

$$\min Annual\ Cost = Annuity(Investment) + \ O\&M + Fuel\ Cost$$

$$s.t.$$

$$Reliability_x < \frac{Demand\ Served}{Annual\ Demand_y}$$

The above problem formulation for cost minimization essentially states that the system investment and operational cost should be minimized, but subject to a certain level of reliability. Given that additional reliability will always incur additional cost, it is reasonable to conclude that the reliability constraint will always be binding for the cost sub-optimization.

Each variable above is typically a calculation based on the system design and the generation dispatch of the resulting system design.

Eq. 13 $Annuity(Investment) = \frac{Investment \cdot r_{WACC}}{1-(1+r_{WACC})^{-t}}$

Eq. 14 $O\&M = Cost_{Fuel} + Cost_{Replacement} + Cost_{Maintenance} + Cost_{SG\&A}$

Eq. 15 $Demand\ Served = f_{Dispatch}(System\ Design, Demand,\ Solar_{Resource})$

System Design is actually a combination of the Solar PV Size, Battery Size, Diesel Generation Size, and Dispatch Algorithm. In implementation, this is an array of variables passed to the dispatch algorithm

Eq. 16 $System\ Design = [Size_{PV},\ Size_{Battery},\ Size_{Genset}, Dispatch\ Strategy\ ]$

The cost of fuel, the replacement cost, and the O&M cost are all functions of the dispatch simulation:

Eq. 17 $Cost_{Fuel} = f_{Dispatch}(System\ Design, Demand,\ Solar_{Resource})$

Eq. 18 $Cost_{Replacement} = f_{Dispatch}(System\ Design, Demand,\ Solar_{Resource})$

Eq. 19 $Cost_{Maintenance} = f_{Dispatch}(System\ Design, Demand,\ Solar_{Resource})$

The Sales, General, and Administrative Cost are simply a function of the number of customers

Eq. 20 $Cost_{SG\&A} = \sum_{n=1}^{n} f_{SG\&A}(Customer\ Score_n)$

$$f_{SG\&A} = \begin{cases} Per\ Customer\ SGA, & Cust\ Score > Cust\ Score \\ 0, & otherwise \end{cases}$$

Through substitution, the NPV_{Cost} sub-optimization can be reformulated as follows:

Eq. 21 $\min Annual\ Cost = f(Reliability, Customer\ Score, Size_{PV},\ Size_{Battery},\ Size_{Genset})$

$$s.t.$$

$$Customer\ Score = Customer\ Score_x$$

$$Reliability_x < \frac{Demand\ Served}{Annual\ Demand_y}$$

$$Size_{PV} \geq 0$$

$$Size_{Battery} \geq 0$$

$$Size_{Genset} \geq 0$$

Optimization Algorithm

Discovery of the global minimum for the cost-minimization problem can be difficult due to local minimum which exist throughout the design space. Rather than use a generalized reduced gradient method to step in the direction of the minima or a linear programming approach, LREM utilizes an iterative method to explore the design space.

In order to fully explore the design space, LREM uses a nested hierarchical structure to explore each layer of design variables. The upper layer search uses fixed generator sizing as a design variable, with floating variables for the PV and battery sizing.

The lower layer optimization problem finds the optimum PV and battery sizing, assuming a fixed generation size (as set by the upper layer search). The optimal PV and battery sizing is then passed back to the upper level optimization for generator sizing [15].

The process is described below in Figure 1.

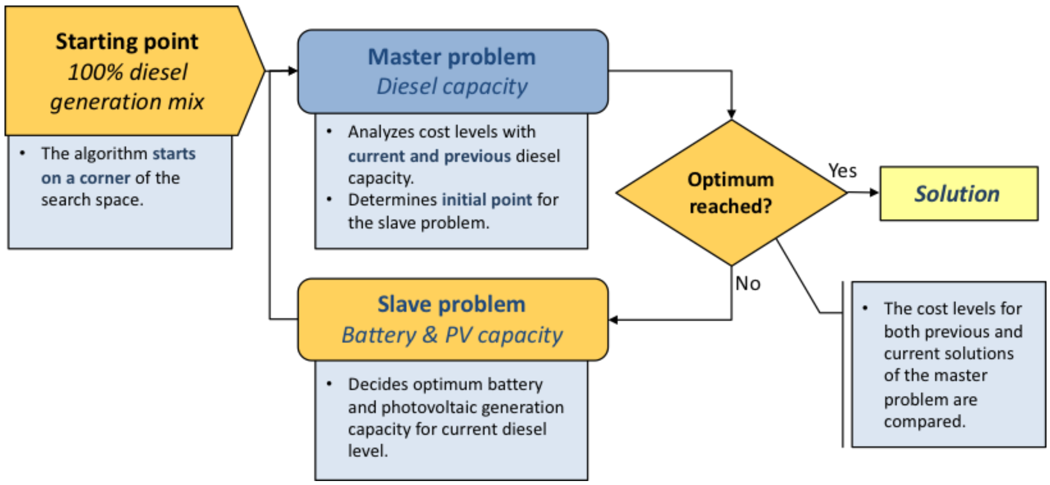

Figure 1. Optimization Structure of Local REM (Source: Cuadra, 2018)

Shortcomings of the Existing Optimization Problem

The optimization structure presented in Figure 1 describes only the sub-optimization to minimize cost for the minigrid. The highest-level optimization attempts to maximize firm value and feeds the customer demand parameters to the sub-optimization described in Figure 1. This technique is adequate for an iterative search of the design space, but limits the operational methods of the minigrid.

An obvious shortcoming is illuminated when considering the day-to-day operation of the diesel generator. The utilized dispatch technique of "load following" dispatches all generation resources to meet the load whenever possible. In the case of the diesel generator, the control algorithm would dispatch the diesel generator during inefficient operational periods simply to meet demand. This may actually reduce the profitability of the minigrid, but information related to pricing and cost is not incorporated into the day-to-day dispatch. Some design improvements and operational efficiencies may be gained if the optimization was formulated into a single objective function without the nested cost minimization and sub-nested dispatch simulation.

Temporal Aspects:

At the lowest layer of optimization, the Load Following dispatch simulation assumes a given minigrid generation system and simulates a full year of operation. This dispatch algorithm is uniform throughout the year regardless of solar insolation, weather conditions, or demand. A single dispatch algorithm may simplify operation of the minigrid, but may sacrifice performance during certain periods of the year. For instance, during the rainy season, a cycle charging strategy may be more suitable, but during the dry season, a load following strategy may be optimal.

At the middle optimization layer for cost minimization, the selected minimum cost design assumes demand is static from year-to-year. With some increase in demand assumed over the first few years of operation, this demand assumption will typically result in systems which are overdesigned for the first few years of operation.

From an engineering perspective, over-estimation of demand provides a margin of safety, but does increase cost. Because battery and diesel replacement must take place every 3-7 years, an iterative design process may provide significant cost savings. An optimization which accounts for year-to-year fluctuations in demand may produce system designs in year 1 and 2 which are significantly different from the system design required in year 20.

Discount Rates for Optimization: Real and Nominal Rates

When selecting the discount rate for the optimization, aside from the importance of selecting a rate which properly incorporates the investor perception of risk, the rate must properly correspond to the incoming and outgoing cash flow of the project. The annuity calculation shown in Eq. 13 assumes that the cost incurred every few years year for battery, ICE, or PV replacement does not increase. In reality, inflation is a significant factor which causes the prices of fuel, operation, and capital expenditures to increase each year.

For the purposes of optimization, the nominal discount rate provided by the CAPM and WACC must be converted to a real discount rate. This complicates the calculation of non-annual annuities, which must properly incorporate the growth rates due to inflation. An accurate calculation of the real discount rate for annuities is shown in Eq. 22. Although this calculation will not hold for periodic investment occurring at 3 years, 5 years, or 25 years, it will be suitable for the purpose of optimization.

Eq. 22 $$(1 + r_{nominal}) = (1 + r_{real}) \cdot (1 + r_{inflation})$$

$$r_{real} = \frac{(1 + r_{nominal})}{(1 + r_{inflation})} - 1$$

Annuity Minimization vs Net Present Value Minimization

The optimization structure which maximizes the net present value as an annuity is appropriate for a project which extends indefinitely, but many minigrid projects anticipate incorporation into the national grid at a later date.

There is some difference in project valuation if the minigrid project is assumed to terminate after 25 years or continue indefinitely. However, any cash flows in year 20 or beyond are so heavily discounted that they cannot be assumed to create any significant changes in cost for the purposes of optimization. However, if the minigrid operator only plans to operate a minigrid for 10 years, the difference in design between a 10-year project and an indefinite project could be significant.

Case Studies For Minigrid Firm Behavior

Purpose of Case Studies

These case studies of three minigrid markets attempt to anticipate how investors may design and implement minigrid projects. The use of the optimization structure described previously allows for exploration of issues related to reliability and customer selection.

Throughout these case studies, the sensitivity of project valuation to parameters such as renewable energy standards and discount rate will be evaluated.

The three case studies examine minigrid project in Northern Nigeria, Rwanda, and Bihar, India.

Renewable Energy Requirements for Case Studies

For each of the case studies presented below, the generation design is constrained to maintain 60% renewable energy. This choice of constraint derives from government preferences to support renewable energy such as solar photovoltaics but still allows for some diesel generation.

This constraint results in interesting designs in which the diesel generator is not fully utilized throughout the year. With the Load Following algorithm selected for these case studies, the diesel generator is typically only used during evening hours when the battery capacity reaches the minimum allowable state of charge. However, due to the minimum renewable energy threshold, excess diesel capacity is typically available, resulting in minigrid designs which always maintain high levels of reliability.

Nigeria Minigrid Case Study:

Introduction

The urban electrification rate of Nigeria is 86%, but the rural electrification rate is 28% [1]. To address the low electrification rates in Nigeria, the Rural Electrification Agency plans to develop 10,000 minigrids throughout Nigeria by 2023 [38].

The Universal Access Group at MIT is currently working with the Rural Electrification Agency of the Government of Nigeria in order to assess the viability and cost of these systems in rural Nigeria. An accurate assessment of the behavior of these firms is crucial to understanding the effective design of policy for these systems.

Village Demand Characteristics

The Nigerian Village used in this case study is a mix of industrial, commercial, and residential customers. Table 1 below describes the characteristics of each customer type.

Table 1. Description of Customer Types in the Nigerian Village Case Study

Customer Type	Number of Customers	Peak Demand (kW)	Annual kWh	Villiage Peak Demand (kW)	Village Annual kWh
Small Household	764	0.09	275	67.92	209,901
School	1	1.83	4,439	1.83	4,439
Health Center	1	4.87	15,949	4.87	15,949
Religious Center	1	0.91	996	0.91	996
Grinder	1	9.00	36,573	9.00	36,573
Petty Trader	12	0.07	475	0.86	5,699
Phone Service	1	0.50	1,304	0.50	1,304
Restaurant	1	0.55	3,431	0.55	3,431
Tailor	1	0.10	241	0.10	241
Total	783	17.92	63,684	86.54	278,534

Each Small Household will consume electricity for lighting, phone charging, and powering small appliances such as televisions and fans. As shown in the subsequent case studies for both Rwanda and Bihar, the Nigerian households have much higher consumption patterns than those in the other case studies.

The geographic layout of the village is shown in Figure 2. The village is approximately 1 km in diameter and contains a number of smaller clusters. The larger village loads such as the Grinder, School, and Health Center are not located in the center of the village, but are dispersed throughout the middle fringes.

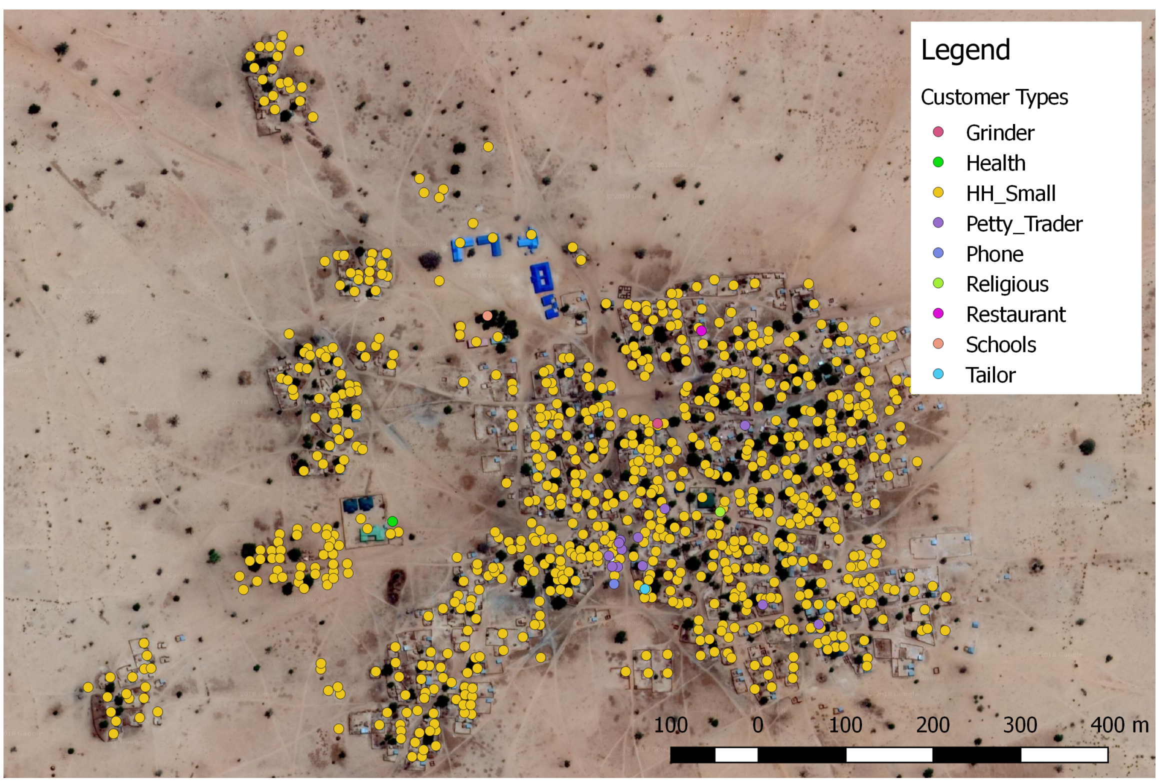

Figure 2. Nigerian Village Geographic Customer Layout

Village Ability to Pay

The Government of Nigeria Rural Electrification Agency reports that consumers in Nigeria typically pay approximately \$0.40 / kWh for diesel generation. This model assumes this is the upper limit for larger commercial and industrial consumers given the alternative of diesel generation. The ability to pay of rural households may be above \$0.40 / kWh for very low levels of consumption. However, at the levels of consumption shown in Table 1, \$0.40 / kWh corresponds to approximately \$9 per month. The initial tariff for the profit maximization model throughout the village in a free-market scenario is set at \$0.40 / kWh.

Results of Full Design Space Simulation

The profit maximization model is first executed for all combinations of customer score and reliability. Using Net Present Value as the objective function, the results of each design combination are shown below in the Figure 3 heat map.

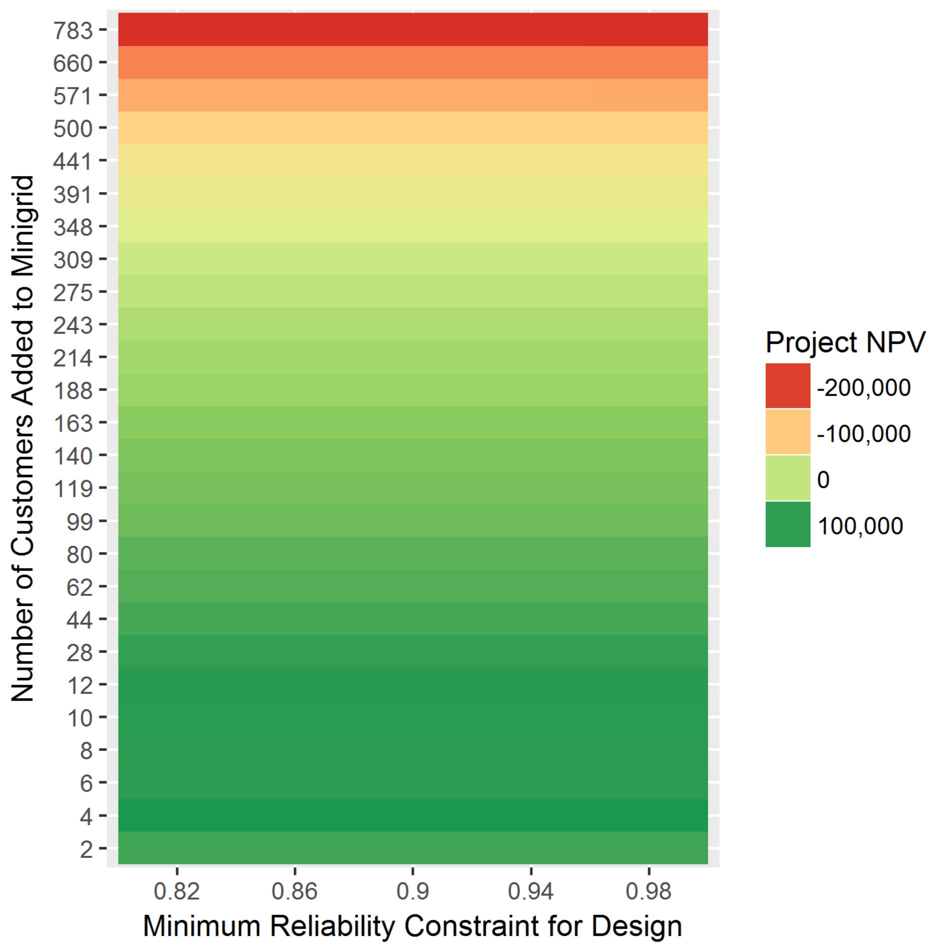

Figure 3. Selection of the Four Largest Customers and A Reliability Level of 98% Maximizes the Minigrid Firm Project Value

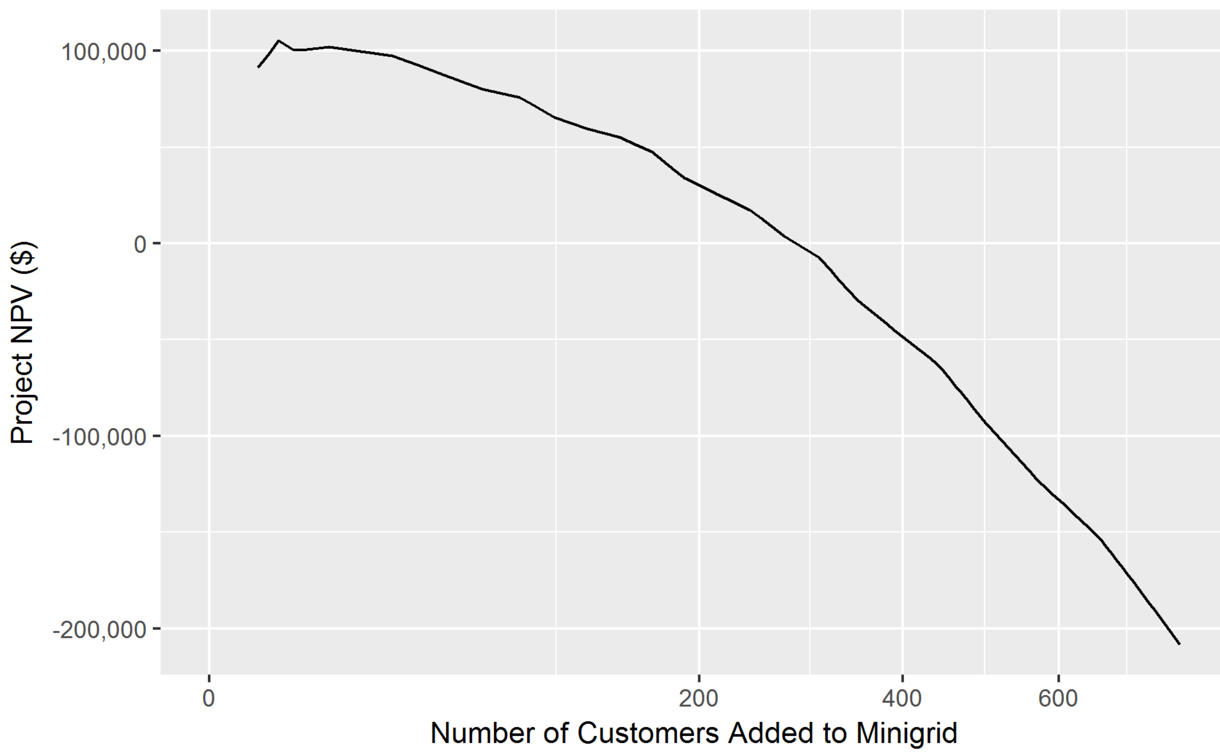

Figure 4. The NPV of the Nigerian Minigrid Project as Customers are Added to the Minigrid

As seen in Figure 3, the most profitable customer selection includes the four largest commercial and industrial customers, but none of the petty traders or households. These results clearly indicate that regardless of the reliability constraint, the minigrid profitability is unchanged. Closer inspection of each case study indicates that due to the renewable energy constraint, excess diesel capacity is always available. The incremental cost of diesel generation is less than the tariff rate applied to these customers, and thus the operator is incentivized to run the diesel generator and supply as much power as possible.

