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TITLE **Microgrids and High-Quality Central Grid Alternatives: Challenges and Imperatives Elucidated by Case Studies and Simulation**

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Microgrids and High-Quality Central Grid Alternatives: Challenges and Imperatives Elucidated by Case Studies and Simulation

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IN

ENGINEERING & PUBLIC POLICY

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More than many students, I have had other obligations in addition to being a doctoral student. I am very grateful to our former department head, M. Granger Morgan, as well as Jay, for being understanding of the commitments I've made to my organization, EarthSpark International, in Haiti. I am also grateful to the EPP staff, especially Vicki Finney, Barbara Bugosh, and Adam Loucks, for their patience and willingness to help me while so often out of town and/or failing to meet deadlines.

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ABSTRACT

Energy poverty – the circumstance of depending on low quality fuels and inefficient end-uses, or conversely, the lack of access to modern energy services – is one of the defining global issues of our time. Access to electricity is essential to eradicating energy poverty and empowering individuals, communities and economies, to reach their potential. Globally, 1.3 billion people, mainly in less developed countries, lack access to electricity. While central grid extension often provides electricity at very low cost, the reliability of the central grid in less developed countries is so low that the priority given by policy makers to central grid extension must be questioned. Rather than maximizing the extent of often unreliable or simply unenergized central grid extensions, we demonstrate the imperative to consider a multi-track approach to electricity access that includes microgrids and high quality solar lighting products. Through case studies and modeling efforts based on extensive empirical data, we provide new insight to this imperative and elucidate the nature of the challenges and solutions for microgrids to eradicate energy poverty.

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Chapter 1: INTRODUCTION

Energy poverty – the circumstance of depending on low quality fuels and inefficient end-uses, or conversely, the lack of access to modern energy services – is one of the defining global issues of our time. Access to electricity is essential to eradicating energy poverty and empowering individuals, communities and economies, to reach their potential. The strong rate of diminishing marginal benefit to the Human Development Index (HDI) from per capita electricity consumption is striking, with a sharp increase in HDI within the first few kilowatt-hours per capita of annual consumption, as shown in Figure 1.

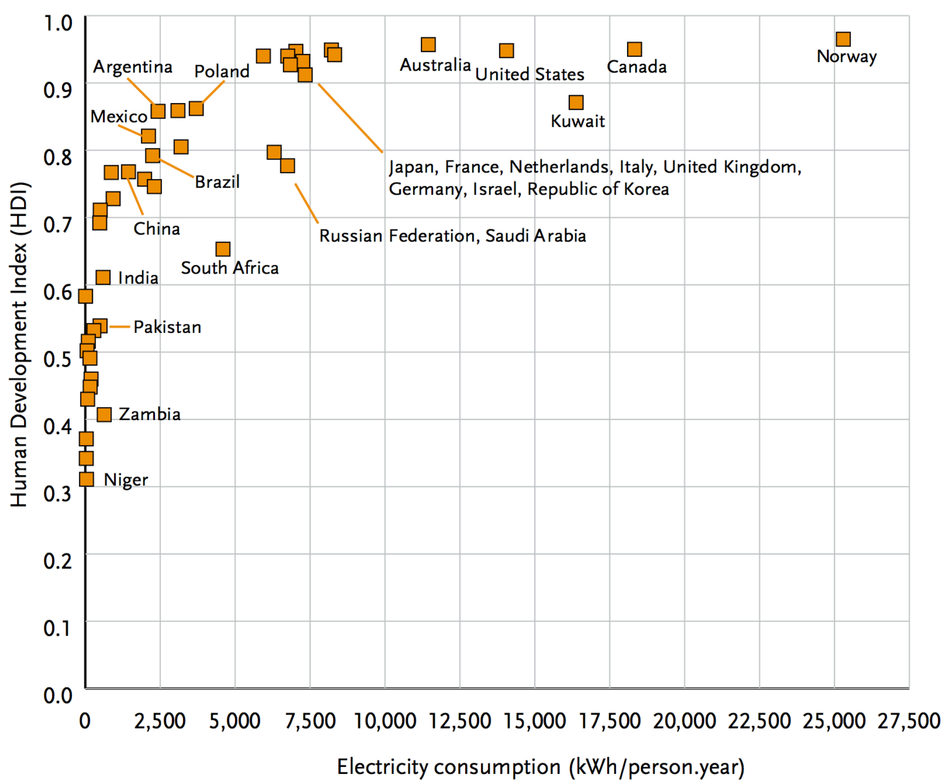


Figure 1: Relationship between Human Development Index (HDI) and per capita Annual Electricity Consumption (United Nations Development Programme, 2006)

While the levels of consumption afforded by access to the central grid have the potential to greatly enhance human development, actual consumption is subject to the reliability and availability of the central grid. Due to the institutional complexities of extending the central grid, a policy whose goal is grid extension may not result in actual electricity access for years. Many developing countries have low levels of grid reliability, especially in rural areas, which results in dependence on low quality lighting fuels like kerosene as a back-up to the grid, and their continued use while waiting for a grid extension to arrive. High quality alternatives for lighting, such as solar lamps, solar home systems and microgrids have the potential to be deployed more quickly than central grids and may have higher levels of reliability. Not to be used as a replacement for central grid electricity access, these alternatives offer a potentially compelling route to ameliorate energy poverty if they are pursued in parallel.

In this dissertation, I highlight the imperative of increasing access to electricity while commenting on the nature of the challenges and solutions for microgrids to do so. This is achieved through case studies as well as modeling efforts based on extensive empirical data.

In Chapter two, consumer surplus for lighting provided by low quality fuels, high quality grid alternatives and the central grid is modeled based on demand curves derived from the Lighting Africa Market Assessment (International Finance Corporation and The World Bank, 2008). Using the expressions for consumer surplus from lighting, a functional form for the willingness to pay for high quality grid alternatives at empirical rates of central grid outage, and a functional form for a consumer's maximum acceptable central grid outage rate are made explicit. The analysis demonstrates that electric lighting reduces consumer expenditures and increases consumer surplus. Furthermore, the analysis shows that high quality lighting alternatives are preferable to central grids operating below specific levels of reliability. Unless countries take a parallel path approach to electrification, where high quality lighting alternatives are strategically deployed to areas that will not be connected to the central grid for years or that are connected but experience high outage rates, consumers will forgo substantial economic value.

In Chapter three, the dismal state of Haiti's rural microgrid context is discussed at length. All 36 of Haiti's diesel micro-grids operate for far fewer hours than their nominal operating schedules, which are typically three to four hours a night for four to five nights per week. On one closely studied microgrid we find that tariffs are set at levels 10% below operating costs, which prevent them from operating at their scheduled output, and that grid operators do not have sufficient working capital to make up for gaps in untimely customer tariff payments. For this microgrid, we model 23 demand- and supply-side interventions to determine whether operating costs can be reduced to levels below tariffs, and, if so, what the equivalent increase in hours of availability would be. We then model a subset of interventions to simulate the effect of working capital. Replacing incandescent light bulbs with CFLs and using a smaller diesel generator or a hybrid PV-diesel system halves operating costs relative to the existing system and would allow the grid to double its operating hours while yielding a positive return on investment with the existing tariffs. Other demand-side interventions, such as LED light bulbs, load-limiters, and load-shifting, coupled with an appropriately sized diesel generator do not offer as great a level of operational cost savings or as many additional hours of availability as the CFL-replacement intervention.

Chapter four presents a case for the commercial viability of microgrids based on a case study of a private rural microgrid in Haiti. Situated at a level of energy service availability between solar home systems and central grids, microgrids are emerging as a scalable model for rural electrification. However, their potential to scale is contingent on their commercial viability. Earlier work has begun to assess the commercial viability of microgrids based on a comparison of total levelized unit energy costs to customer tariffs. Assuming appropriate tariffs, two arguments have emerged against the case for commercial microgrids: 1. User-specific costs on microgrids are high, which make them unsuitable for pay-as-you-go tariffs; and 2. Low-income customers are too poor to make consistent payments for electricity for microgrid operators to earn cost recovery (Economic Consulting

Associates Limited , 2013). The operation of a rural microgrid in Haiti shows that neither argument is generally applicable. Anonymized consumption and payment data from customers' smart meters for ten months of operations was analyzed to assess these claims. I found that pay-as-you-go payments were sufficient for user-specific costs to be recovered within 5 years for 78% of users, and 3 years for 57% of users. I also found that the frequency, quantity and magnitude of user payments are sufficient to provide regular cash flow to the utility.

In Chapter five, we analyze best practices from the microgrid literature through the lens of detailed case studies constructed from in-person interviews and field visits to microgrid developers in India, Malaysia, and Haiti. This chapter is a stand-alone adaptation of a chapter from the report, "Microgrids for rural electrification: A critical review of best practices based on seven case studies" published in 2014 by the United Nations Foundation under its Sustainable Energy for All banner (Schnitzer et al., 2014). Our analysis takes into account developers' varying objectives, which range from delivering societal benefits to delivering profits to shareholders. In doing so, we obtain a new set of lessons learned, which incorporate the unique challenges and opportunities that arise in the real world. Our objective in publishing this analysis is to improve the likelihood of success for developers who face the unpredictability and idiosyncrasies of the real world on a daily basis.