The specific factors contributing to the disincentive to add additional customers to the minigrid are discussed in the section on customer marginal cost.

These design exploration plots indicate that due to the sunk cost of distribution network, generation assets, and SG&A, the marginal cost of providing improved reliability is less than the marginal revenue from the additional sale of kilowatt-hours.

Results of the Profit Maximizing Minigrid Design

The simulation results and network design of the profit maximizing solutions are shown below in Figure 5. The value of the minigrid firm is maximized by serving only the four largest customers.

A more detailed financial analysis is performed by inserting the cost and revenue data into a detailed pro-forma income statement which accounts for interest payments, inflation, working capital, and depreciation. The results of this analysis are shown below in Table 2. The income statements and cash flows associated with these designs can be found in Appendix A.

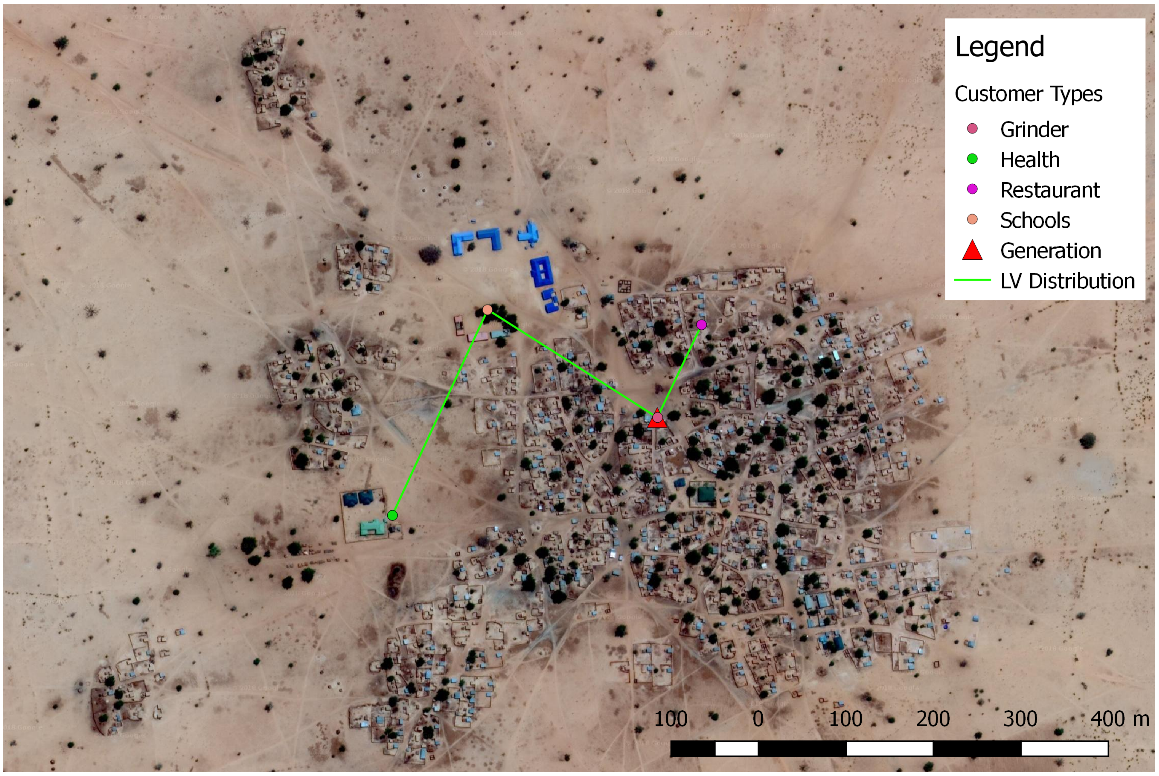

Figure 5. Network Layout of Profit Maximization Design

Results of the Universal Service Design

Figure 6 contains the minigrid design which incorporates all customers located in the village. Figure 7 plots one week of generation dispatch for this minigrid during July. As seen in Table 2, this universal service design has a much higher annual revenue of \$111,000, but due to the high investment and operational cost, the net present value of the project is negative. Examining the marginal cost of the residential customers as shown in Figure 9 indicates that the combined generation and network cost exceeds the \$0.40 / kWh willingness to pay of rural consumers. If the willingness to pay of residential consumers was higher than the marginal cost of \$0.55 / kWh, expansion of the minigrid to these customers would be an attractive proposition for the minigrid operator.

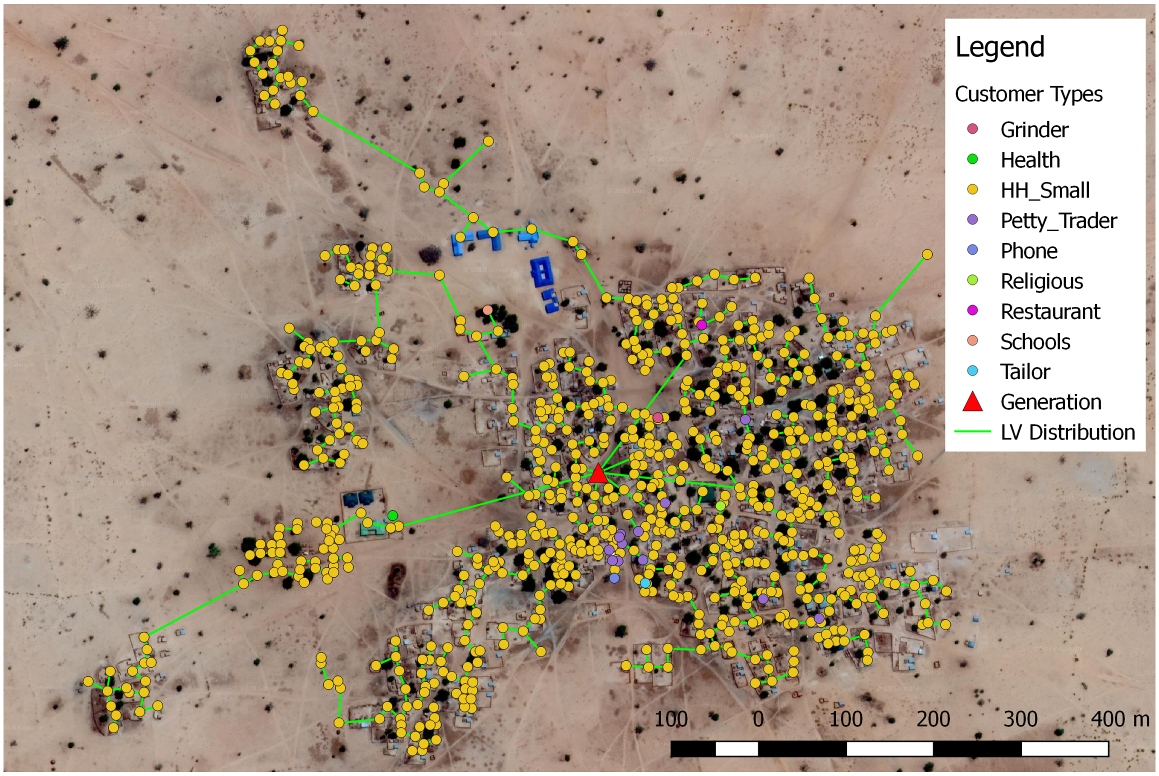

Figure 6. Network Layout of Universal Service Design

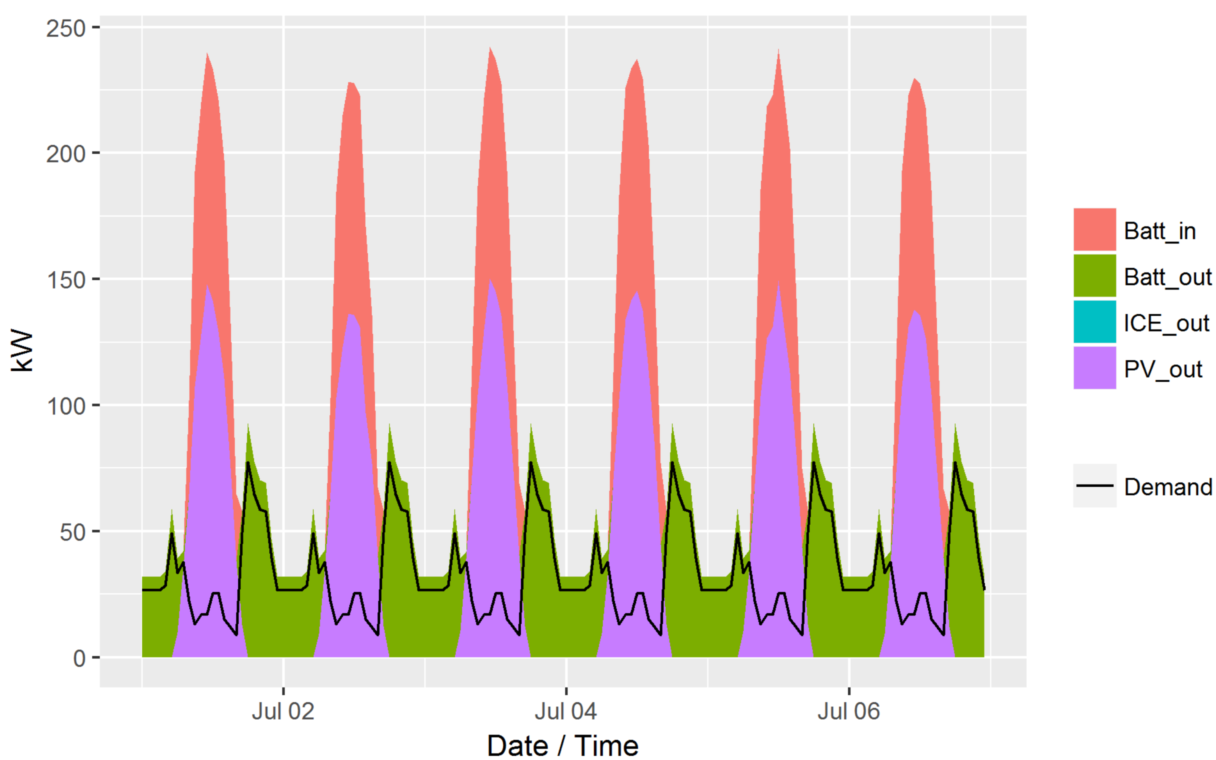

Figure 7. Generation Profile of Nigerian Village Universal Service Design

Table 2. Financial and Design Information for Nigerian Minigrid Case Study

	Profit Maximization	Universal Service - Market Tariff	Universal Service - Breakeven Tariff	Universal Service - Gov. Subsidy
Project NPV	$ 63,958.90	$ (258,788.21)	$ -	$ -
# Comm. / Ind. Customers	4	19	19	19
Comm. / Ind. Tariff	$ 0.40	$ 0.40	$ 0.52	$ 0.40
Comm. / Ind. Sales	$ 24,144	$ 27,453	$ 35,975	$ 27,453
# HH Customers	-	764	764	764
HH Tariff	$ 0.40	$ 0.40	$ 0.52	$ 0.40
HH Sales	$ -	$ 83,960	$ 110,021	$ 83,960
HH Subsidy Per Year	$ -	$ -	$ -	$ 45
Total Subsidy / Year	$ -	$ -	$ -	$ 34,582
Total Annual Revenue	$ 24,144	$ 111,414	$ 145,995	$ 145,995
PV Size	38	167	167	167
Storage Size	-	845	845	845
ICE Size	8	60	60	60
Investment Cost	$ 54,015	$ 546,915	$ 546,915	$ 546,915
Annual Fuel Cost	$ 7,275	$ 35,355	$ 35,355	$ 35,355
Reliability	100%	100%	100%	100%
Renewable %	68%	61%	61%	61%

Required Tariff and Subsidy for Profitability in the Nigerian Village Minigrid

As shown in Table 2, the universal service design results in a negative net present value for the minigrid project. The universal service design includes a significant amount of cross-subsidization from the industrial customers to the residential customers, which still does not fully cover the cost of the minigrid operator.

In order to achieve universal service without a government subsidy, the minigrid operator would need to charge $0.52 / kWh to each customer in the village. As shown in Table 2, this results in a minigrid project with a Net Present Value of zero. Assuming all risk, cost, and revenue is captured in this model, an NPV zero project should be a financially attractive investment.

However, as shown in Figure 12, a tariff of $0.52 / kWh is significantly higher than the cost of diesel at $0.40 / kWh. In the marketplace, the commercial / industrial customers always retain the option to procure energy through a diesel generator, and may elect to defect from the minigrid if tariff rates become too high. To avoid any customer defection, minigrid operators will have to maintain lower tariff rates for these customers.

If the government policy aims to provide universal service for all residents, the government may elect to provide incentives to the minigrid provider to connect unprofitable customers to the minigrid. As shown in Table 2, an annual per customer subsidy of $ 45 / household / year would incentivize the minigrid provider to connect every customer in the example village. This represents a total annual subsidy of $34,500 in year 1, increasing each year based on inflation.

Exploration of the Customer Marginal Cost

Determination of the marginal cost for each consumer indicates the level of consumer and producer surplus occurring within the system. This assists with understanding the level of cross-subsidization which is occurring throughout the village and the threshold at which minigrid firms are no longer incentivized to connect consumers.

Figure 8 colors each customer according to the marginal cost of connecting the particular consumer to the minigrid.

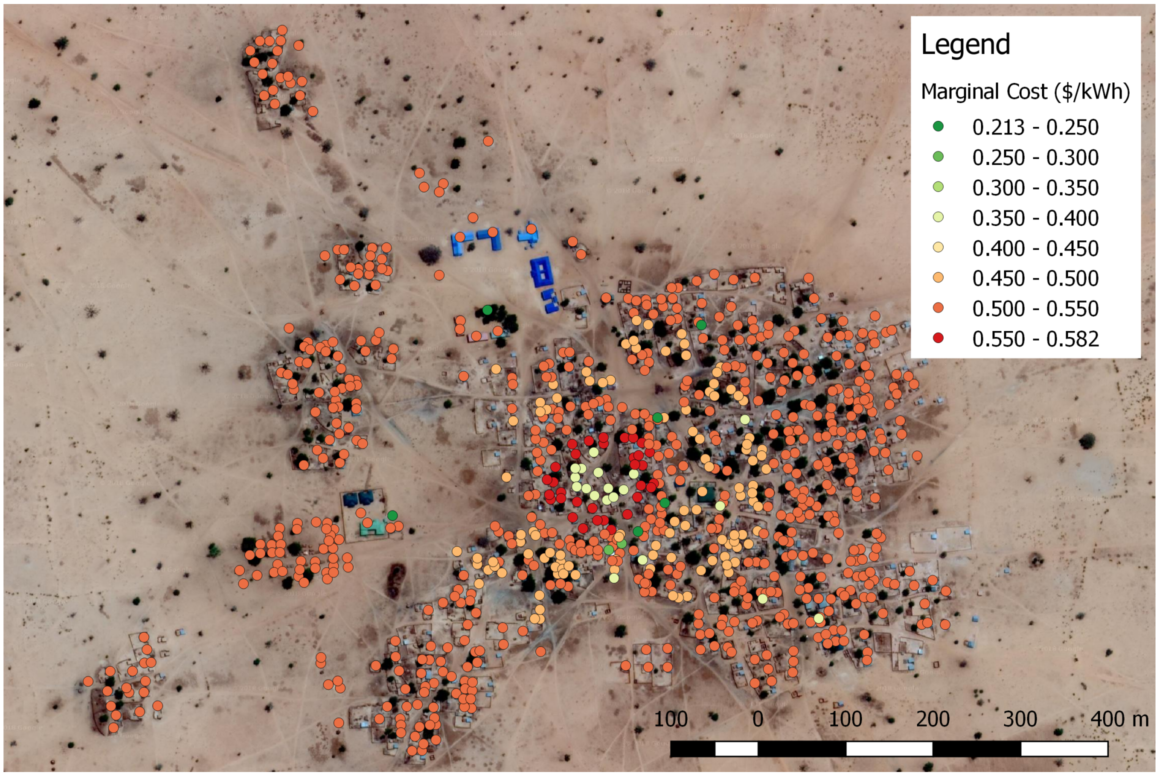

Figure 8. Marginal Cost of Service for Nigerian Village Customers

From this figure, the lowest cost customers are quickly identified as the commercial customers (green) and are also found in the Figure 5 profit maximization design. Apart from the large commercial customers, the least expensive customers are found in the center of the village and then radiate outwards in bands. As expected from a physical constraints of network design, the higher marginal cost customers are located on the fringes of the village.

The banding effect seen as customer are added to the minigrid is due to the discrete sizing of the diesel generators. The increased marginal cost of generation occurs when the generator is increased in size to meet load. This results in ample capacity but a necessity to operate at lower efficiencies.

Figure 9 indicates that the marginal cost of adding additional customers to the minigrid is driven primarily by the generation cost of energy. The network cost for each additional customer does not appear to rise above $0.10 / kWh due to the density of the village and the relatively high consumption per household.

Figure 10 and Figure 11 plot the details of the generation technology as customers are added to the minigrid design. As expected, the marginal cost of diesel generation tends to decrease as greater efficiencies are seen with larger generators, but the marginal cost of solar PV and battery remains relatively flat. Figure 11 also clearly indicates that the large commercial and industrial customers are the least expensive due to the daytime load and reliance on solar PV and diesel generation for all required power.

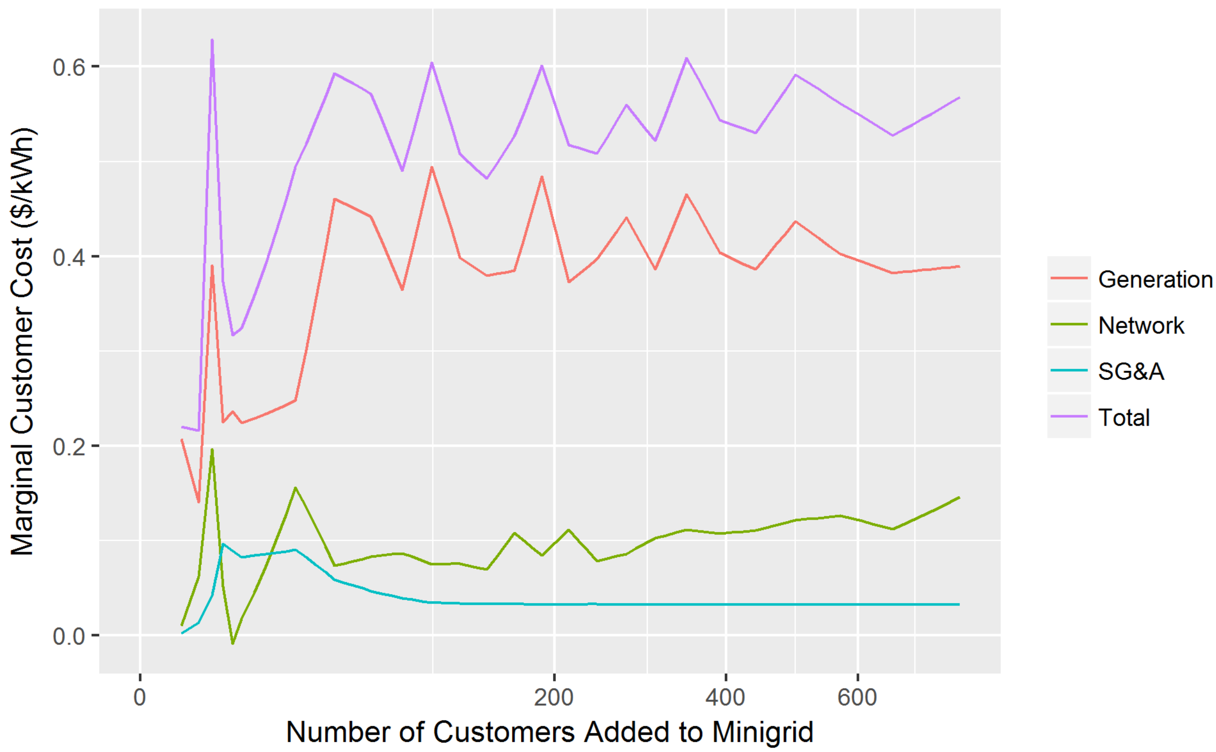

Figure 9. Marginal Cost Breakdown for Village Consumers in Nigerian Village Minigrid