Chapter 2: Alternatives to Unreliable Central Grids for Lighting Can Increase Consumer Surplus

Abstract

Central grid extension is the predominant policy taken by governments in developing countries towards increasing access to electricity. While the levels of consumption afforded by access to the central grid have the potential to greatly enhance human development, actual consumption is subject to the reliability of the central grid. Further, due to the institutional complexities of extending the central grid, a policy towards grid extension may not result in actual construction for many years. Many developing countries have low levels of grid reliability, especially in rural areas, which results in dependence on low quality lighting fuels like kerosene as a back-up to the grid, and their continued use while waiting for a grid extension to arrive. High quality alternatives for lighting, such as solar lamps, solar home systems and microgrids have the potential to be deployed more quickly than central grids and may have higher levels of reliability. Using demand curves for lighting in five African countries derived from the Lighting Africa Market Assessment, we model consumer surplus for lighting provided by low quality fuels, high quality grid alternatives and the central grid. We derive a functional form for the willingness to pay for high quality grid alternatives at empirical rates of central grid outage, and a functional form for a consumer's maximum acceptable central grid outage rate. Our analysis demonstrates that electric lighting saves consumers on the order of 1 to 5 USD per month, and increases consumer surplus by 2 to 18 USD per month. We find that high quality lighting alternatives are preferable to central grids that have an average system unavailability index (ASUI) of 13% to 40%. Unless countries take a parallel path approach to electrification,

where high quality lighting alternatives are strategically deployed to areas that will not be connected to the central grid for years or that are connected but experience high outage rates, consumers will forgo substantial economic value.

This paper was written with Santosh Harish.

2.1 Introduction

Universal access to modern energy services is the defining goal of the energy for development paradigm (United Nations, 2013). Globally, 1.3 billion people, mainly in developing countries, lack access to electricity. Without dramatic changes in the means to address energy poverty, the International Energy Agency projects that 2030 will look almost identical to today in terms of the population without electricity access, highlighting the tremendous task before the global community if universal electricity access is to be achieved (International Energy Agency, 2012). Here, we want to refocus the objective on providing essential energy services rather than maximizing the extent of the central grid.

Governments will play an essential role in improving electricity access. Around the globe, governments rely on a wide range of institutional models and technologies to meet their electricity access goals and provide different levels of energy services to end-users. The policy of choice has been central grid (CG) extension. While this strategy has been successful in developed countries and more recently in China, it has not been effective in many populous areas; the median electrification rate in African countries is just 36%, and in developing Asian countries it is 66% (International Energy Agency, 2012). While central grid extension often provides electricity at very low cost, the reliability of the central grid in less developed countries is so low that the priority given by policy makers to central grid extension must be questioned.

As reported in the World Bank's Enterprise Survey on infrastructure, respondents in African countries suffer from a median of 6 outages per month, with respondents in 10 countries experiencing over 5% of the year without electricity from the central grid (World Bank, 2014). The former figure is equivalent to a monthly expression of the System Average Interruption Frequency Index (SAIFI). The latter figure is equivalent to the ratio of the System Average Interruption Duration Index (SAIDI) to the total number of hours in a year, 8,760. This figure is also equivalent to the Average Service Unavailability Index (ASUI). Figure 2 presents monthly SAIFI and ASUI data for 29 of the 33 African countries with respondents to the World Bank Enterprise Survey.

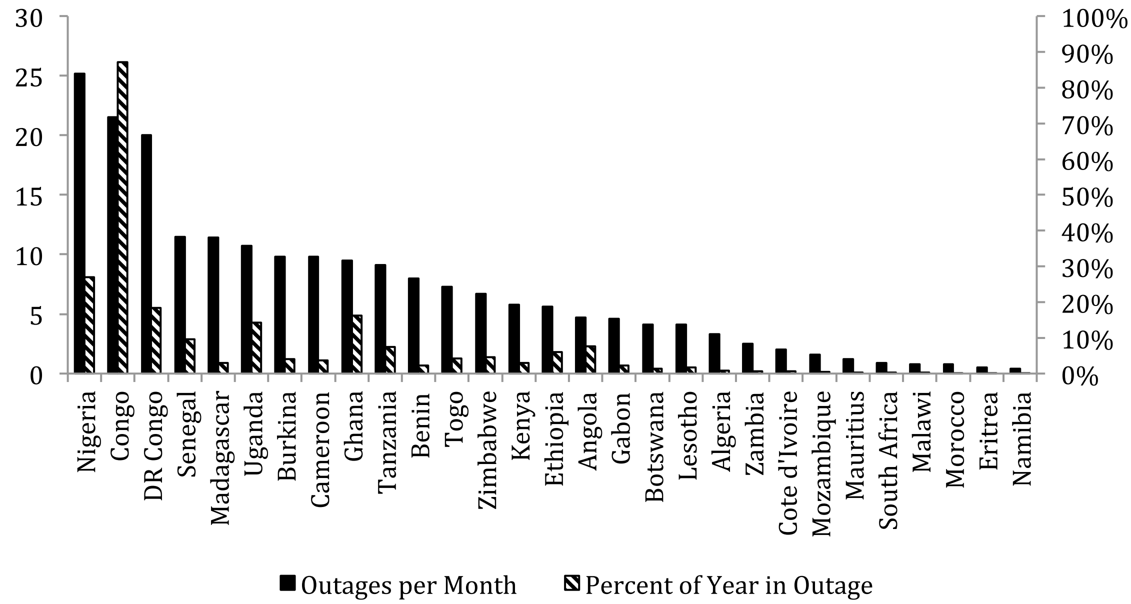


Figure 2: Frequency of Central Grid Outages (SAIFI) on the left scale and Average System Unavailability Index (ASUI) on the right scale for African Countries. Sorted in descending order by SAIFI.1

Some governments are promoting a variety of decentralized technologies that include microgrids, solar home systems, and smaller off-grid solar lighting devices as alternatives to the central grid. Solar home systems and off-grid solar lighting devices are affordable and quick to deploy, but they are capable of providing limited electricity services such as lighting and cell phone charging. Microgrids are defined as one or more local generation units supplying electricity to domestic, commercial, or institutional consumers over a local distribution grid and can be an important alternative or enhancement to the effectiveness of central grid extension to increase access to reliable electricity services in developing economies (Kirubi et al., 2008). In its "Energy for All" scenario, the IEA projects that 55% of additional connections needed for universal energy

[1] Data sourced from (World Bank, 2014). Percent of year in outage (ASUI) is calculated by multiplying response to survey question of number of outages per month (SAIFI) by response to survey question of average duration of outage. This result is multiplied by 12 (months per year) and divided by 8,760 (hours per year) to calculate percent of year in outage.

access by 2030 will depend on microgrids and off-grid solutions, with roughly 60% of those connections occurring on microgrids and 40% on smaller household-scale devices (International Energy Agency, 2012).

The UN's Sustainable Energy for All (SE4All) definition for access is useful. The International Energy Agency (IEA) and the World Bank's Energy Sector Management Assistance Program (ESMAP) developed the following definition in their "Global Tracking Framework" for SE4All: "Access is defined as the ability to obtain energy that is adequate, available when needed, reliable, of good quality, affordable, legal, convenient, healthy, and safe for all required energy applications across households, productive enterprises, and community institutions." (Banerjee, et al., 2013).

This definition differs from conventional definitions of access to electricity, which have typically been measured as a binary feature of a household having an electrical connection or not. The "binary" definition, along with other definitions that go so far as to specify a particular number of Watts or kilowatt-hours (kWh) of consumption to qualify as "access," is supply-oriented, thus failing to take into account the use of electricity services in fostering development. The World Bank and IEA continue to use a supply-oriented definition of access for their modeling exercises, and define consumption levels in Watts and kWh that are aligned with the service "tiers" of access as shown in Table 1. The level of consumption specified as "access" for rural households is 250 kWh per year, and 500 kWh for urban households in IEA World Energy Outlook scenario modeling (International Energy Agency, 2012; Banerjee, et al., 2013).

Table 1: Tiers of Services Provided to Consumers and Supply Tiers Under SE4All Global Tracking Framework (Banerjee, et al., 2013)

	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Electricity services	--	Task lighting AND phone charging OR electric radio	General lighting AND television AND air circulation	Tier 2 package AND light appliances	Tier 3 package AND medium or continuous appliances	Tier 4 package AND heavy or continuous appliances
Consumption (kWh) per household per year	<3	3 – 66	67 – 321	322 – 1,318	1,319 – 2,121	>2,121
Peak available capacity (W)	--	>1	>50	>200	>2,000	>2,000

The faults of the supply-oriented definition are several: it ignores the role of energy efficiency in providing access to electricity services (directly contradicting the second stated goal of SE4All, doubling energy efficiency); it leads to the conclusion that large investments in central grid capacity and extension are necessary to reach universal access and that grid alternatives have little to no role to play; and it neglects the differential in the way consumers value electricity for different end uses or services – be it lighting, entertainment, or refrigeration.

Recent reports have similarly critiqued the supply-oriented definitions and highlighted the prudence of using a services-based definition. One report shows how a services-based definition can yield an estimate of the effect of investment on the dimensions of access (reliability, duration, price, etc.) and not just the quantity and cost per unit kWh supplied (Erichsen et al., 2013). In the same vein, another recent white paper presents a business model, the Distributed Energy Services Company (DESCO), that profits by providing access to electricity *services* rather than some quanta of electricity as measured in kilowatt-hours (Bardouille & Muench, 2014).

The "supply"-based definitions fit into a category that reduces access to a "binary" outcome, as depicted in Figure 3. Other traditional definitions that depend on capacity (W) or consumption (kWh) targets, like the one implemented in India's 2005 National Electricity Policy, and the one that is used under the SE4All Global Tracking Framework and the IEA's World Energy Outlook, are inherently supply-focused.