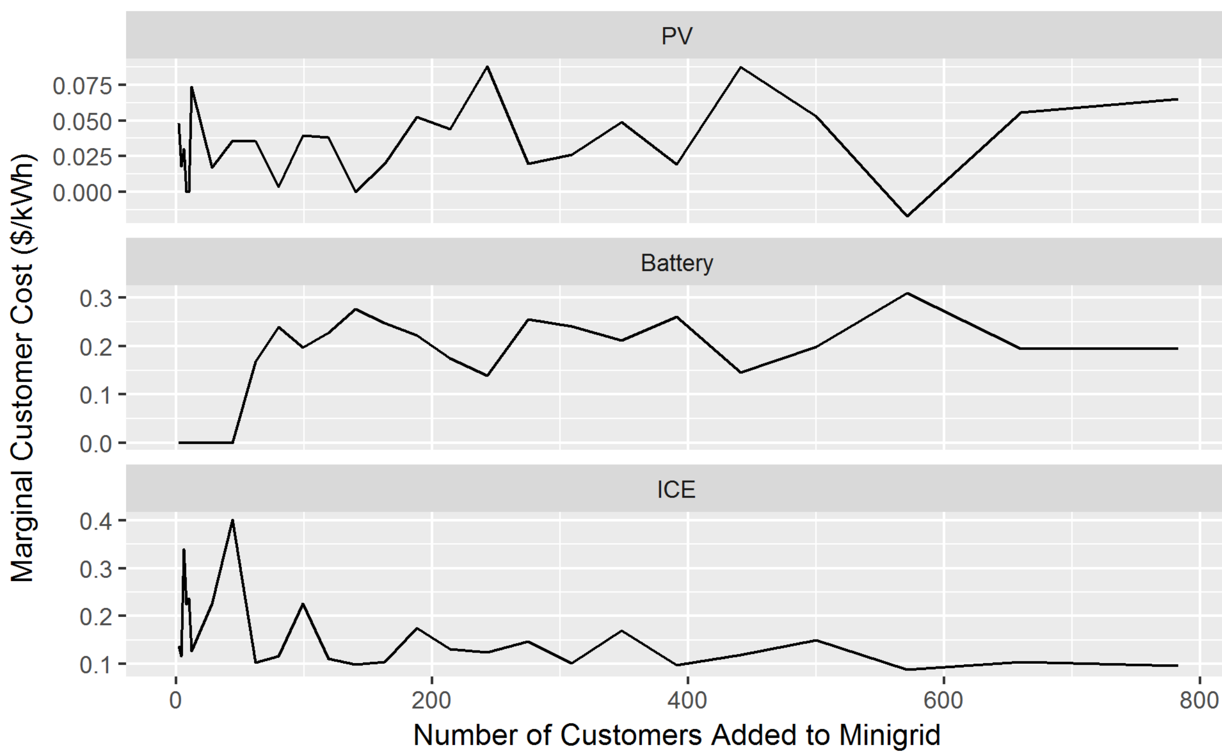

Figure 10. Marginal Cost Breakdown of Generation in Nigerian Village Minigrid

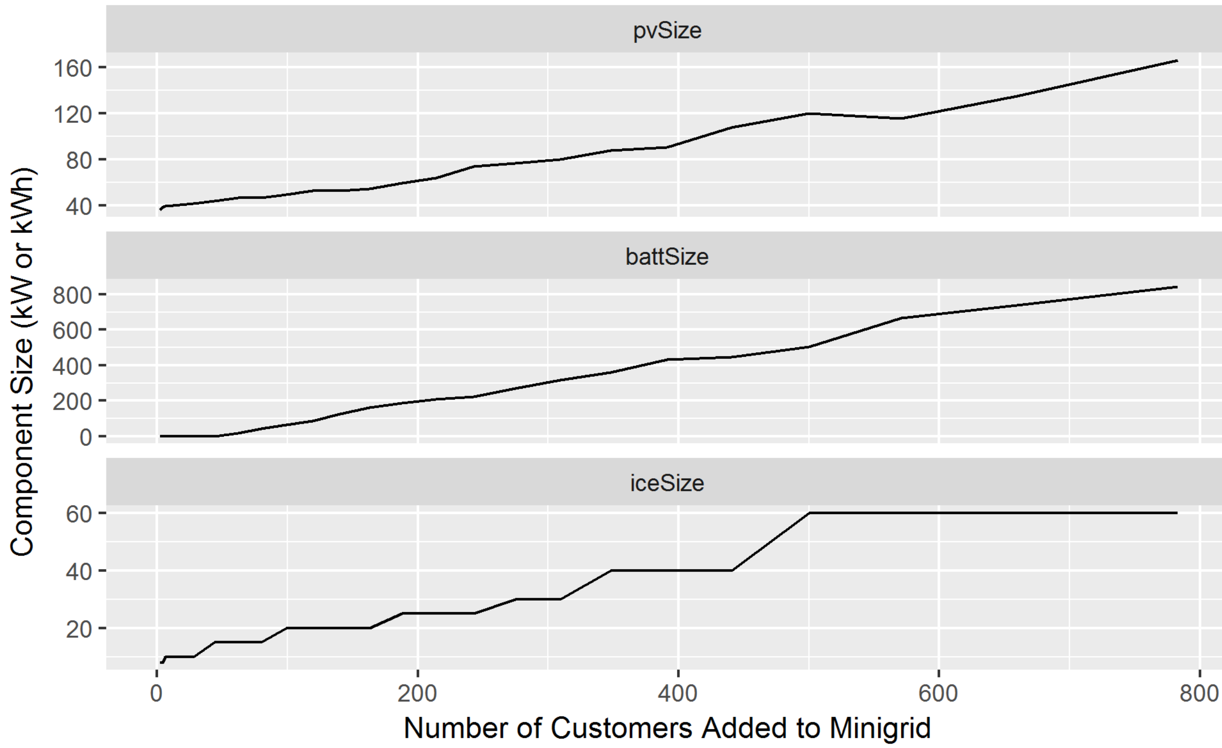

Figure 11. Generation Component Sizing as Customers are Added to the Nigerian Village Minigrid

Comparison to Alternative Technologies

The marginal cost of each customer in the minigrid can be used to identify competing technologies for energy services in each customer group. This analysis assumes an upper limit to willingness to pay based on diesel as an alternative at $0.40 / kWh. Additional options for the customers include solar home systems, which have a slightly different pricing structure. Solar home systems typically have a fixed cost. This analysis assumes the SHS cost for the Nigerian household is equivalent to two 30 W solar home system. This results in a total cost range of $160 - $212 / year for a 60W SHS including lighting, cell phone charging, fan, and television [35]. In order to compare this system to the marginal cost of minigrid service, the estimated annual payment for a Solar Home System was divided by the estimated consumptions of a household connected to a minigrid.

Despite the ease of comparing technologies based simply on cost / kWh, comparison between technologies such as stand-alone DG, minigrids, and SHS purely on the basis of cost is dangerous. Stand-alone DG has negative externalities such as pollution and noise, which are not captured in these cost comparisons. For solar home systems, the relatively inexpensive cost compared to minigrid service does not account for the differences in service quality and ability to expand appliance usage at will.

Figure 12. Comparison of the Marginal Cost of Minigrid Services to Standalone Diesel Generation and Solar Home Systems.

The least expensive approach to providing power to the larger customers (left side of Figure 12) is through minigrid service. After approximately 50 customers are added to the minigrid however, the least expensive technology may be Solar Home Systems depending on the services and cost structure. Although this technology is cost-effective, service quality is significantly worse than minigrid service with 98% reliability.

For the minigrid entrepreneur, given that the cost of service may be higher than the equivalent appliances through a solar home system, it becomes increasing important to sell on aspects of minigrid service including the reliability of the minigrid and the ability to add additional appliances at will.

The Effect of Minimum Renewable Energy Requirements on Minigrid Designs

As mentioned previously, all minigrid case studies presented in this thesis maintain a minimum renewable energy fraction of 60%. Although this is beneficial from an environmental standpoint, it may slow minigrid industry growth due to the higher cost of energy generation through renewable technologies such as solar photovoltaics combined with battery storage.

Figure 13 shows the net present value of the Nigerian village minigrid if the developer is allowed to use the least cost generation methods without restrictions on diesel generation. As seen in the figure, the most profitable designs still include only the largest commercial customers, but all designs are now NPV positive.

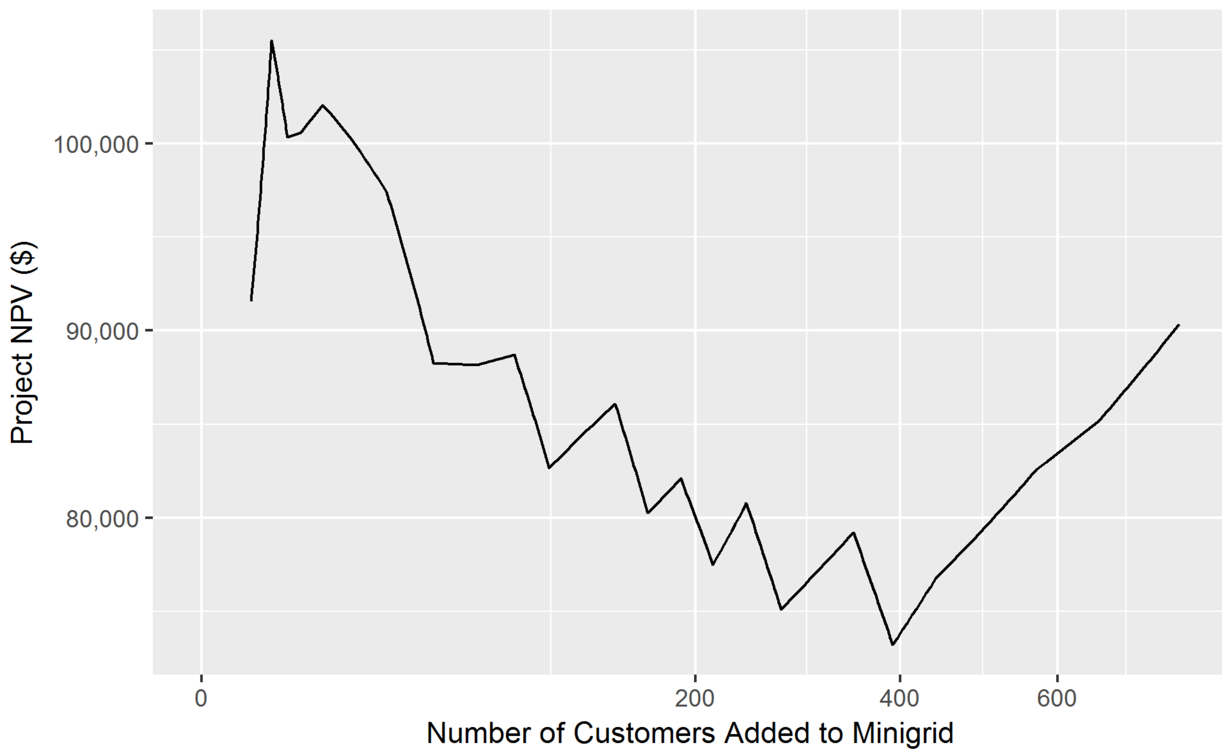

Figure 13. The NPV of the Nigerian Minigrid Project without Minimum Renewable Regulations

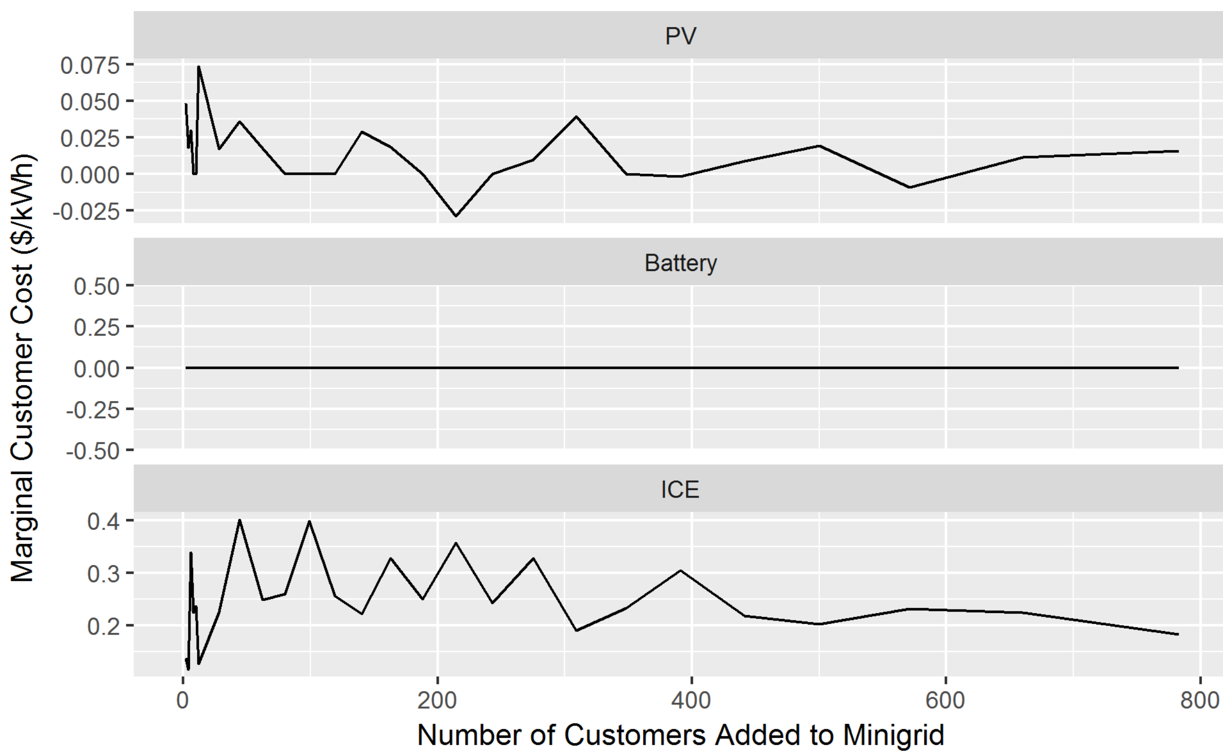

Figure 14. Marginal Generation Cost for the Unrestricted Diesel Minigrid.

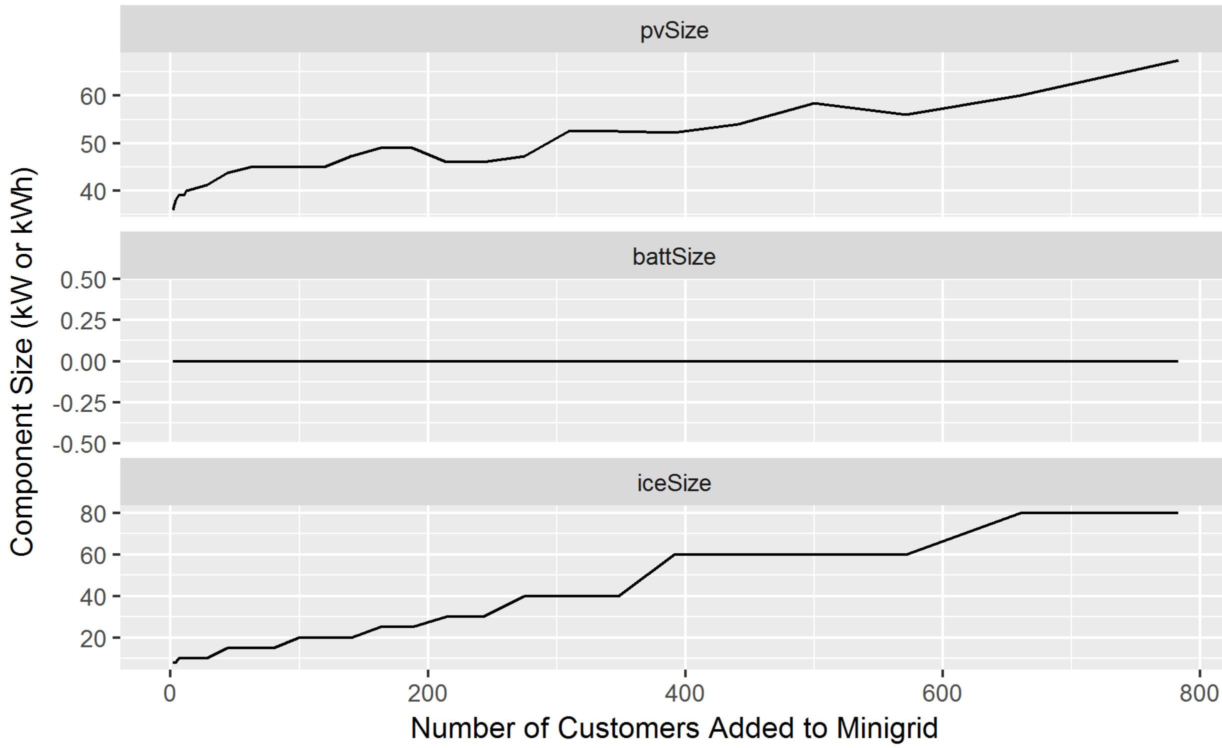

Figure 15. Component Sizing for the Unrestricted Diesel Minigrid.

The Effect of Diesel Bans on Minigrid Design and Firm Behavior

If the government chooses to ban diesel generation from minigrid designs, generation cost will increase and the necessary government subsidies to provide universal service will subsequently increase. The resulting marginal cost of generation for these minigrid designs in shown below in Figure 16 and Figure 17.

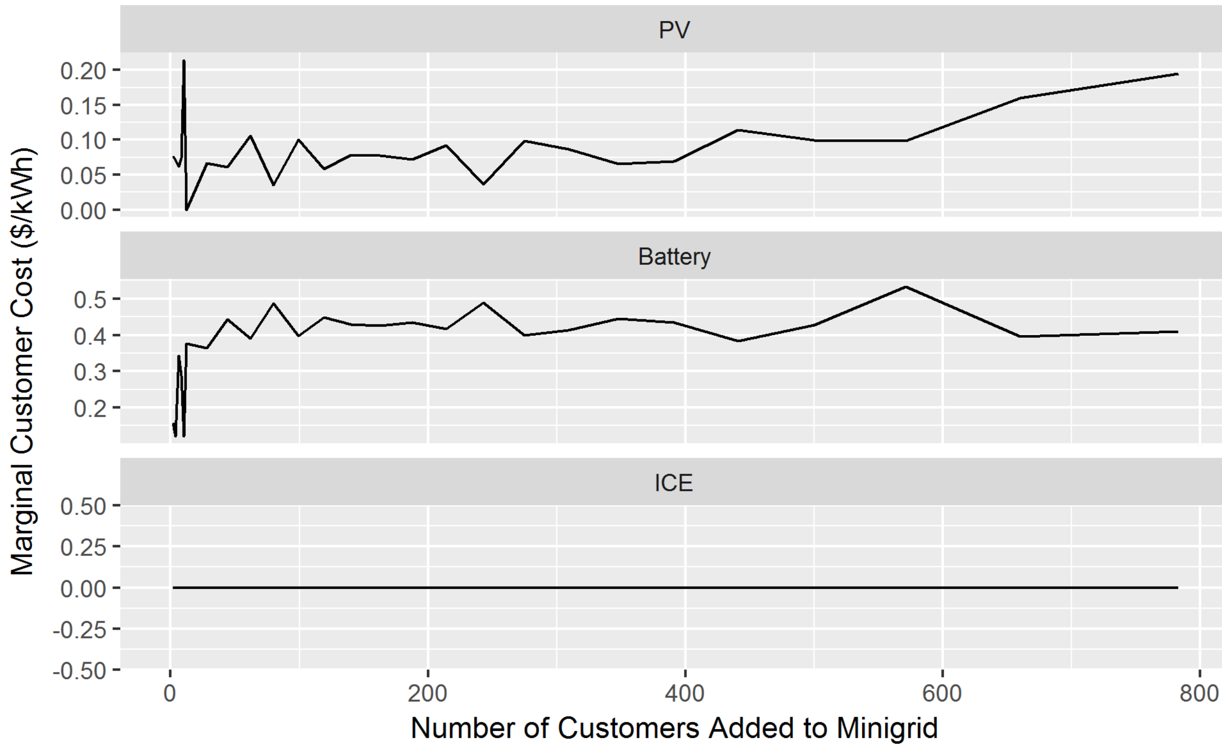

Figure 16. Marginal Generation Cost for the 100% Renewable Minigrid Projects

Figure 17. Component Sizing for the 100% Renewable Minigrid Projects

The Effect of Discount Rate on Minigrid Projects

The discount rate assumed for the case studies in this project is 14%. However, depending on the views of the investor and the financing available, the discount rate for the project may be higher or lower. Despite the results provided by the CAPM or another market models, the discount rates demanded by investors ultimately control the market.

A brief sensitivity study is presented below which highlights the changes to Net Present Value when the discount rate is lowered to 10% and increased to 25%.

Figure 18 shows the net present value of the Nigerian village minigrid project as customers are added to the minigrid. The project valuation is higher, but the most profitable design for the investor remains similar. However, when compared to the base study presented in Figure 4, the minigrid firm could now justify expanding grid coverage to over 600 consumers and still maintain a profitable project.