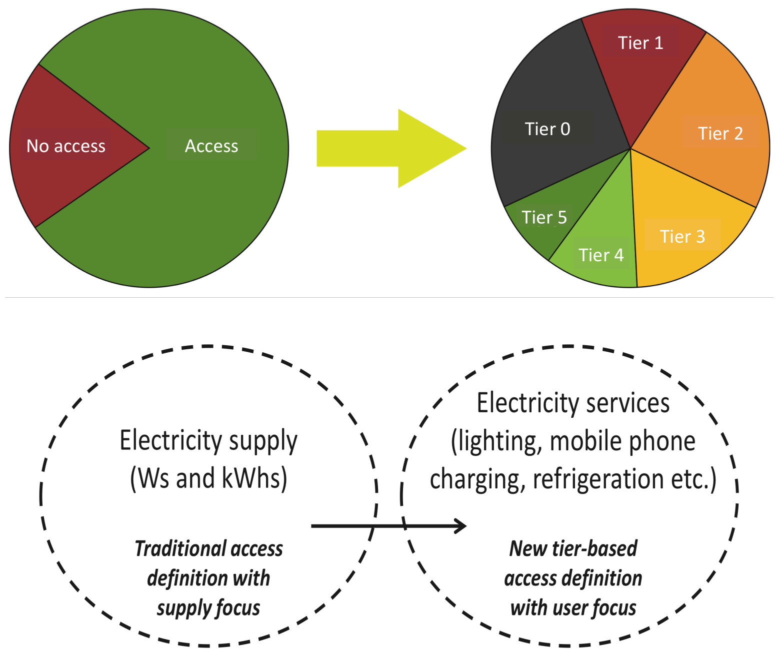


Figure 3: Contrast in Binary vs. Tiered definitions of access (Banerjee, et al., 2013), and Supply vs. Services Definitions of Access (Erichsen et al., 2013).

It should be noted that the SE4All services-based definition in principle, the concept that energy efficiency can drastically reduce the number of kWh required to deliver "modern energy services," and the role that grid alternatives are to play in providing access to electricity services are not without their detractors. The services-based definition, low targets for kWh consumption to qualify as "access," and use of grid alternatives are criticized for being unambitious and diverting resources away from central grid extension (Caine, et al., 2014). Instead, rapid and massive investment in fossil fuel central power generation is advocated for less developed countries. These arguments are predicated on the claim that the modest quantity of kWh consumed to achieve universal access to modern energy services under the SE4All definition are insufficient for households to escape poverty (Moss et al., 2014; Bazilian & Pielke, Jr., 2013). As stated in two similar reports, the SE4All target quantities of 2,121 kWh at "Tier 5" consumption is "less than 10 percent of Bulgarian [household] consumption…still much lower than what typical energy services would imply in even the least energy-consumptive wealthy countries." (Bazilian & Pielke, Jr., 2013), and that it is "nonsensical to argue, as these goals implicitly do, that a household has achieved equitable access to modern energy when consuming 50 to 100 kWh per person annually—less than the average American's cable television box." (Caine, et al., 2014)

The authors of these critiques protest the use of high quality grid alternatives to meet these targets for consumption not only on the grounds that the thresholds are low in comparison to per-capita consumption in richer countries, but that they "have little capacity for scaling up and meeting the expanding needs of economically productive, non-household activities like manufacturing, transportation, or commercial agriculture." (Caine, et al., 2014) Such an argument, however, is a straw man fallacy that presents policymakers with a false dichotomy, an either-or choice to be made rather than presenting a vision for a multi-track approach that acknowledges that the grid alternatives and central grid extension each have a role to play in benefiting the world's poor.

The problem with abandoning the services-based definition, abandoning low-consumption targets, and pursuing only rapid investment in central-station generation is that it fails to acknowledge realities of central grid systems in less developed countries. While these systems often provide electricity at affordable price points thanks to central government subsidies, they are often unreliable and of low quality (Besant-Jones, 2006). These systems need not only more generation capacity, they need a full suite of enhancement measures and reforms. These include: governance, business and technical training; increased use of electricity meters; investment in transmission and distribution systems; clear legislative frameworks that delineate roles between the state and the private sector, create laws around customer service, and potentially establishes an independent regulator (Besant-Jones, 2006; Zhang et al., 2008).

While these measures and reforms are worthy means towards the end of increasing the reach of the central grid, they are complex and time-consuming. Deploying high quality grid alternatives like solar lighting devices and microgrids do not face as many hurdles to providing affordable and reliable energy services – albeit at relatively low levels of consumption. This is the practical rationale for taking a multi-track approach to electricity access. Furthermore, despite these modest consumption levels of electricity – "Tier 1" of the SE4All Global Tracking Framework – the first few units of an energy service are the most highly valued[2], which creates a massive opportunity to greatly enhance the lives of those without access by providing them with small amounts of electricity. While detractors of grid alternatives decry their deployment as having unacceptably high opportunity costs that prevent a "moral" outcome of equitable access to much higher levels of consumption (Caine, et al., 2014), we find that the forgone consumer surplus of not rapidly deploying solutions to meet low electricity consumption targets is unacceptably high. Our modeling results presented in the "Results and Discussion" section show large gains to household budgets and consumer surplus by switching households from low-quality lighting fuels to high quality electric alternatives, which in many cases can be achieved much more quickly than central grid expansion alone. This is the economic rationale for taking a multi-track approach to electricity access.