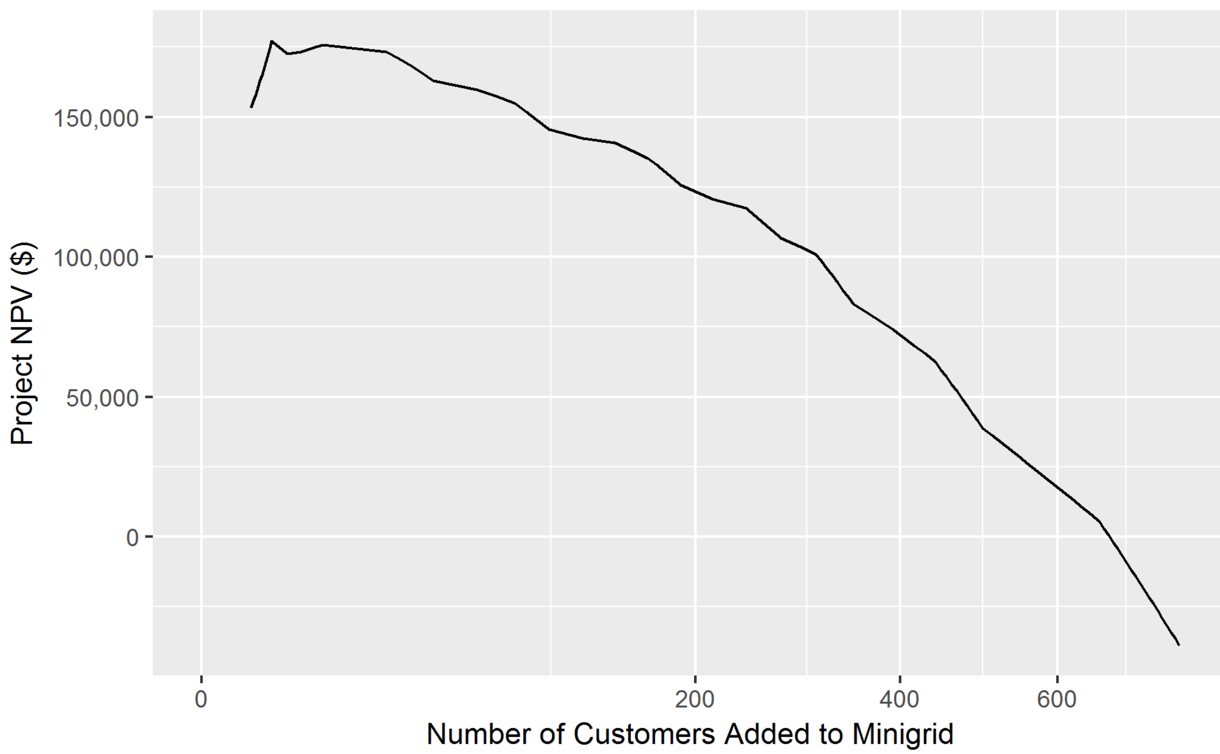

Figure 18. The Minigrid Project NPV with an Assumed Discount Rate of 10%

Figure 18 is contrasted with Figure 19, which plots the NPV of the Nigerian village minigrid if the assumed discount rate is 25%. In this plot, the most profitable design remains the same, with only four customers connected. However, the project NPV is significantly reduced, and the point at which the project becomes NPV negative occurs below 200 consumers.

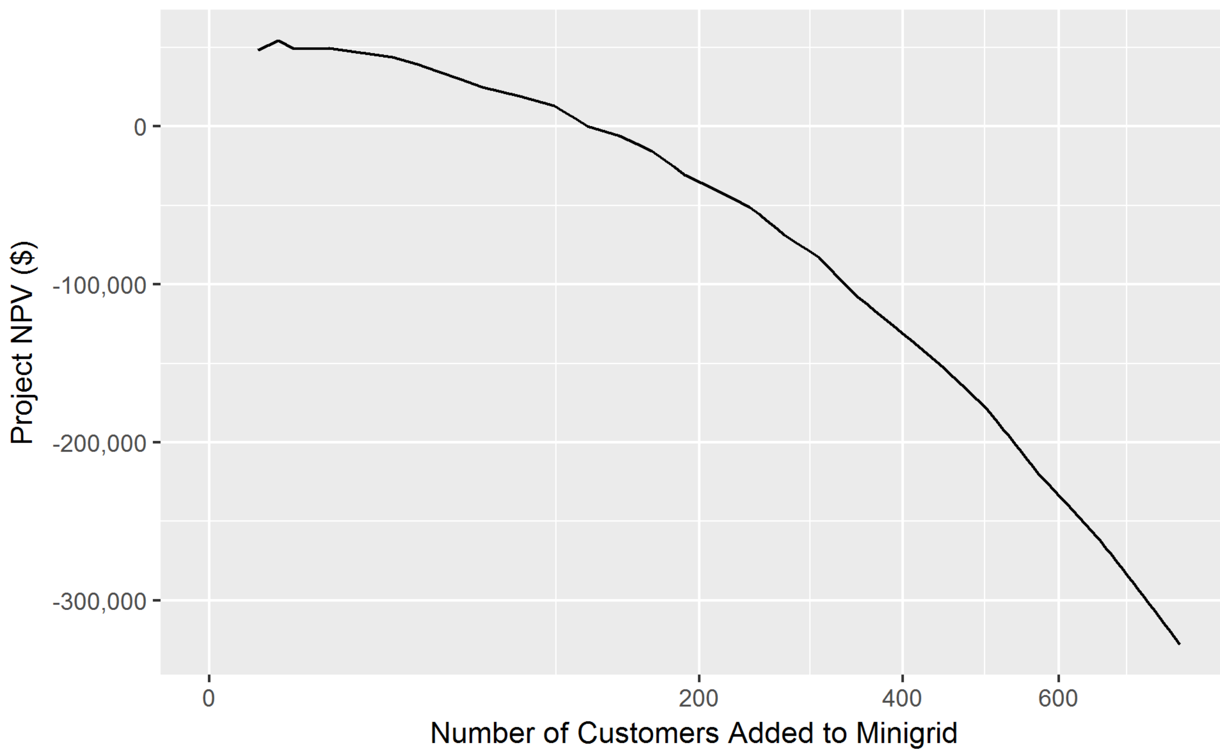

Figure 19. The Minigrid Project NPV with an Assumed Discount Rate of 25%

Rwanda Minigrid Case Study:

Introduction

The current electrification rate in Rwanda is 72% for urban areas, but only 12% for rural areas [1]. A number of minigrid entrepreneurs have built projects in these areas, the most widespread being those of MeshPower [39].

Throughout 2017 and 2018, the Universal Access Group at MIT has been working with the Government of Rwanda and the Rwanda Energy Group Limited (REG) to develop a master electrification plan for the country. Minigrids are a significant component of this plan, providing service for villages in areas beyond the reach of the national grid.

Village Demand Characteristics

The village selected for this case study contains 402 residential customers and 15 commercial customers. The proposed minigrid site would include each of these customers and provide electricity service for the next 25 years.

The residential households in this village have a lower consumption pattern than the households in the Nigerian village. Each household is assumed to own two 5 W LED lights and one 5 W phone charger. These appliances are used primarily at night and rarely during the day. The annual consumption for these customers is 57 kWh, which is approximately 1/5th the consumption of the average household in the Nigerian village.

The businesses in the village range from welding shops, hair salons, restaurants/bars, tailors, to food storage. The aggregated load for the village is 100,000 kWh for a single year.

The 417 households and business are spread across an area that spans 1 km by 1 km, with the majority of the businesses located in the center of the village. Figure 20 shows the geographic dispersion of the customers.

Table 3. Rwanda Village Description

Customer Type	Number of Customers	Peak Demand (kW)	Annual kWh	Villiage Peak Demand (kW)	Village Annual kWh
LightResHH	402	0.01	57	4.42	22,858
Restaurant	3	0.64	4,583	1.92	13,750
Refrigeration	3	0.81	7,052	2.42	21,155
Welding	2	4.82	11,189	9.64	22,378
Tailor	2	2.42	5,773	4.84	11,546
Hair Salon	1	0.74	1,786	0.74	1,786
Shop	1	0.01	88	0.01	88
Mill	1	0.99	3,832	0.99	3,832
Phone Charging	1	0.03	123	0.03	123
Popcorn	1	1.31	3,160	1.31	3,160
Total	417	-	-	26.30	100,674

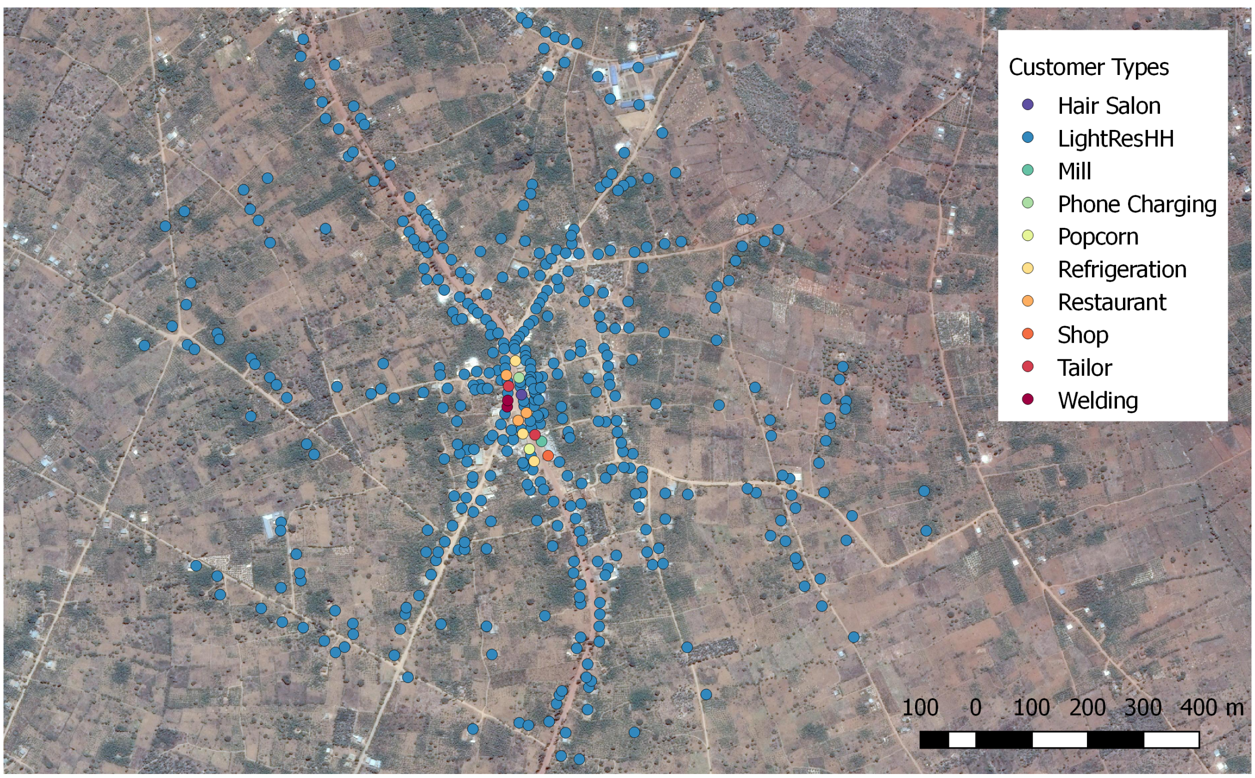

Figure 20. Customer Locations in the Rwanda Village

Village Ability to Pay

We assume that each household in the village can afford to pay approximately \$0.45 / kWh, which is approximately \$2.14 / month, or \$25.65 / year.

Existing business must rely on diesel generation in order to operate, which gives an existing market price for electricity in the area. Similar to the Nigerian village case study, this case study assumes diesel generation is approximately $0.40 / kWh.

These pricing assumptions assume that customers would be willing to substitute their existing energy sources for minigrid service provided they received the same or better quality of service.

Results of the Full Design Space

Based on the results from the Nigerian Village Case Study, the Rwandan village design space is only explored for reliability levels of 98%. Figure 21 plots the project net present value as additional customers are added to the minigrid. A clear peak of maximum firm value occurs at 12 customers. Table 4 list the results of the more detailed financial analysis for a number of minigrid projects. The profit maximizing design has an estimated net present value of $18,000.

Despite the peak profitability of the minigrid occurring at only 12 customers, a minigrid provider could choose to add additional customers to the minigrid project and still remain profitable. For the given household tariff rates of $0.45 / kWh in this project, additional customers could be added until approximately 250 customers are attached to the minigrid.

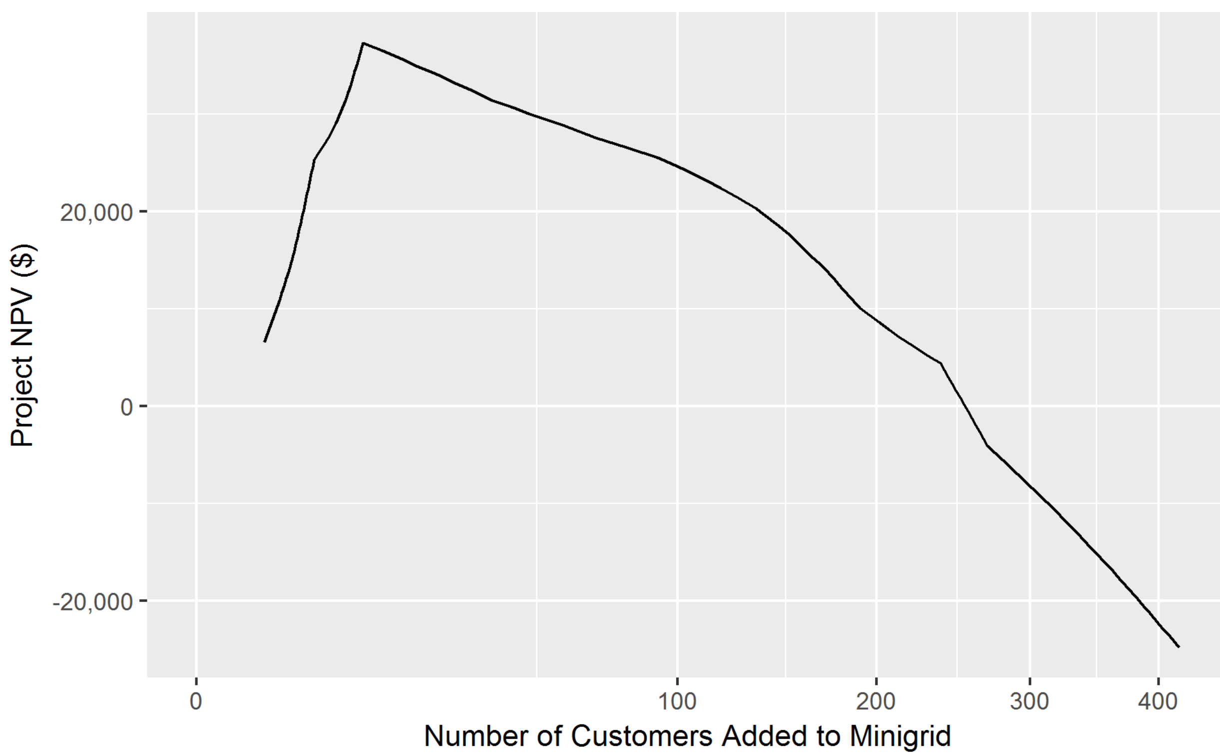

Figure 21. NPV of the Rwanda Minigrid is maximized at 12 customers.

Table 4. Rwanda Minigrid Design Results

	Profit Maximization	Universal Service - Market Tariff	Universal Service - Breakeven Tariff	Universal Service - Gov. Subsidy
Project NPV	$ 18,323.20	$ (36,345.23)	$ -	$ -
# Comm. / Ind. Customers	12	15	15	15
Comm. / Ind. Tariff	$ 0.35	$ 0.35	$ 0.47	$ 0.35
Comm. / Ind. Sales	$ 14,174	$ 13,116	$ 17,553	$ 17,972
# HH Customers	-	402	402	402
HH Tariff	$ 0.45	$ 0.45	$ 0.47	$ 0.45
HH Annual Fixed Charge	$ -	$ -	$ -	$ -
HH Sales	$ -	$ 10,256	$ 10,675	$ 10,256
HH Subsidy Per Year	$ -	$ -	$ -	$ 12
Total Subsidy / Year	$ -	$ -	$ -	$ 4,857
Total Annual Revenue	$ 14,174	$ 23,372	$ 28,228	$ 28,228
PV Size	33	38	38	38
Storage Size	-	91	91	91
ICE Size	8	10	10	10
Investment Cost	$ 37,174	$ 84,443	$ 84,443	$ 84,443
Annual Fuel Cost	$ 5,163	$ 8,712	$ 8,712	$ 8,712
Reliability	100%	100%	100%	100%
Renewable %	67%	61%	61%	61%

Results of the Profit Maximizing Design

Figure 22 shows the resulting minigrid design if the minigrid firm chooses to maximize profits by only connecting customers in which the marginal revenue exceeds the marginal cost. This is a small subset of consumers, including only 12 of the commercial customers in the village. Table 4 contains the financial details of this minigrid project.

As indicated in Table 4, the profit maximizing design includes only solar PV for generation and does not require any battery storage. The daytime load for these customers is significant enough that the 60% renewable threshold can be met completely with the solar PV during the day and the diesel generation during the evening.

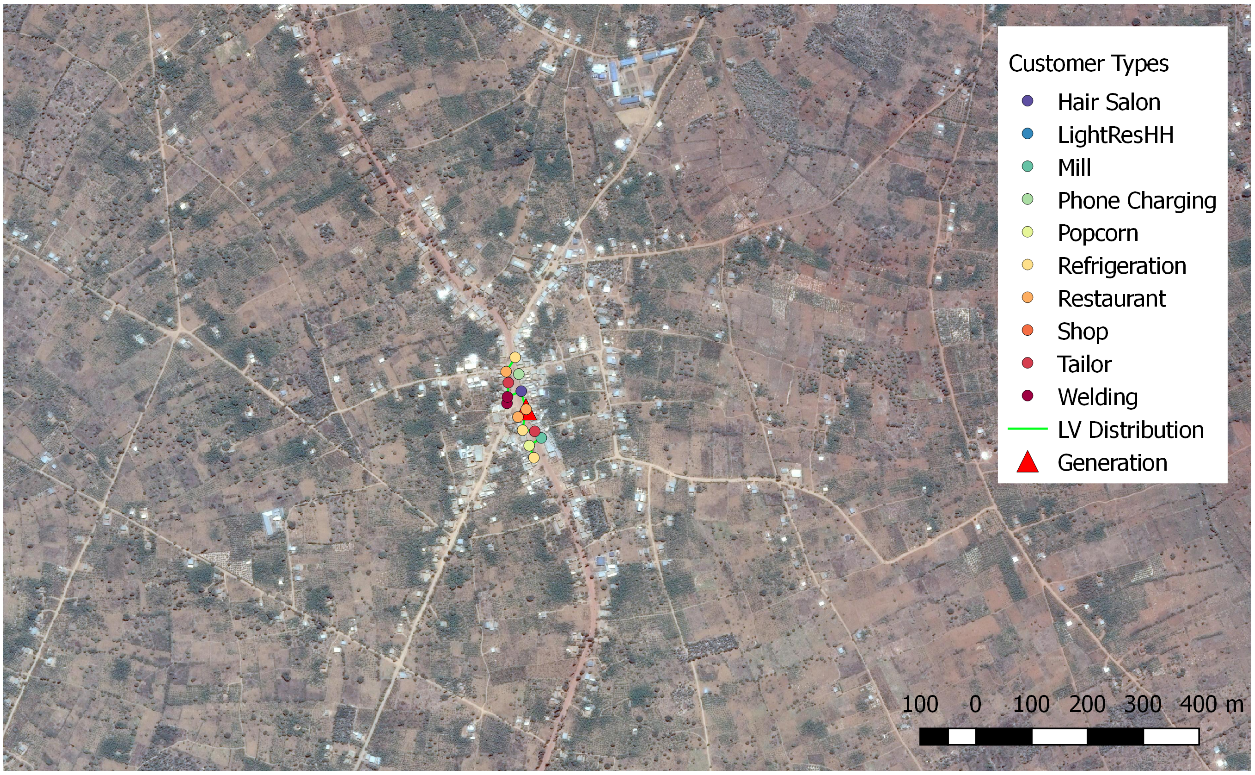

Figure 22. The Minigrid Design if the Minigrid Firm Prioritized Profit Maximization

Results of the Universal Service Design Minigrid

The network design for universal service in the Rwanda village minigrid is shown below in Figure 23. As seen in the network map, the generation site is located close to the center of the village and the network radiates outward. The minigrid generation dispatch for the universal service dispatch is shown below in Figure 24. For the Universal Service design, the minimum renewable threshold can only be met with a significant amount of battery storage during the evening.