We present an empirical analysis that calculates consumer surplus for the energy service of lighting as provided by grid alternatives, the central grid, and low-quality alternatives such as kerosene using empirical levels of consumption, prices, and reliability.

We seek to quantify the extent to which parallel energy systems, such as microgrids and solar lighting systems, may recover forgone consumer surplus due to central grid unreliability and sporadic usage of kerosene/candles in the absence of electricity. In this analysis, actual central grid reliability (ASUI) is taken as a fixed empirical input, and price points of high quality grid alternatives

[2] See the demand curves for low levels of lighting consumption, Figure 6.

are adjusted to reflect the point at which the consumer surplus they deliver is equal to that of the unreliable grid. This is effectively the maximum consumer willingness to pay for these grid alternatives.

For areas not connected to the central grid, we seek to quantify the extent to which the high quality grid alternatives may offer greater consumer surplus to end-users than an unreliable central grid. In this analysis, central grid reliability is taken as variable, and price points of alternatives are provided as fixed empirical inputs. Reliability of the central grid (ASUI) is adjusted until the surplus it delivers is equalized to the surplus delivered by the alternatives. This is effectively the "maximum acceptable grid outage rate."

2.2 Modeling Approach

This analysis endeavors to determine whether an argument can be made for rapid, widespread adoption of high-quality grid alternatives to replace dependence on kerosene and candles rather than depending on the central grid to do so. The argument is predicated on the high value that consumers place on the first few units of lighting consumption. As a result of diminishing marginal utility, demand curves are downward sloping. The more of a good that is consumed, the less benefit an individual derives from consuming the next unit of the good. This results in an unwillingness to pay as much for the next unit of consumption. When the central grid is not functioning, consumers are forced to fall back on kerosene, candles or other low-quality lighting supplies, resulting in high levels of forgone consumer surplus.

The modeling approach for this analysis must therefore rest on a demand curve model to estimate consumer surplus tradeoffs at different lighting consumption points, depending on the price paid for the lighting source and its level of reliability relative to the customer's willingness to pay. The method used for estimation of the demand curves is presented below.

The demand curve model is then used to determine two outputs to assess whether high-quality grid alternatives are a good deal for consumers. One output is the consumer's maximum willingness to pay for a high-quality grid alternative at given central grid outage rates. The less reliable the central grid, the more the customer will fall back on low-quality alternatives. The more this occurs, the more consumer surplus they are forgoing without having a lower-cost, higher-quality lighting option. The second output is the maximum acceptable central grid outage rate. At given price points for high quality grid alternatives, there will be a threshold level of grid unreliability at which consumer surplus will be greater when using high quality grid alternatives than the central grid. The modeling approach to the consumer surplus estimation for these two outputs is presented.

2.2.1 Summary of Data Used

The first objective of this analysis is to estimate household demand for lighting as measured in kilo-lumen-hours (klmh) as a function of the unit price of lighting.[3] The primary data source for this exercise is the raw dataset of the 2008 Lighting Africa Market Assessment (International Finance Corporation and The World Bank, 2008). The dataset contains nearly 5,000 household responses across five Sub-Saharan African countries (Ethiopia, Ghana, Kenya, Tanzania and Zambia) to a comprehensive survey on consumer lighting habits.

Survey data were collected for off-grid households that typically depend on kerosene and candles for lighting, though other lighting appliances such as battery-powered flashlights and lanterns as well as solar-powered lights were used by some households. Survey questions included the number of each appliance typically used, the daily operating duration, and the monthly operating cost of each.

[3] The use of kilo-lumen-hours has its strengths and weaknesses. The strengths are that it is useful in accounting for different energy sources and different lighting output, and can accommodate the increase in output per unit input from energy efficient lighting technologies. The weaknesses are that one must assume a linear valuation of lumen output, which may not be the case at all. While there is a large willingness to pay for some light versus no light, this behavior may not exist between lighting output levels.

We calculated monthly household consumption of lighting and unit price paid as follows. The total monthly klmh consumption for each of the four main lighting appliances was calculated as

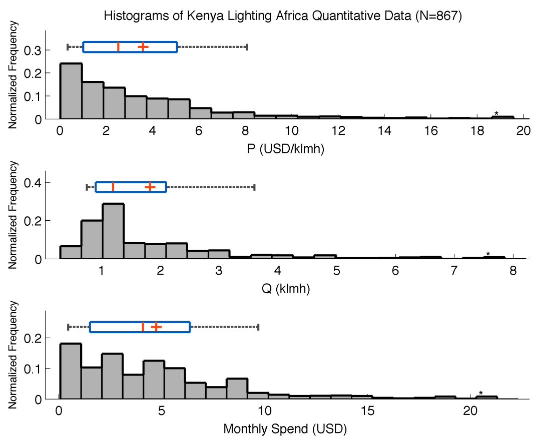
$$Q_i = n_i \cdot l_i \cdot d$$

where n_i is the number of a particular appliance that was used to light the main room of the household in the previous evening, l_i is the lumen output of that appliance, and d is the length of time from when the household turns its lights on to when it turns them off, summed over the month. Assumptions for the lumen output of each of the four lighting appliances for which there was corresponding expenditure data are shown in Table 2. Total monthly household lighting consumption, Q, is then ΣQ_i.

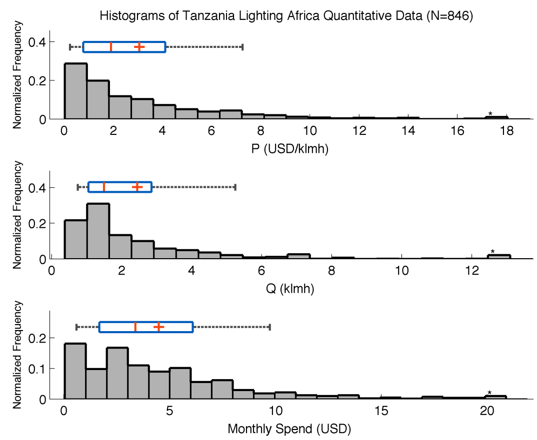
Table 2: Lighting Output Assumptions for Main Lighting Appliances in Lighting Africa Market Assessment

Appliance	Lumen output
Kerosene lamp	10
Candle	10
Battery-powered lantern	15
Battery-powered flashlight	4

We calculated unit prices by dividing the survey response to the monthly operating cost of each appliance by the calculated total household lighting consumption, Q_i. Operating costs were converted to USD using 2008 exchange rates. The product of the calculated unit prices and total household lighting consumption is the total monthly lighting expenditure. Summary histograms of these data for each of the five countries are in Figure 4.



(a)



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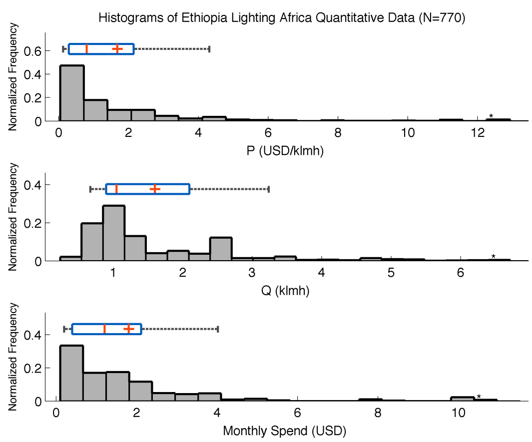
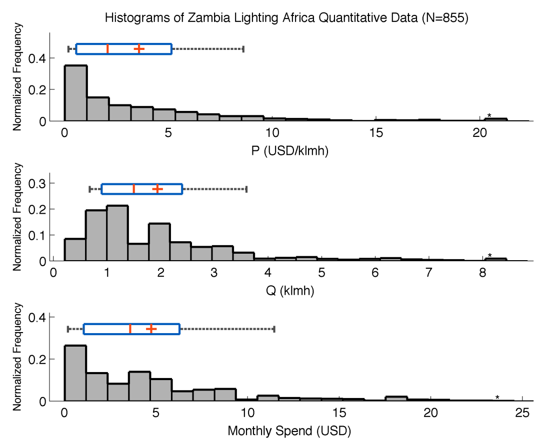
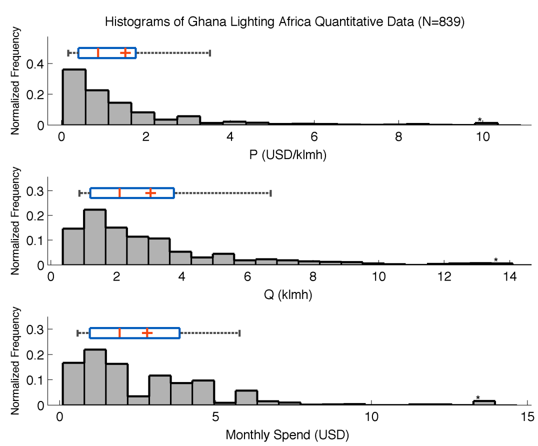


(c)



(d)



(e)

Figure 4: Histogram of Lighting Price (USD/klmh), Quantity Consumed per Month (klmh), and Total Monthly Expenditure on Lighting (USD) for Kenya (a), Tanzania (b), Ethiopia (c), Zambia (d) and Ghana (e)

As is evident from these histograms, the levels of consumption, unit price paid and total monthly expenditures are relatively consistent across the countries, and across results from other comparable studies on low-quality lighting sources, such as Mills (2003) and Wilson et al. (2010). The total monthly expenditure is useful as a check on the raw data. Surveys on monthly household energy expenditures in Africa and Asia by The World Bank in 2005 show average expenditures of $3.00 in the first quintile of consumers to $7.50 in the top quintile in Kenya for rural households, and $4.00 in the first quintile of consumers to $11 in the top quintile for urban households (Bacon et al., 2010). These figures fit within the distribution of the calculated monthly lighting expenditure from the 2008 Kenya Lighting Africa Market Assessment surveys, shown in Figure 4(a). The calculated average monthly lighting expenditures for Kenya from the Lighting Africa results in quintiles are $0.57, $2.04, $4.09, $5.85 and $11.20. It is worth noting that the expenditures reported in the World Bank study are exclusive to kerosene, whereas the distribution shown in Figure 4(a) includes expenditure on all lighting sources, though kerosene is dominant.