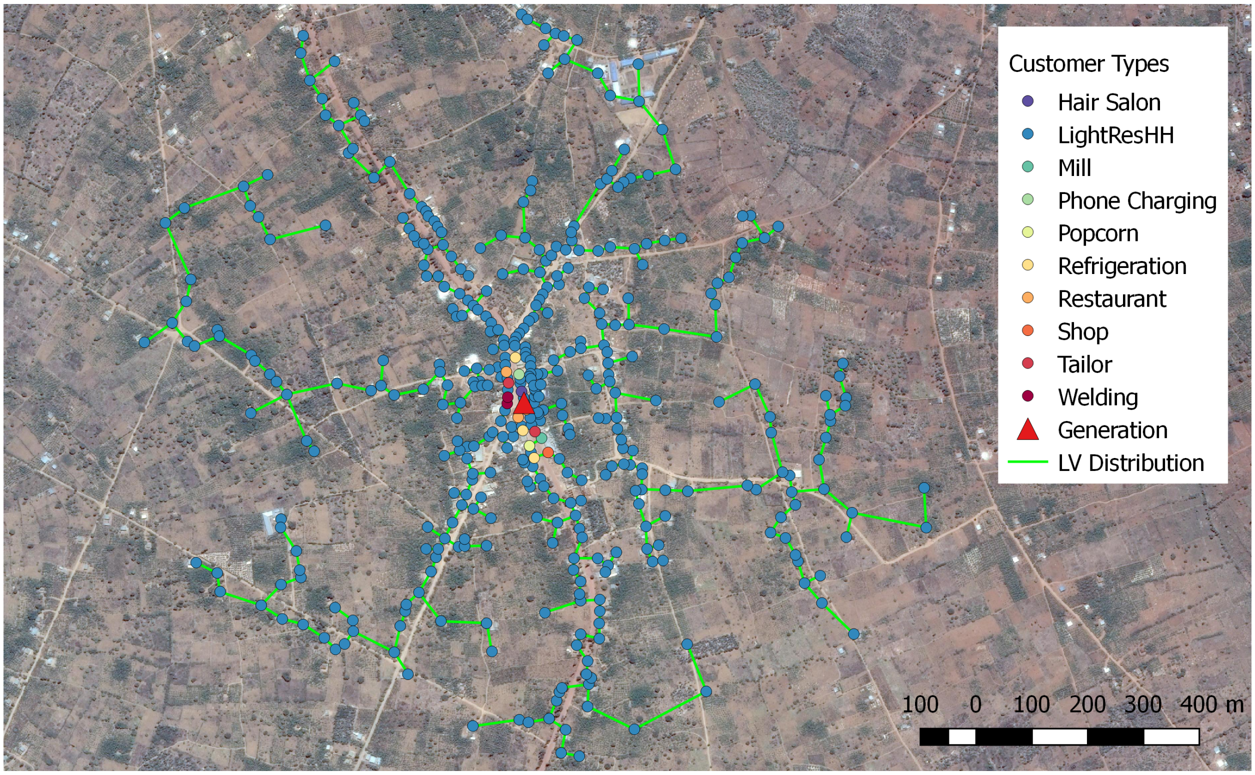

Figure 23. Network Layout for the Rwandan Village Universal Service Design

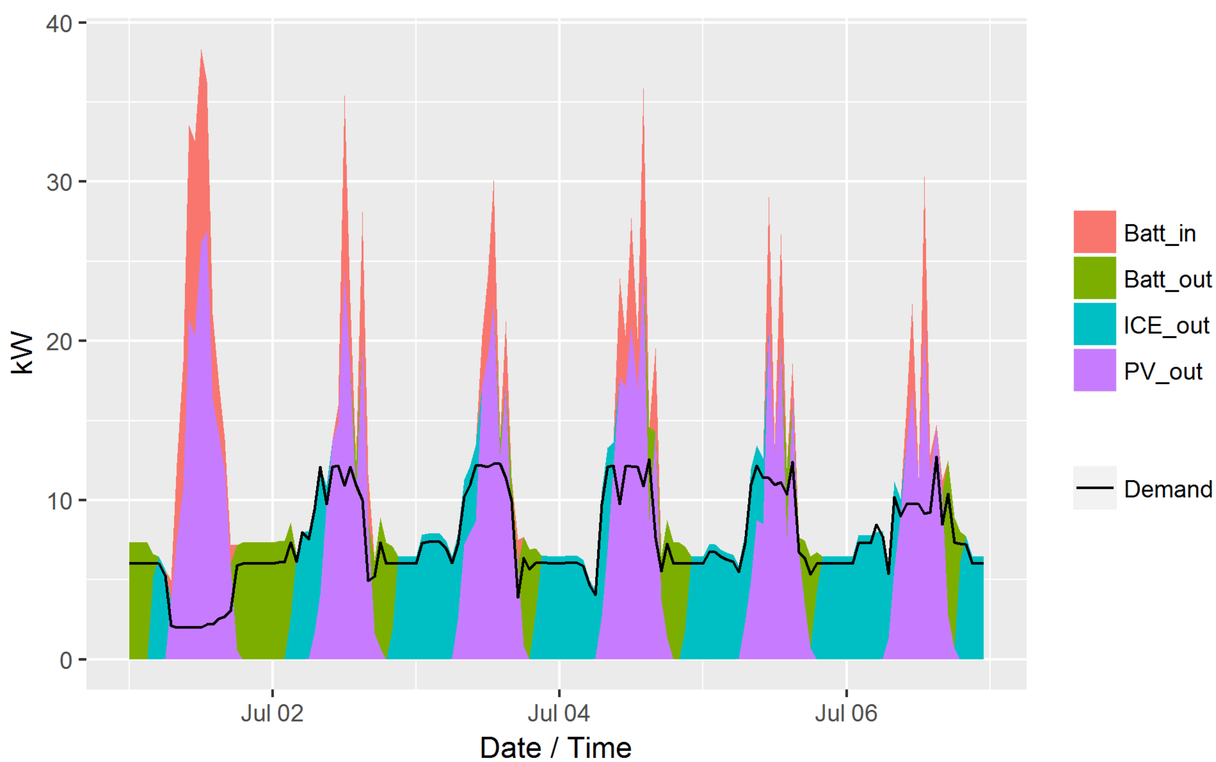

Figure 24. Generation Dispatch for the Rwandan Village Universal Service Design

Required Tariffs and Subsidy for Profitability in the Universal Service Design

As clearly shown in Figure 21 and Table 4, the minigrid design which serves every customer in the village would be an unprofitable investment for a minigrid developer. Table 4 indicates that in order to maintain profitability of this minigrid, the flat tariff for every customer in the village must be increased to $0.47 / kWh.

If the government wants to maintain the proposed tariffs of $0.35 and $0.45, a subsidy or similar incentive would be necessary to encourage the developer to expand the system beyond the commercial/industrial customers. Table 4 shows that a per household subsidy of $12 / HH / year would be required to encourage a developer to connect the entire village to the minigrid. For the system explored in this case study, this translates to a total village subsidy of $4,857 / year.

Exploration of the Marginal Customer Cost

Exploration of the marginal cost indicates the threshold at which a developer would no longer be incentivized to add additional customers to the minigrid. In Figure 25, the marginal cost of additional customers falls below $0.35 / kWh for the first 12 customers. However, after addition of the twelfth customer, the marginal cost rises above the marginal revenue of $0.35 / kWh. At this customer threshold, the minigrid firm no longer has incentive to connect additional customers. Figure 26 plots the marginal cost for each customer within the village.

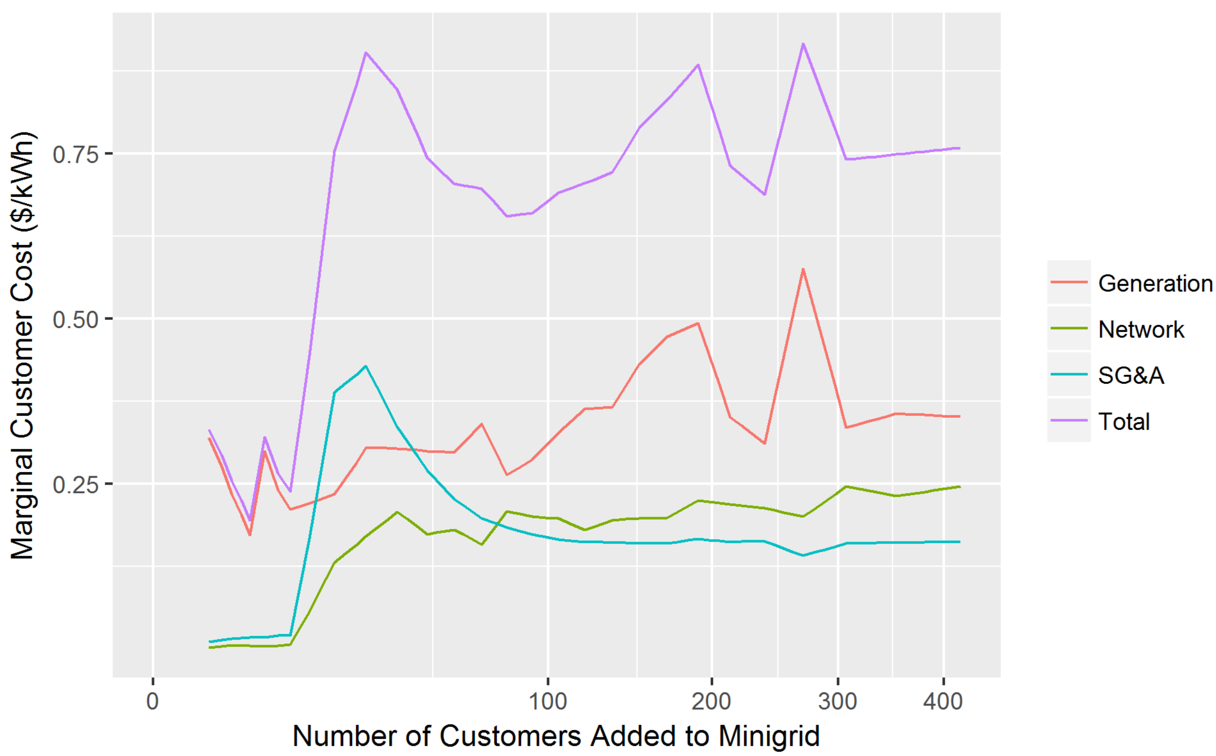

Figure 25. Marginal Cost Breakdown for the Rwanda Minigrid

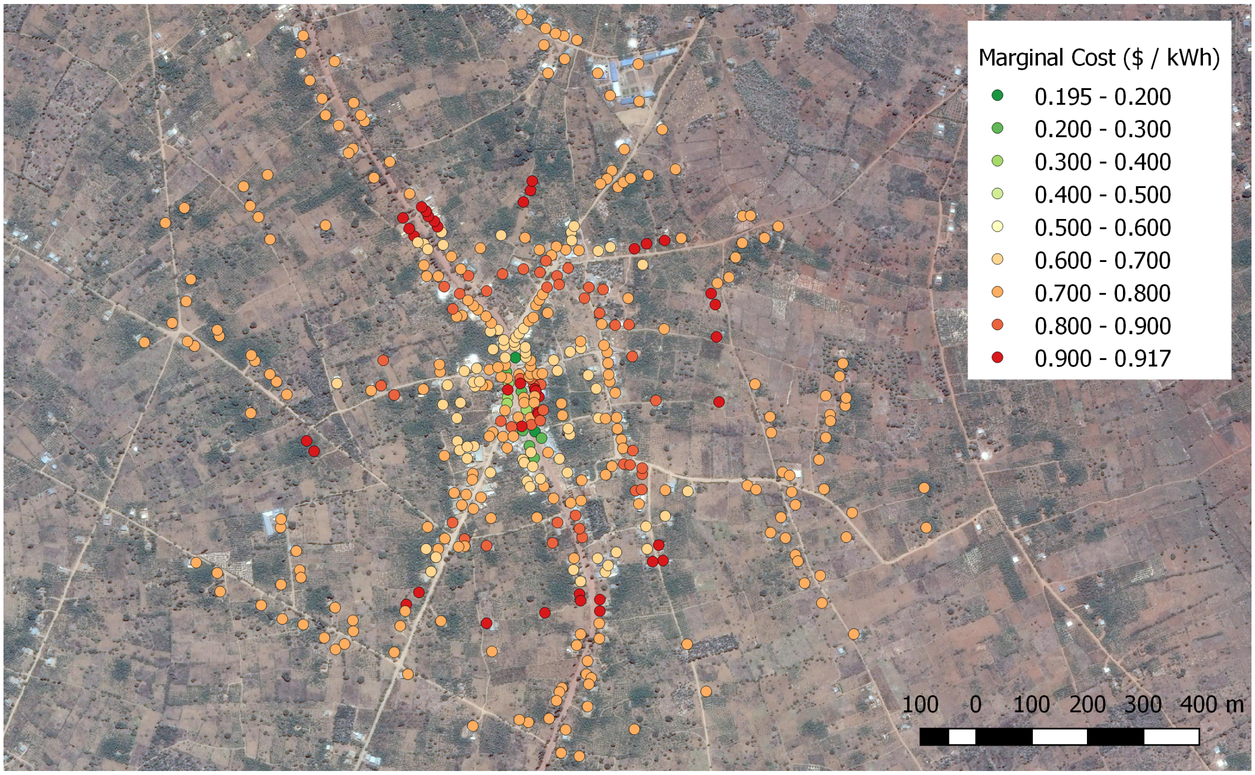

Figure 26. The Marginal Cost of Consumers in the Rwandan Minigrid Project

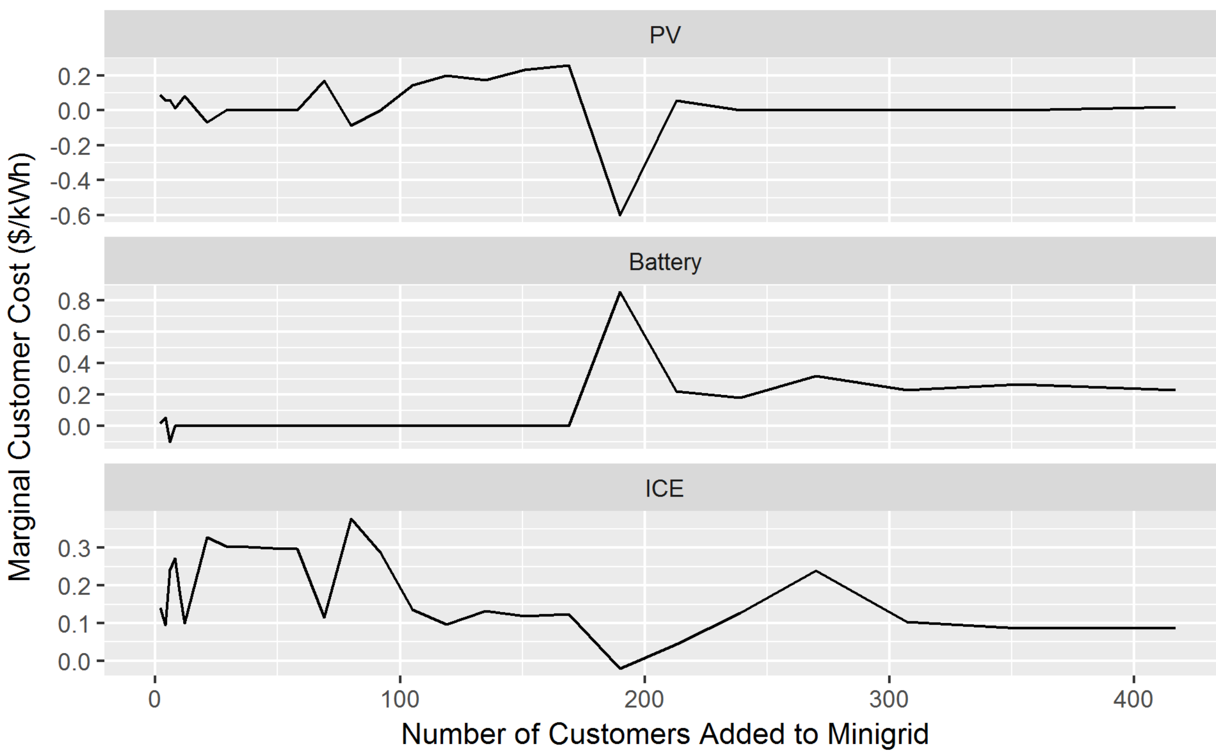

Figure 27. Breakdown of the Marginal Cost of Generation for the Rwandan Minigrid

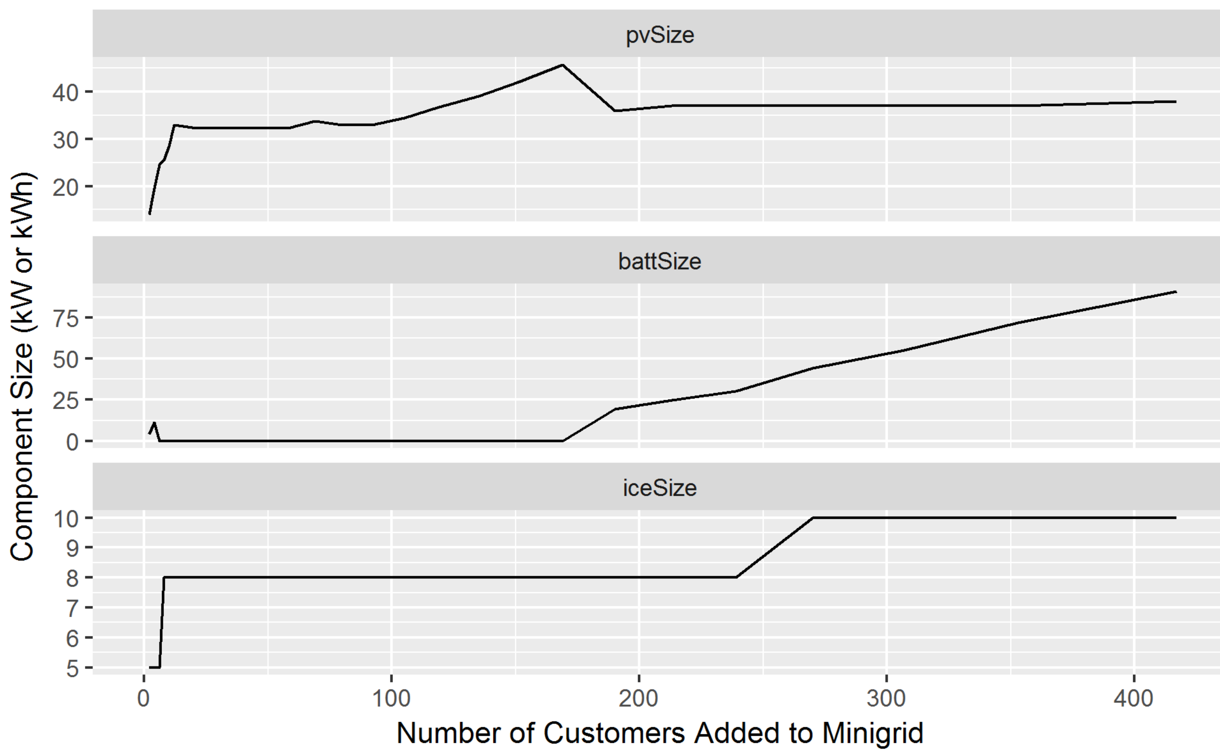

Figure 28. Component Size of the Rwandan Minigrid as Customers are Added.

In the case of the Rwandan Village, the SG&A, or customer management cost becomes a significant barrier to connecting residential customers to the minigrid. This is partially due to the low consumption patterns of the residential customers but fixed cost for customer management. These SG&A cost are largely a function of the firm management and may be lowered through efficient customer management and scale.

Figure 27 and Figure 28 highlight the marginal cost of generation for the minigrid and the component sizing required to meet loads as the minigrid expands.

Battery storage is not required for the first 175 customers. This is due to the high daytime loads of commercial customers which offset the diesel generation during the evenings for the residential consumers. This offset is great enough to meet the threshold of 60% renewable energy generation of the village.

Comparison to Alternative Technologies

When competing with standalone diesel generation and solar home systems, the Rwandan Village shows similar results to the Nigerian village, although with more extreme differences. The commercial customers are better served by a minigrid than stand-alone diesel generation.

Solar home system prices in this case study are based on annual solar home system payments of $37-$49 / year for a basic system with lighting and cell phone charging [35]. To compare this to the minigrid service, the annual price of $37-$49 / year was divided by the predicted consumption of 57 kWh per year with minigrid services. This results in a comparable price of $0.69 - $0.85 / kWh for solar home system service.

The solar home system may be more cost effective for providing basic service to the residential households, especially given the lower transactional cost and barriers to market entry. As mentioned earlier, the minigrid offers intangible benefits to consumers such as higher reliability and the ability to expand appliances in an ad-hoc manner. These have not been quantified in this analysis, but are real, tangible benefits that consumers may prefer when receiving electricity service.

Figure 29. Comparison of Minigrid Cost to Alternative Technologies

India Minigrid Case Study

Introduction

In 2015, the State of Bihar in Northern India had a rural household electrification rate of 54% [40]. Although efforts in recent years have significantly increased the rate of electrification, household electrification remains low. In Bihar, a number of minigrids are currently operated by various firms throughout the area.

Village Demand Characteristics

The village of Bhalolpur is located on the island of Raghopur near Patna, Bihar. The difficult location of the island, in the middle of the Ganges river, suggests that electricity service provided by a minigrid may be the least cost solution.

On-ground surveys from the village indicate a number of households and commercial shops which require electrification. The characteristics of the village customers are shown below in Table 5. Unlike the villages in Nigeria and Rwanda, the tariff rates typically charged for minigrids in India are often based on a flat monthly rate for service. This rate is typically dictated by the appliances available to the household. Light residential households are typically equipped only with cell-phone charging and two 5 W LEDs. In this village, Medium service households are provided enough electricity for three 5 W LEDs, a 50 W fan and a 50 W television.

Anchor Load

For the purposes of this case study, an anchor load is added to the minigrid to increase the revenue for the minigrid provider. The anchor load is modeled as a cellular network tower, with a peak load of approximately 3.1 kW and a stand-by power consumption of 0.8 kW. This study assumes that an anchor load customer would prefer to purchase service from a minigrid rather than incur the cost of maintaining and providing stand-alone generation.

Table 5. Customer Characteristics for Bhalolpur Village

Customer Type	Number of Customers	Peak Demand (kW)	Annual kWh	Villiage Peak Demand (kW)	Village Annual kWh
Light Residential HH	169	0.01	58	1.86	9,724
Medium Residential HH	30	0.08	329	2.51	9,870
Commercial Shop	10	0.06	125	0.61	1,245
Cellular Tower	1	3.10	16,569	3.10	16,569
Total	210	-	-	8.08	37,408

The village of Bhalolpur measures approximately 1 km from north to south and 0.7 km from east to west. Unlike the Nigerian village, houses in Bhalolpur are spread apart, creating a higher network cost per customer.

As shown in Figure 30 below, the residential households and commercial shops are intermingled throughout the village, and the cellular tower has been located in the center of the village in an area of low density.

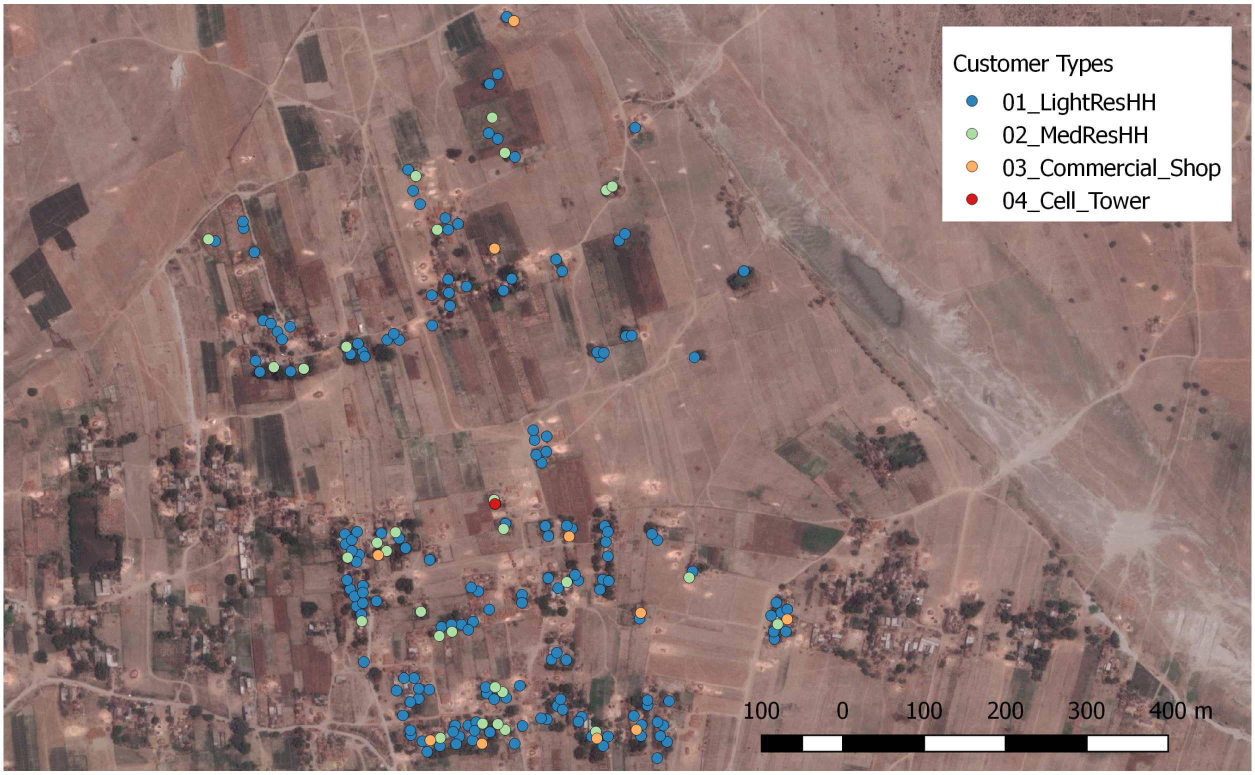

Figure 30. Customer Types in Bhalolpur Village

Village Ability To Pay

Based on interviews with minigrid operators in Bihar and Uttar Pradesh, the ability to pay of a common household in rural Bihar is $2 / month ($24 / year) for basic service including lighting and cell phone charging. For households with a medium level of service, the assumed charge is $10 / month ($120 / year).

Commercial customers and anchor tenants such as the cellular tower specified in this case study are expected to pay $0.40 / kWh, which is similar to the Nigeria and Rwanda case studies.

Results of Full Design Space Simulation

In the Bhalolpur village, higher consumption loads such as medium service households are not concentrated in the center of the village. Although the anchor tenant may represent the most profitable customer for the minigrid entrepreneur, connecting the medium service households requires a significant network investment cost.

Similar to the medium service households, the commercial shops are scattered throughout the outskirts of the village and are not concentrated in any single location.

Constraining the system to 60% renewable energy naturally provides nearly 100% reliability for the minigrid due to the excess diesel capacity which is always available. For this reason, only the design space for the high reliability system (98%) is shown below in Figure 31.

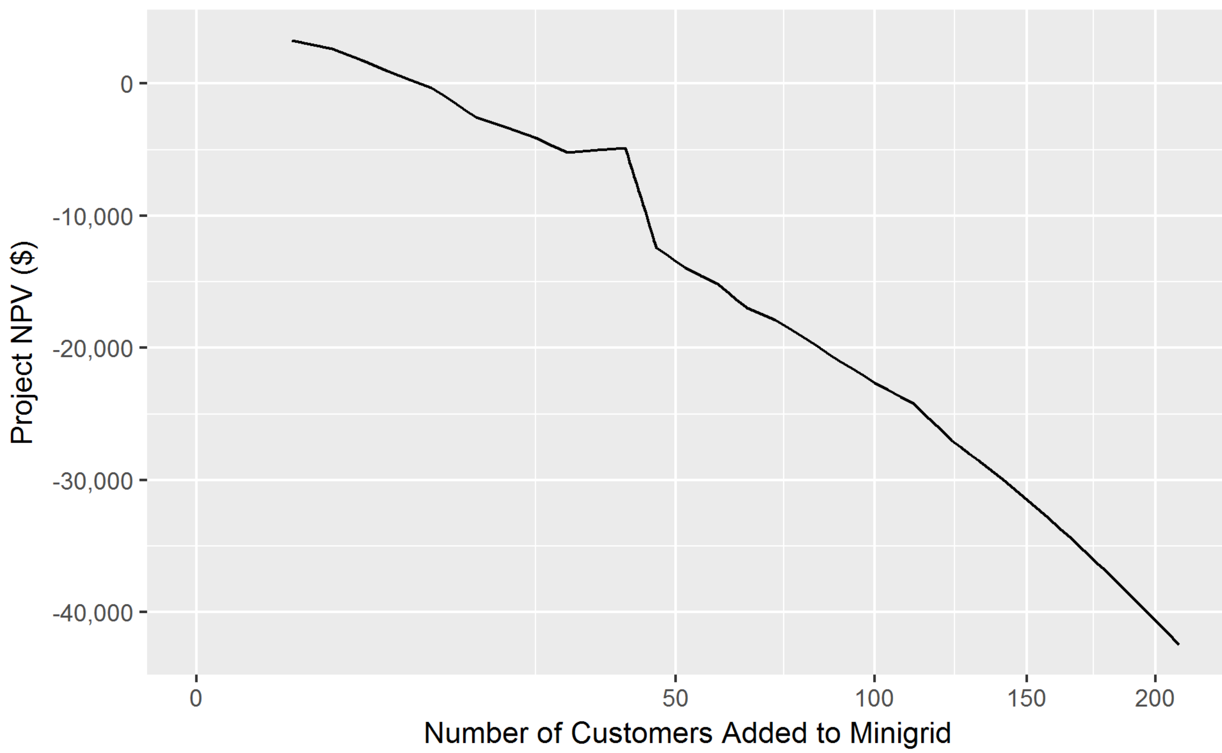

Figure 31. Bhalolpur Village Project NPV as Customers are Added to the Minigrid

Table 6. Details for Bhalolpur Minigrid Project Designs

	Profit Maximization		Universal Service - Market Tariff		Universal Service - Breakeven Tariff		Universal Service - Gov. Subsidy	
Project NPV	$	(5,558.66)	$	(40,373.36)	$	-	$	-
# Comm. / Ind. Customers		1		11		11		11
Comm. / Ind. Tariff	$	0.40	$	0.40	$	0.54	$	0.40
Comm. / Ind. Sales	$	6,628	$	7,126	$	9,609	$	7,126
# HH Customers		1		199		199		199
HH Tariff	$	-	$	-	$	0.54	$	-
HH Annual Fixed Charge		$24 or $120		$24 or $120	$	-		$24 or $120
HH Sales	$	120	$	7,656	$	10,568	$	7,656
HH Subsidy Per Year	$	-	$	-	$	-	$	27
Total Subsidy / Year	$	-	$	-	$	-	$	5,395
Total Annual Revenue	$	6,748	$	14,782	$	20,177	$	20,177
PV Size		10		23		23		23
Storage Size		32		102		102		102
ICE Size		5		8		8		8
Investment Cost	$	22,790	$	59,991	$	59,991	$	59,991
Annual Fuel Cost	$	2,804	$	5,699	$	5,699	$	5,699
Reliability		100%		100%		100%		100%
Renewable %		60%		61%		61%		61%

As shown in Figure 31, the Net Present Value of the minigrid project begins at a positive value with the anchor load and a single medium residential household located adjacent to the anchor load. However, beginning with only the addition of a few medium residential households, the project quickly becomes NPV negative. This low net present value is due to the sparse customer dispersion in the village and the low-ability to pay. For the medium residential households paying $10 / month, this revenue stream is not capable of supporting appliances such as fans and televisions.

Results of the Profit Maximizing Design

Figure 32 maps the resulting minigrid design when including only the anchor load customer and the nearest medium residential household. The details of this minigrid design are included in Table 6.

Table 6 highlights that despite the apparent profitability from the design calculation, once other financial aspects are added to the project such as working capital, taxes, depreciation, and finite project lifetimes, the project may no longer be viable.

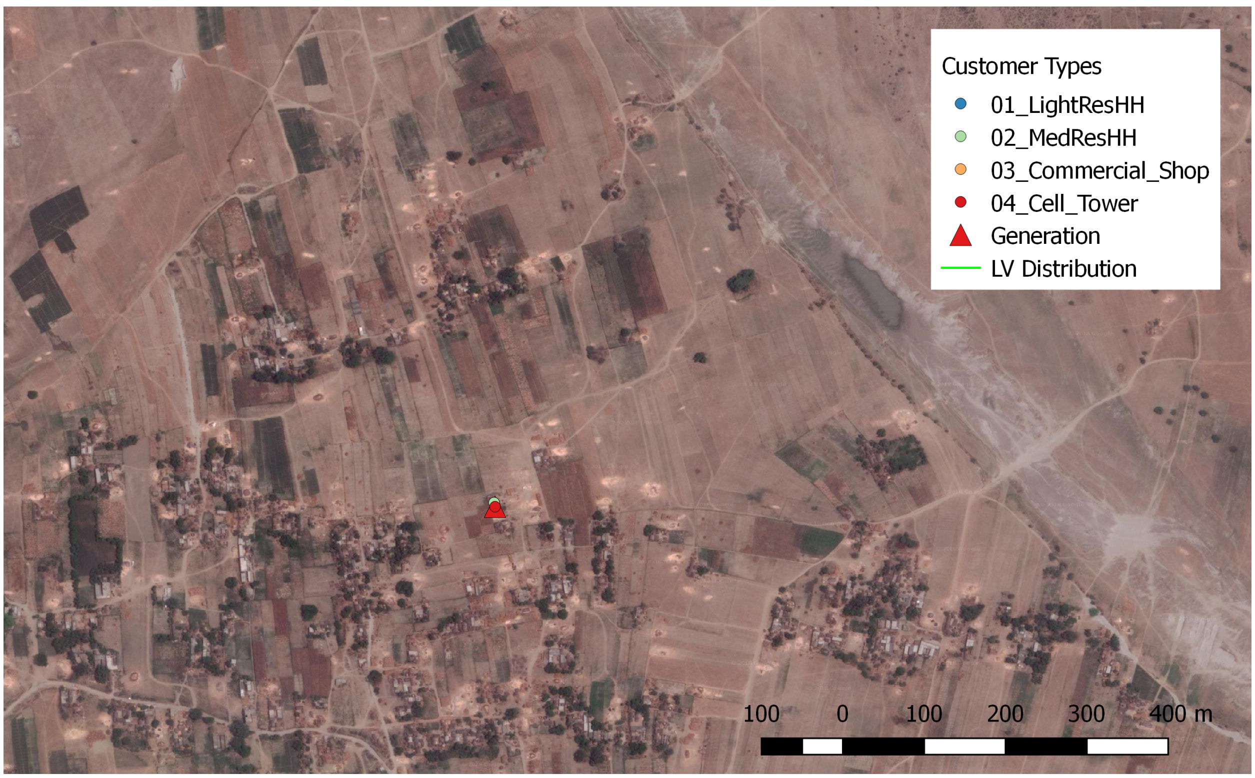

Figure 32. The Minigrid Design if the Minigrid Firm Prioritized Profit Maximization

Results of the Universal Service Design

Figure 33 and Figure 34 display the network design and generation dispatch for the Bhalolpur minigrid project. As can be seen in Figure 33, significant amounts of network are required to connect customers on the outskirts of the village.

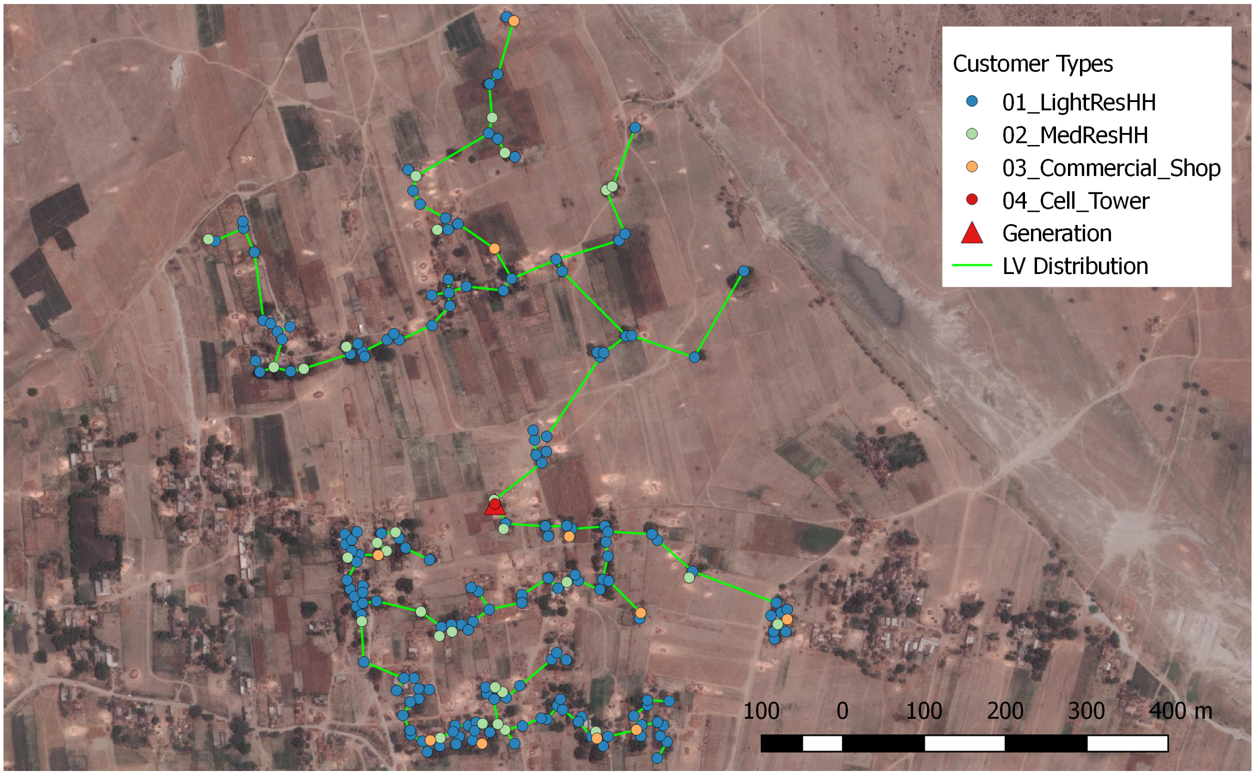

Figure 33. Network Layout for Universal Service Minigrid Design

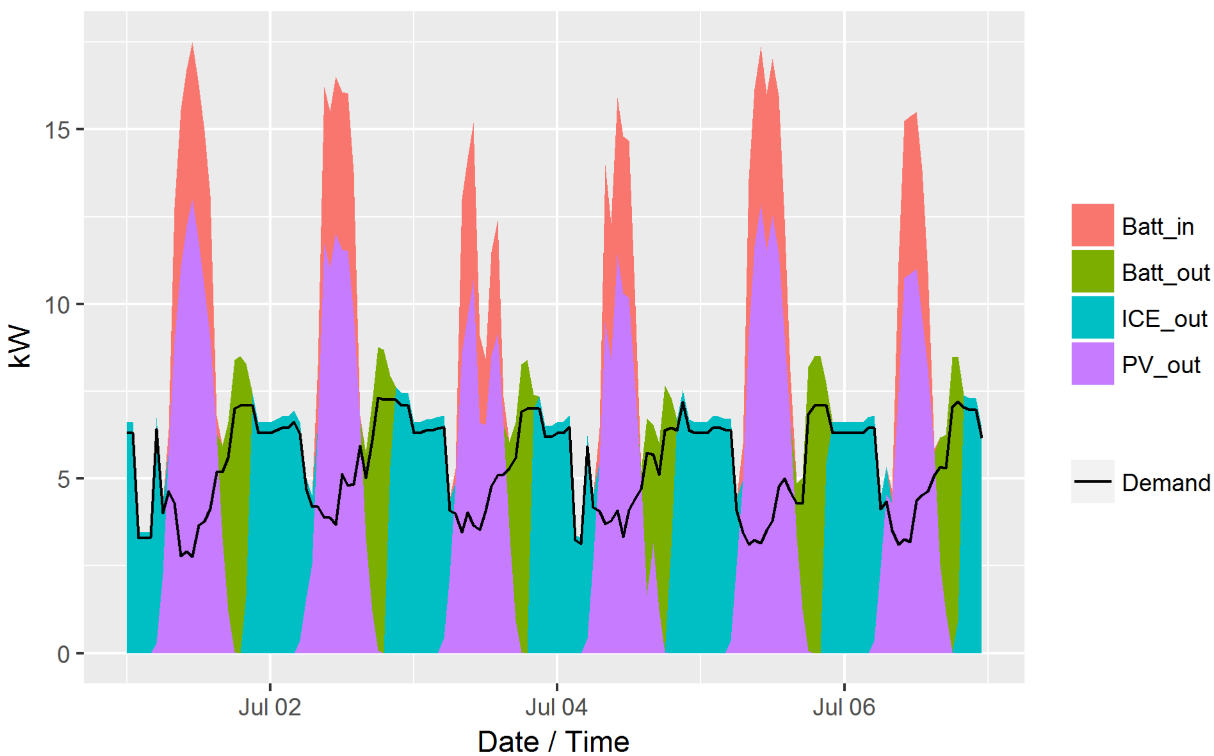

Figure 34. Generation Dispatch for the Bhalolpur Universal Service Design.

Required Tariffs and Subsidies for the Universal System Design

If the minigrid provider chooses to provide service for all customers in the village, the provider would be forced to increase the tariff to maintain profitability. If the tariff is increased to $0.54 / kWh, the minigrid project would be considered a feasible investment (See Table 6). However, if the tariffs were increased to $0.54 / kWh, the anchor tenant would likely defect from the minigrid. This would eliminate a substantial source of revenue for the provider and necessitate an even higher tariff for the residential consumers.

If the government opted to provided subsidies for the minigrid while retaining the tariff structure of $2 / month and $10 / month, the required annual subsidy per household is $27. This creates a total annual subsidy of $5,395 for the minigrid project.

Exploration of the Customer Marginal Cost

Figure 35 and Figure 36 plot the marginal cost of connecting additional customers to the minigrid as service expands. As seen in Figure 35, a significant increase in marginal cost occurs before the fiftieth customer is added to the minigrid. Figure 38 highlights that as this group of customers are added to the minigrid, the generator size must increases from 5 kW to 8 kW. This increased size results in operation at a lower capacity with lower efficiencies.

As shown in Figure 35, the marginal cost of generation remains relatively flat. However, inspection of Figure 37 indicates an inverse relationship between the marginal cost of PV generation and battery storage. This is an artifact of the 60% renewable energy constraint, which can be satisfied either with additional battery storage or additional PV generation. As PV generation is increased, the battery storage can be decreased and the system can still satisfy the 60% renewable constraint.

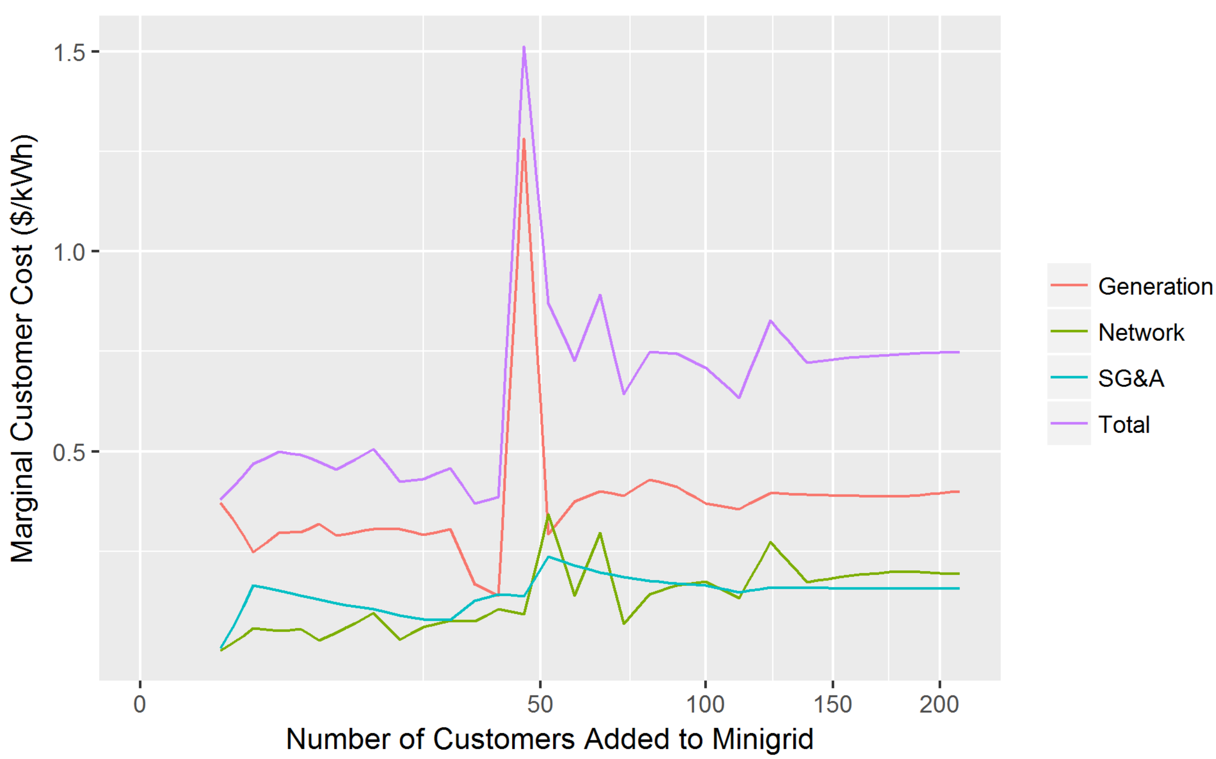

Figure 35. Marginal Breakdown for the India Village Minigrid

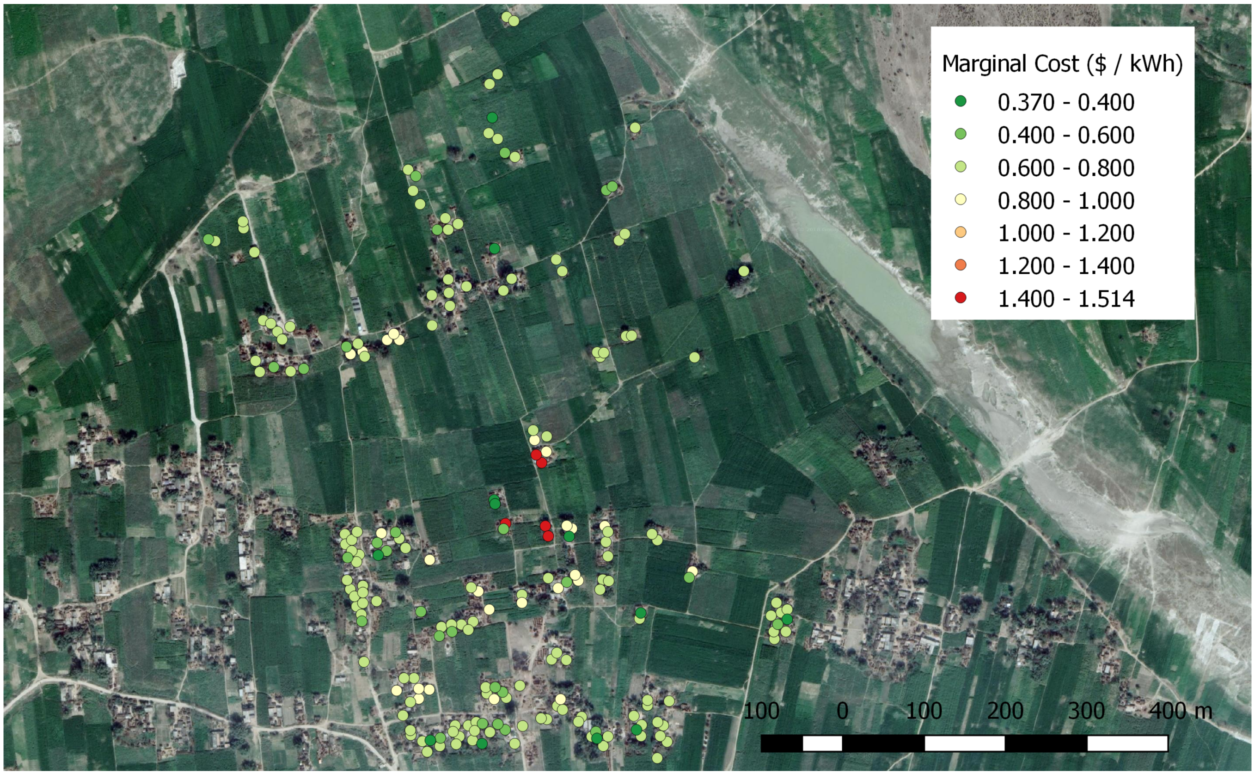

Figure 36. The Marginal Cost of Connecting Consumers in the Bhalolpur Village Minigrid.

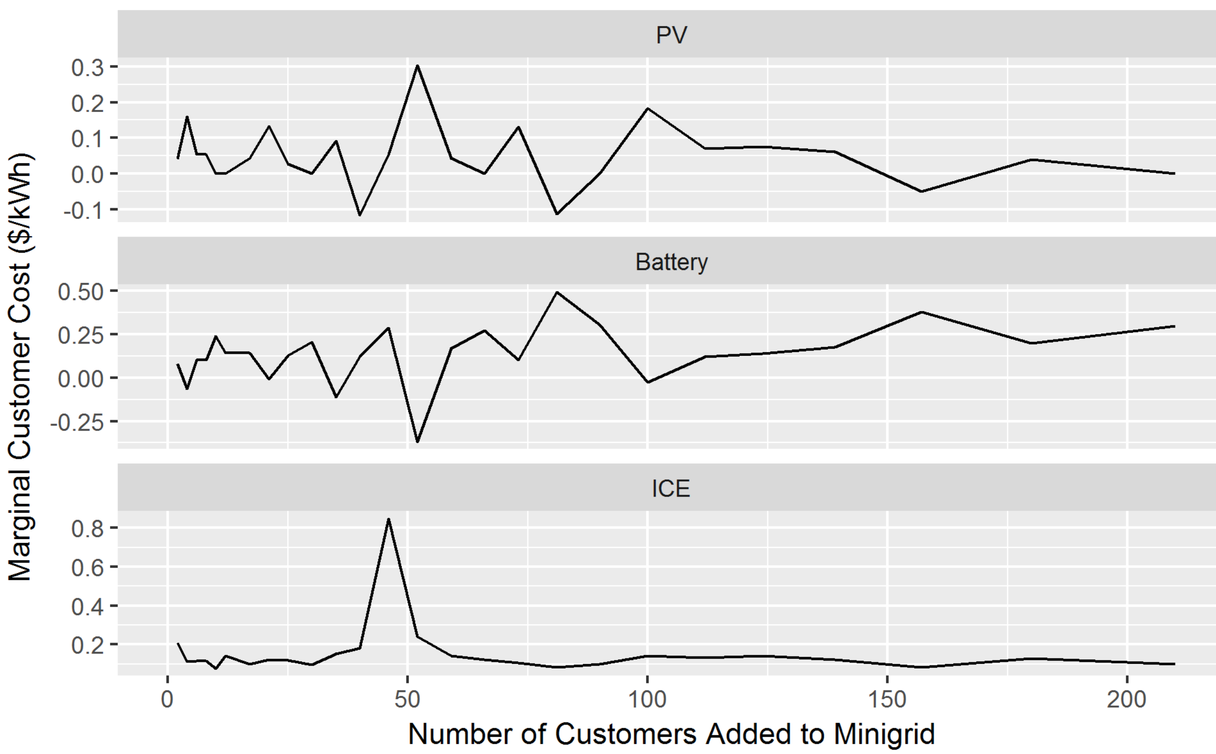

Figure 37. Marginal Cost of Generation for the Bhalolpur Minigrid

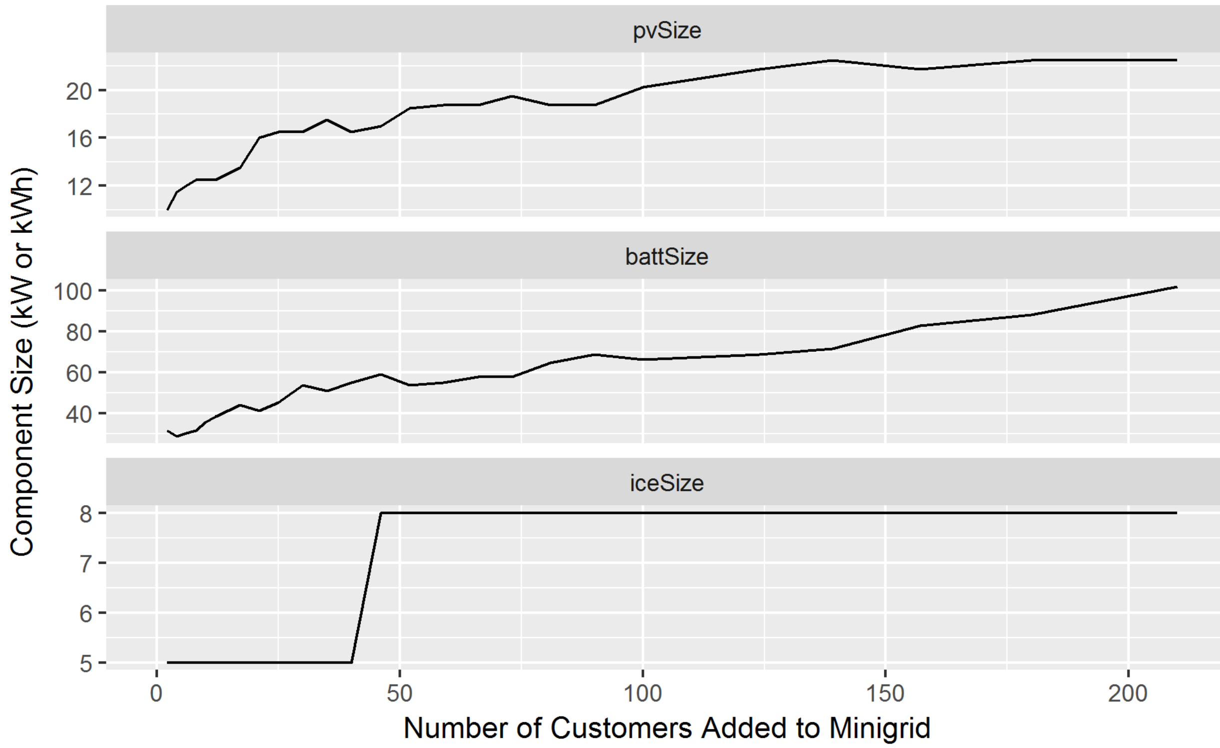

Figure 38. The size of PV, Battery, and ICE as the Bhalolpur Village Minigrid Expands.

Comparison to Alternative Technologies

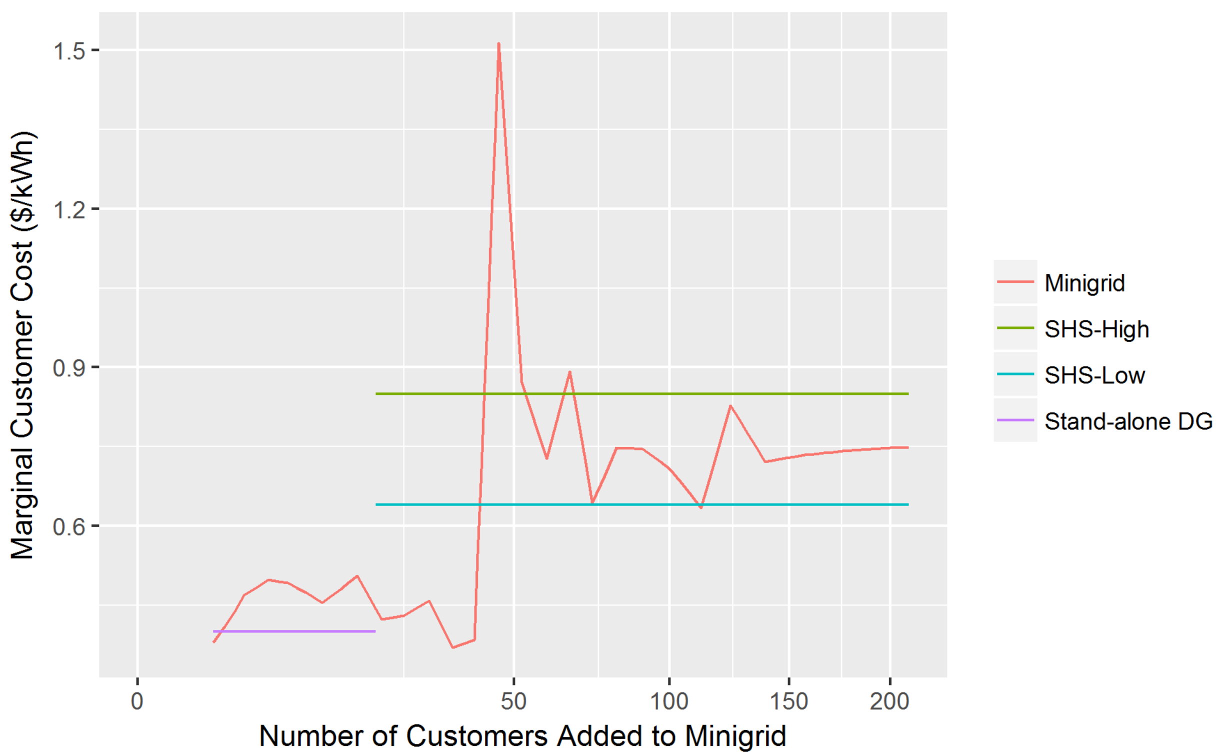

Figure 39. Comparison of Bhalolpur Minigrid to Alternative Technologies

Figure 39 compares the cost of minigrid service to the cost of alternative technologies such as diesel generation and solar home systems. The minigrid is less expensive than diesel generation for the cellular communications tower (anchor load), but only by a slight margin.

The residential consumers may be better served by solar home systems in this area. In this location, there is not a clear cost advantage with either technology, although quality of service with a minigrid would be higher.

Conclusions

The Behavior of Firms in the Free Market

Firms are incentivized to provided high reliability

Minigrid providers are generally motivated to provide high reliability levels. A significant portion of minigrid cost is due to fixed assets, and each additional kWh of sales translates to additional revenue. Typically, if the battery is depleted, the marginal cost of generation on a given day is set by the cost of diesel fuel as all other cost are sunk. An additional kWh during peak periods is usually provided by the diesel generator. This marginal cost is typically lower than the marginal revenue of additional sales.

Firms have little incentive to connect residential customers

As seen in the Nigeria case study, the most profitable scenario for the minigrid firm is to build a small network connecting just four commercial / industrial customers. This is mirrored in the Rwanda minigrid, where the most profitable minigrid includes only some of the commercial customers. The Bhalolpur village minigrid includes only the cellular phone tower and a single residential household located adjacent to the anchor load.

In the Nigeria and Rwanda case studies, the minigrid provider may still consider the project profitable with some residential customers connected to the minigrid, but the project would have a higher valuation if these residential customers were not included.

If the minigrid operator were to minimize generation cost as much as possible and rely extensively on diesel generation, the marginal cost of providing service may drop below the marginal revenue for some residential households. Due to the high reliance on diesel generation for these lower cost systems, this may not be a viable system design given governments policies to support renewable energy technologies.

Lastly, these studies are based on a consumer willingness to pay of approximately \$0.40-\$0.45 / kWh for electricity service in sub-Saharan Africa, and \$2/month for basic service in India. For the Nigerian village and Rwandan village presented, if the minigrid firms are capable of charging tariffs between \$0.50 – 0.80, connection of residential customers may become a profitable undertaking. For the village studied in Bihar, the flat subscription charges required for profitability are \$51 / year (\$4.26 / month)

Falling prices of solar PV and battery storage may expand the minigrid market

This thesis does not explore the effect of declining prices for solar photovoltaics and battery storage technologies. As the prices for these generation assets fall, the marginal cost of generation for residential customers will also decrease. Although this would not apply for minigrids constructed today, falling prices will have beneficial effects for future minigrids. For example, in five years, less expensive generation may lower the price of service such that connecting residential customers becomes profitable. Unfortunately, the price of distribution networks is likely to grow with inflation and may not see similar downward trends in cost.

Implications for Policy

Regulations for Reliability

Reliability levels should naturally remain high without regulatory intervention, however, if policy-makers desire to regulate the minimum reliability for minigrids, they can do so without fear of creating an additional cost burden.

This should be caveated with the condition that minigrid operators be allowed to utilize some amount of diesel generation which allows for excess capacity and high reliability levels.

Improving Access Through Minigrids

An aggressive cross-subsidization tariff at a minigrid site will not encourage providers to connect the most distant customers. Once the marginal cost of connecting a consumer exceeds the revenue provided, the minigrid expansion will halt. Customers which are overcharged, such as industrial and commercial customers, may disconnect if the tariff exceeds the cost of alternatives such as stand-alone diesel generation.

Adding baseload customers will not incentivize expansion of the minigrid. Adding baseload customers will not affect the marginal cost of adding additional customers, and minigrid expansion halts based on the threshold at which marginal cost exceeds marginal revenue. The addition of profitable baseload will not shift this boundary.

Incentives or subsidies based on maximizing customer connections will help extend minigrids to a point. However, this tariff or subsidy could be viewed as simply an increase in the marginal revenue per customer. The firm will still halt expansion once the increased marginal revenue due to the subsidy is exceeded by the marginal cost.

Strict stipulations on the number of customer connections are required if universal service is to be achieved. In a given territory, the firms must be incentivized to connect all consumers. These incentives must be maintained year-over-year. Given the high cost of battery replacement and diesel generation, unless the incentives are tied to future performance of the minigrid, operators may cut service to high cost customers. These high cost customers are typically residential customers with high evening loads requiring battery and diesel generation.

Cross-subsidizing remains a dangerous plan for governments to use in promoting minigrids. For high profit margin customers which could be used to cross-subsidize service, firms face competition from not only stand-alone generation, but other energy service firms. Other firms could offer cheaper service by serving only the commercial and industrial customers.

Implications for Planning

The Use of Minigrids in Planning

Due to the inherent market forces working against cross-subsidization schemes, unless the ability-to-pay of residential customers increases substantially, universal access through minigrids may only be achieved with significant subsidies from the government. With the decreasing price of solar home systems, minigrid providers will likely be competing with these firms when offering service to smaller households. Due to the competition from both diesel generation and solar home systems, minigrid providers should focus on high consumption customers who would realize benefits by switching from stand-along diesel generation to minigrid service. Planning for large-scale minigrids with hundreds of residential customers may be a least-cost solution in many cases, but will likely not attract significant investment unless government subsidies and service territories are guaranteed.

The Difficultly of Calculating a Levelized Cost of Energy

Planning tools such as LREM and HOMER provide a levelized cost of energy (LCOE) for minigrid service or distributed generation, but these numbers should not be construed as a price which could be offered to consumers.

These calculations do not account for the taxes which must be paid based on profits. LCOE calculations typically do not account for any net working capital and may not properly account for the tax advantage (or disadvantage) due to depreciation standards.

A pro-forma income statement which projects expected cash flows, accounts for working capital, and incorporates any necessary debt payments should be used when determining the tariffs required for a minigrid project.

The Impact of Network and Generation Cost in Planning

As expected, the generation costs remain relatively flat for residential consumers regardless of the geographic distribution of these customers. The marginal cost of the distribution network varies. In India, the marginal cost of the distribution network is as high as $0.25 / kWh for some residential customers. In Nigeria, due to higher consumption patterns, the marginal cost for the distribution network is only $0.10 / kWh for the fringe customers.

Areas for Improvement

Reliability modeling

The model assumes the same willingness to pay for all reliability levels. Higher reliability levels are rewarded due to higher quantities of sale for the minigrid operator. A model which modifies consumer willingness to pay based on reliability may provide a more accurate representation of this important minigrid characteristic.

Consumer Demand

Consumer demand is currently considered as a static input to the model with the assumption that consumers will not change behavior based on price. There are shortcomings to the approach. Basic microeconomics teaches that consumers will likely respond to price changes. Given the significant difference in energy cost between day-time consumption and evening consumption, it is possible that consumers may shift consumption patterns if minigrid providers used time-of-use pricing. A consumer demand model which varies demand based on price may yield interesting insights, although this would significantly increase the complexity of the model and expand the design space.

To some extent, the willingness to pay for various consumption levels is captured through the case studies. The Nigerian village represents the high consumptions customers with a lower willingness to pay on a per-unit basis ($0.40 / kWh). In the context of the Indian village, a flat willingness-to-pay of $2/month corresponds to a rate of approximately $0.41 / kWh for the modeled service.

Calculation of Marginal Cost

The model currently calculates a flat tariff regardless of the time during which energy is consumed. Additional complexity could allow minigrid providers to see the marginal cost for daytime load and evening load.

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Appendices

Appendix A: Income Statements for Minigrid Project Designs

Table 7. Pro-forma Income Statement for Profit Maximizing Nigerian Minigrid Design. Only the first eight years of operation are shown in this table. All values are in 1000 USD.

PRO - FORMA INCOME STATEMENT									
Timeline									
Calendar year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Nominal year	0	1	2	3	4	5	6	7	8
Revenues ($k USD)									
Operating Revenues									
Sale of electric power ($k USD)	-	25.4	26.6	28.0	29.3	30.8	32.4	34.0	35.7
Other revenue ($k USD)	-	-	-	-	-	-	-	-	-
Gross Revenue	-	25.4	26.6	28.0	29.3	30.8	32.4	34.0	35.7
Cost of Goods Sold ($k USD)									
Production Costs									
Fuel	-	7.3	7.6	8.0	8.4	8.8	9.3	9.7	10.2
Overhead Costs									
Labor	-	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3
Cost of Goods Sold	-	7.5	7.9	8.3	8.7	9.1	9.6	10.1	10.6
Gross Profit	-	17.8	18.7	19.7	20.7	21.7	22.8	23.9	25.1
Operating Expenses ($k USD)									
O&M Generation	-	0.6	0.6	0.6	0.7	0.7	0.7	0.8	0.8
O&M Network	-	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Depreciation and Amortization	-	5.4	5.4	5.4	5.4	5.4	5.4	6.0	6.0
Other expenses	-	-	-	-	-	-	-	-	-
Total operating expenses	-	6.1	6.2	6.2	6.2	6.3	6.3	6.9	7.0
Net Operating Income (EBIT)	-	12	13	13	14	15	16	17	18
Interest income/expense	-	(4)	(4)	(4)	(3)	(3)	(3)	(3)	(3)
Non operating income	-	-	-	-	-	-	-	-	-
Pretax Income	-	8	9	10	11	12	13	14	16
Net Income									
Tax	-	2	2	2	2	2	3	3	3
Net Income	-	6	7	8	9	10	11	11	12

VALUATION (DCF)									
Timeline									
Calendar Year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Nominal year	0	1	2	3	4	5	6	7	8
Free Cash Flow									
EBIT * (1 - tau)	-	9	10	11	12	12	13	14	14
+ Depreciation	-	5	5	5	5	5	5	6	6
- CAPEX (w/ inflation)	54	-	-	-	-	-	6	-	-
- ΔNWC	0.6	5.1	0.3	0.3	0.3	0.3	0.3	0.4	0.4
Free Cash Flow	(54.62)	9.67	15.17	15.87	16.61	17.39	12.68	19.17	20.07
Discounted Cash Flow									
Discount factor	1.00	0.87	0.76	0.66	0.58	0.51	0.44	0.38	0.34
Discounted cash flows (FCF)	(54.62)	8.43	11.54	10.54	9.62	8.79	5.59	7.37	6.73

PV of FCF	63.96	**IRR (FCF)**	**28%**
PV of Perpetuity	-		
Total NPV	**63.96**		

Table 8. Pro-forma Income Statement for Universal Service Nigerian Minigrid Design. Only the first eight years of operation are shown in this table. All values are in 1000 USD.

PRO - FORMA INCOME STATEMENT

	2018	2019	2020	2021	2022	2023	2024	2025	2026
Timeline									
Calendar year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Nominal year	0	1	2	3	4	5	6	7	8
Revenues ($k USD)									
Operating Revenues									
Sale of electric power ($k USD)	-	117.0	122.8	129.0	135.4	142.2	149.3	156.8	164.6
Other revenue ($k USD)	-	-	-	-	-	-	-	-	-
Gross Revenue	-	117.0	122.8	129.0	135.4	142.2	149.3	156.8	164.6
Cost of Goods Sold ($k USD)									
Production Costs									
Fuel	-	35.4	37.1	39.0	40.9	43.0	45.1	47.4	49.7
Overhead Costs									
Labor	-	8.5	8.9	9.4	9.8	10.3	10.9	11.4	12.0
Cost of Goods Sold	-	43.9	46.0	48.4	50.8	53.3	56.0	58.8	61.7
Gross Profit	-	73.1	76.8	80.6	84.7	88.9	93.3	98.0	102.9
Operating Expenses ($k USD)									
O&M Generation	-	3.6	3.7	3.9	4.1	4.3	4.5	4.8	5.0
O&M Network	-	0.9	0.9	1.0	1.0	1.1	1.1	1.2	1.2
Depreciation and Amortization	-	54.7	54.7	54.7	54.7	54.7	74.2	74.2	74.2
Other expenses	-	-	-	-	-	-	-	-	-
Total operating expenses	-	59.1	59.3	59.6	59.8	60.1	79.9	80.1	80.4
Net Operating Income (EBIT)	-	14	17	21	25	29	13	18	22
Interest income/expense	-	(40)	(38)	(36)	(34)	(32)	(30)	(28)	(26)
Non operating income	-	-	-	-	-	-	-	-	-
Pretax Income	-	(26)	(20)	(15)	(9)	(3)	(16)	(10)	(3)
Net Income									
Tax	-	(5)	(4)	(3)	(2)	(1)	(3)	(2)	(1)
Net Income	-	(20)	(16)	(12)	(7)	(2)	(13)	(8)	(3)

VALUATION (DCF)

	2018	2019	2020	2021	2022	2023	2024	2025	2026
Timeline									
Calendar Year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Nominal year	0	1	2	3	4	5	6	7	8
Free Cash Flow									
EBIT * (1 - tau)	-	11	14	17	20	23	11	14	18
+ Depreciation	-	55	55	55	55	55	74	74	74
- CAPEX (w/ inflation)	547	-	-	-	-	195	-	-	-
- ΔNWC	2.9	23.5	1.3	1.4	1.5	1.5	1.6	1.7	1.8
Free Cash Flow	(549.86)	42.36	67.32	70.14	73.10	(119.06)	83.38	86.81	90.41
Discounted Cash Flow									
Discount factor	1.00	0.87	0.76	0.66	0.58	0.51	0.44	0.38	0.34
Discounted cash flows (FCF)	(549.86)	36.95	51.24	46.57	42.34	(60.16)	36.75	33.38	30.33

PV of FCF	(258.79)	**IRR (FCF)**	**3%**
PV of Perpetuity	-		
Total NPV	**(258.79)**		

Table 9. Pro-forma Income Statement for Profit Maximizing Rwandan Minigrid Design. Only the first eight years of operation are shown in this table. All values are in 1000 USD.

PRO - FORMA INCOME STATEMENT

	2018	2019	2020	2021	2022	2023	2024	2025	2026
Timeline									
Calendar year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Nominal year	0	1	2	3	4	5	6	7	8
Revenues ($k USD)									
Operating Revenues									
Sale of electric power ($k USD)	-	14.9	15.6	16.4	17.2	18.1	19.0	19.9	20.9
Other revenue ($k USD)	-	-	-	-	-	-	-	-	-
Gross Revenue	-	14.9	15.6	16.4	17.2	18.1	19.0	19.9	20.9
Cost of Goods Sold ($k USD)									
Production Costs									
Fuel	-	5.2	5.4	5.7	6.0	6.3	6.6	6.9	7.3
Overhead Costs									
Labor	-	0.6	0.6	0.7	0.7	0.7	0.8	0.8	0.9
Cost of Goods Sold	-	5.8	6.1	6.4	6.7	7.0	7.4	7.7	8.1
Gross Profit	-	9.1	9.6	10.0	10.5	11.1	11.6	12.2	12.8
Operating Expenses ($k USD)									
O&M Generation	-	0.5	0.6	0.6	0.6	0.7	0.7	0.7	0.8
O&M Network	-	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2
Marketing and Sales	-	-	-	-	-	-	-	-	-
Other expenses	-	-	-	-	-	-	-	-	-
Total operating expenses	-	4.4	4.4	4.4	4.5	4.5	4.6	5.2	5.2
Net Operating Income (EBIT)	-	5	5	6	6	7	7	7	8
Interest income/expense	-	(3)	(3)	(2)	(2)	(2)	(2)	(2)	(2)
Non operating income	-	-	-	-	-	-	-	-	-
Pretax Income	-	2	3	3	4	4	5	5	6
Net Income									
Tax	-	0	1	1	1	1	1	1	1
Net Income	-	2	2	3	3	4	4	4	5

VALUATION (DCF)

	2018	2019	2020	2021	2022	2023	2024	2025	2026
Timeline									
Calendar Year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Nominal year	0	1	2	3	4	5	6	7	8
Free Cash Flow									
EBIT * (1 - tau)	-	4	4	4	5	5	6	6	6
+ Depreciation	-	4	4	4	4	4	4	4	4
- CAPEX (w/ inflation)	37	-	-	-	-	-	6	-	-
- ΔNWC	0.4	3.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Free Cash Flow	(37.60)	4.50	7.67	8.02	8.38	8.76	3.64	9.69	10.13
Discounted Cash Flow									
Discount factor	1.00	0.87	0.76	0.66	0.58	0.51	0.44	0.38	0.34
Discounted cash flows (FCF)	(37.60)	3.93	5.84	5.32	4.85	4.43	1.61	3.73	3.40

PV of FCF	18.32	**IRR (FCF)**	**20%**
PV of Perpetuity	-		
Total NPV	**18.32**		

Table 10. Pro-forma Income Statement for Universal Service Rwandan Minigrid Design. Only the first eight years of operation are shown in this table. All values are in 1000 USD.

PRO - FORMA INCOME STATEMENT

	2018	2019	2020	2021	2022	2023	2024	2025	2026
Timeline									
Calendar year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Nominal year	0	1	2	3	4	5	6	7	8
Revenues ($k USD)									
Operating Revenues									
Sale of electric power ($k USD)	-	24.5	25.8	27.1	28.4	29.8	31.3	32.9	34.5
Other revenue ($k USD)	-	-	-	-	-	-	-	-	-
Gross Revenue	-	24.5	25.8	27.1	28.4	29.8	31.3	32.9	34.5
Cost of Goods Sold ($k USD)									
Production Costs									
Fuel	-	8.7	9.1	9.6	10.1	10.6	11.1	11.7	12.3
Overhead Costs									
Labor	-	5.0	5.3	5.6	5.8	6.1	6.4	6.8	7.1
Cost of Goods Sold	-	13.8	14.4	15.2	15.9	16.7	17.6	18.4	19.4
Gross Profit	-	10.8	11.3	11.9	12.5	13.1	13.8	14.5	15.2
Operating Expenses ($k USD)									
O&M Generation	-	0.8	0.9	0.9	1.0	1.0	1.1	1.1	1.2
O&M Network	-	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3
Depreciation and Amortization	-	8.4	8.4	8.4	8.4	8.4	8.4	10.7	10.7
Other expenses	-	-	-	-	-	-	-	-	-
Total operating expenses	-	9.5	9.5	9.6	9.6	9.7	9.8	12.0	12.1
Net Operating Income (EBIT)	-	1	2	2	3	3	4	2	3
Interest income/expense	-	(6)	(6)	(5)	(5)	(5)	(4)	(4)	(4)
Non operating income	-	-	-	-	-	-	-	-	-
Pretax Income	-	(5)	(4)	(3)	(2)	(1)	(0)	(2)	(1)
Net Income									
Tax	-	(1)	(1)	(1)	(0)	(0)	(0)	(0)	(0)
Net Income	-	(4)	(3)	(2)	(2)	(1)	(0)	(1)	(1)

VALUATION (DCF)

	2018	2019	2020	2021	2022	2023	2024	2025	2026
Timeline									
Calendar Year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Nominal year	0	1	2	3	4	5	6	7	8
Free Cash Flow									
EBIT * (1 - tau)	-	1	1	2	2	3	3	2	2
+ Depreciation	-	8	8	8	8	8	8	11	11
- CAPEX (w/ inflation)	84	-	-	-	-	-	22	-	7
- ΔNWC	0.7	4.9	0.3	0.3	0.3	0.3	0.3	0.4	0.4
Free Cash Flow	(85.17)	4.54	9.59	9.99	10.40	10.84	(10.82)	12.22	5.86
Discounted Cash Flow									
Discount factor	1.00	0.87	0.76	0.66	0.58	0.51	0.44	0.38	0.34
Discounted cash flows (FCF)	(85.17)	3.96	7.30	6.63	6.02	5.48	(4.77)	4.70	1.97

PV of FCF	(36.35)	**IRR (FCF)**	**6%**
PV of Perpetuity	-		
Total NPV	**(36.35)**		

Table 11. Pro-forma Income Statement for Profit Maximizing Bihar, India Minigrid Design. Only the first eight years of operation are shown in this table. All values are in 1000 USD.

PRO - FORMA INCOME STATEMENT

Timeline									
Calendar year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Nominal year	0	1	2	3	4	5	6	7	8
Revenues ($k USD)									
Operating Revenues									
Sale of electric power ($k USD)	-	7.1	7.4	7.8	8.2	8.6	9.0	9.5	10.0
Other revenue ($k USD)	-	-	-	-	-	-	-	-	-
Gross Revenue	-	7.1	7.4	7.8	8.2	8.6	9.0	9.5	10.0
Cost of Goods Sold ($k USD)									
Production Costs									
Fuel	-	2.8	2.9	3.1	3.2	3.4	3.6	3.8	3.9
Overhead Costs									
Labor	-	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2
Cost of Goods Sold	-	2.9	3.1	3.2	3.4	3.6	3.7	3.9	4.1
Gross Profit	-	4.2	4.4	4.6	4.8	5.1	5.3	5.6	5.9
Operating Expenses ($k USD)									
O&M Generation	-	0.4	0.4	0.5	0.5	0.5	0.5	0.6	0.6
O&M Network	-	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2
Depreciation and Amortization	-	2.3	2.3	2.3	2.3	2.3	2.3	2.3	3.1
Other expenses	-	-	-	-	-	-	-	-	-
Total operating expenses	-	2.8	2.8	2.9	2.9	2.9	3.0	3.0	3.8
Net Operating Income (EBIT)	-	1	2	2	2	2	2	3	2
Interest income/expense	-	(2)	(2)	(1)	(1)	(1)	(1)	(1)	(1)
Non operating income	-	-	-	-	-	-	-	-	-
Pretax Income	-	(0)	(0)	0	0	1	1	1	1
Net Income									
Tax	-	(0)	(0)	0	0	0	0	0	0
Net Income	-	(0)	(0)	0	0	1	1	1	1

VALUATION (DCF)

Timeline									
Calendar Year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Nominal year	0	1	2	3	4	5	6	7	8
Free Cash Flow									
EBIT * (1 - tau)	-	1	1	1	2	2	2	2	2
+ Depreciation	-	2	2	2	2	2	2	2	3
- CAPEX (w/ inflation)	23	-	-	-	-	-	-	8	5
- ΔNWC	0.2	1.4	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Free Cash Flow	(23.02)	1.92	3.41	3.56	3.72	3.88	4.05	(3.86)	(0.15)
Discounted Cash Flow									
Discount factor	1.00	0.87	0.76	0.66	0.58	0.51	0.44	0.38	0.34
Discounted cash flows (FCF)	(23.02)	1.68	2.60	2.36	2.15	1.96	1.79	(1.48)	(0.05)

PV of FCF	(5.56)	**IRR (FCF)**	**10%**
PV of Perpetuity	-		
Total NPV	**(5.56)**		

Table 12. Pro-forma Income Statement for Universal Service Bihar, India Minigrid Design. Only the first eight years of operation are shown in this table. All values are in 1000 USD.

PRO - FORMA INCOME STATEMENT									
Timeline									
Calendar year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Nominal year	0	1	2	3	4	5	6	7	8
Revenues ($k USD)									
Operating Revenues									
Sale of electric power ($k USD)	-	15.5	16.3	17.1	18.0	18.9	19.8	20.8	21.8
Other revenue ($k USD)	-	-	-	-	-	-	-	-	-
Gross Revenue	-	15.5	16.3	17.1	18.0	18.9	19.8	20.8	21.8
Cost of Goods Sold ($k USD)									
Production Costs									
Fuel	-	5.7	6.0	6.3	6.6	6.9	7.3	7.6	8.0
Overhead Costs									
Labor	-	3.1	3.2	3.4	3.6	3.8	3.9	4.1	4.3
Cost of Goods Sold	-	8.8	9.2	9.7	10.2	10.7	11.2	11.8	12.4
Gross Profit	-	6.7	7.1	7.4	7.8	8.2	8.6	9.0	9.5
Operating Expenses ($k USD)									
O&M Generation	-	0.7	0.7	0.8	0.8	0.8	0.9	0.9	1.0
O&M Network	-	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Depreciation and Amortization	-	6.0	6.0	6.0	6.0	6.0	6.0	8.5	8.5
Other expenses	-	-	-	-	-	-	-	-	-
Total operating expenses	-	6.8	6.9	6.9	7.0	7.0	7.1	9.6	9.7
Net Operating Income (EBIT)	-	(0)	0	0	1	1	2	(1)	(0)
Interest income/expense	-	(4)	(4)	(4)	(4)	(3)	(3)	(3)	(3)
Non operating income	-	-	-	-	-	-	-	-	-
Pretax Income	-	(4)	(4)	(3)	(3)	(2)	(2)	(4)	(3)
Net Income									
Tax	-	(1)	(1)	(1)	(1)	(0)	(0)	(1)	(1)
Net Income	-	(3)	(3)	(3)	(2)	(2)	(1)	(3)	(2)

VALUATION (DCF)									
Timeline									
Calendar Year	2018	2019	2020	2021	2022	2023	2024	2025	2026
Nominal year	0	1	2	3	4	5	6	7	8
Free Cash Flow									
EBIT * (1 - tau)	-	(0)	0	0	1	1	1	(0)	(0)
+ Depreciation	-	6	6	6	6	6	6	8	8
- CAPEX (w/ inflation)	60	-	-	-	-	-	25	-	-
- ΔNWC	0.5	3.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Free Cash Flow	(60.47)	2.79	5.97	6.21	6.46	6.72	(17.79)	7.78	8.09
Discounted Cash Flow									
Discount factor	1.00	0.87	0.76	0.66	0.58	0.51	0.44	0.38	0.34
Discounted cash flows (FCF)	(60.47)	2.43	4.54	4.12	3.74	3.40	(7.84)	2.99	2.71
PV of FCF	(40.37)		**IRR (FCF)**	**-3%**					
PV of Perpetuity	-								
Total NPV	**(40.37)**								

Appendix B: Discount Rates for Minigrid Valuation

Table 13. Discount Rates for Minigrid Case Study Valuation

Variable	Value	Unit
Discount rate (WACC)	14.63%	% P.A.
Unlevered Cost of Capital	15.75%	% P.A.
Long Term Debt Rate	7.00%	% P.A.
Inflation rate	5.00%	% P.A.
Tax rate	20.00%	% P.A.
Discount rate (WACC - Real)	9.17%	% P.A.

Appendix C: Common Design Parameters for Minigrid Case Studies

Table 14. Typical Design Parameters and Cost Factors Used in Minigrid Case Studies

Parameter	Value	Units
Diesel Fuel Cost	0.75	USD / L
Minimum Renewable Energy	60	% of Generation
Demand Growth Rate	0	%
Project Lifetime	25	Years
MG Dispatch	Load Following	
PV Panel Cost	125	USD / Panel
PV Installation Cost	40	% of Component Cost
PV Panel Size	250	W
Battery Cost	250	USD / Battery
Battery Installation Cost	20	% of Component Cost
Battery Size	1.38	kWh
Lifetime Throughput	845	kWh
10 kW Generator Cost	4600	USD
Full Load Eff.	0.376	L Fuel / kWh
Lifetime	35000	Hours
60 kW Generator Cost	1200	USD
Full Load Eff.	0.307	L Fuel / kWh
Lifetime	35000	Hours
Genset Installation Cost	80	% of Component Cost
Network Type	Grid-compatible Overhead	
Total Network Investment Cost	2k - 15k	USD / km
Network Lifetime	25	Years
Load Voltage	400	V
Distribution Loss Factor	5%	