2.2.2 Demand Curve Model

Given that this analysis endeavors to estimate consumer surplus for levels of lighting consumption spanning from a few klmh provided by the lowest quality fuels to thousands of klmh provided by electric light, our demand curve must have validity over this entire range. The Lighting Africa Market Assessment dataset contains values of consumption only in the lower range of consumption. For our demand curve model, we estimated a demand curve from this dataset, show that it does not yield a valid elasticity for higher levels of lighting consumption in any of the five countries, and then merge this model with a more robust demand curve model at higher levels of lighting consumption found in Wilson, et al. (2010).

For our low-consumption demand curve, we assumed a model of constant price elasticity to derive a demand curve from the price-quantity data found in the Lighting Africa Market Assessment. This model has the following functional form:

$$\ln Q = a + b \cdot \ln P$$

where *a* is a constant and *b* is the price elasticity.[4] Single-variable regression was performed on the log of price-quantity pairs to yield a demand curve model for lighting for each of the five countries.

The regression results are provided in Table 3. The coefficient of ln(*lighting price*) is the elasticity in the constant price elasticity demand curve model.

Table 3: Regression Results for ln(lighting consumption)

	Kenya	Tanzania	Ethiopia	Zambia	Ghana
Constant	0.539***	0.721***	0.218***	0.505***	0.747***
	(0.023)	(0.024)	(0.019)	(0.023)	(0.023)
ln(*lighting price*)	-0.216***	-0.309***	-0.232***	-0.174***	-0.343***
	(0.016)	(0.017)	(0.015)	(0.015)	(0.020)
R squared	0.175	0.279	0.236	0.144	0.265
n	867	846	770	855	839

*** *p-value<0.01.*

Scatter plots of the price-quantity data and the derived demand curve are shown in Figure 5. All coefficients are significant at the 1% level, as suggested by the low coefficient standard errors (shown in parentheses). The R-squared value may be interpreted as the percent of change in consumption that is explained by this model. The coefficients of ln(*lighting price*) are the price elasticities, which are interpreted as the percentage by which consumption will decrease for every percent increase in price. For Kenya, a 1% increase in price will result in a decreased consumption of 0.22% (elasticity of -0.22), and in Tanzania, 31% (-.31). Not surprisingly, these price elasticities

[4] A demand curve of this functional form is mildly contrived, but has substantial precedent in microeconomic literature (Dixit & Stiglitz, 1977). Its use may be made with the following caveats: 1., It is uncertain whether consumers value lighting in this manner. While it is assumed that there is constant price elasticity of demand across the range of the data in the Lighting Africa Market Assessment, it is not necessarily the case that it is valid to apply elasticity measured at small quantities to higher levels of demand. 2., The idea that light outputs from different energy sources can be added up in a linear way to find Q is an assumption we must make. 3., Solar lamps and solar lighting systems may not fit in this framework because of their upfront costs. The price paid for these systems by the consumer does not follow the same type of unit operating cost paid for kerosene or central grid electricity. This is discussed in further detail below, but it is an important caveat none-the-less.

are much higher than those found for the price elasticity for residential electricity demand in the United States, which can range from -0.02 to -0.08 (Faruqui & Wood, 2008). It is understood that elasticity at different points on a demand curve may differ, and the elasticity being measured in our regression extends over a very short distance at the lowest levels of consumptions. The elasticities typically recorded in studies for electricity demand in the United States are much lower, but are *arc* elasticities recorded at a much higher level of consumption[5].

The elasticities found from the Lighting Africa data set are smaller than price elasticity estimates found in other studies at slightly larger quantities of lighting or electricity consumed – though still small by United States standards. The study most comparable to ours used price-quantity pairs for klmh consumed from over 3,000 households in Yemen. This study found a price elasticity of -0.82 (Wilson et al., 2010) over a much wider range of quantity of klmh consumed per month: up to 3,500 for the maximum household and approximatley 600 for the median household, compared to a median of 1 to 2 klmh/mo. for the Lighting Africa Market Assessment countries.

5 Household price elasticity of demand for electricity in rural India was found to be in the range of -0.3 to -0.4 in a recent analysis of central grid reliability (Harish et al., 2014), very similar to the elasticities we find in Africa at low levels of lighting consumption.

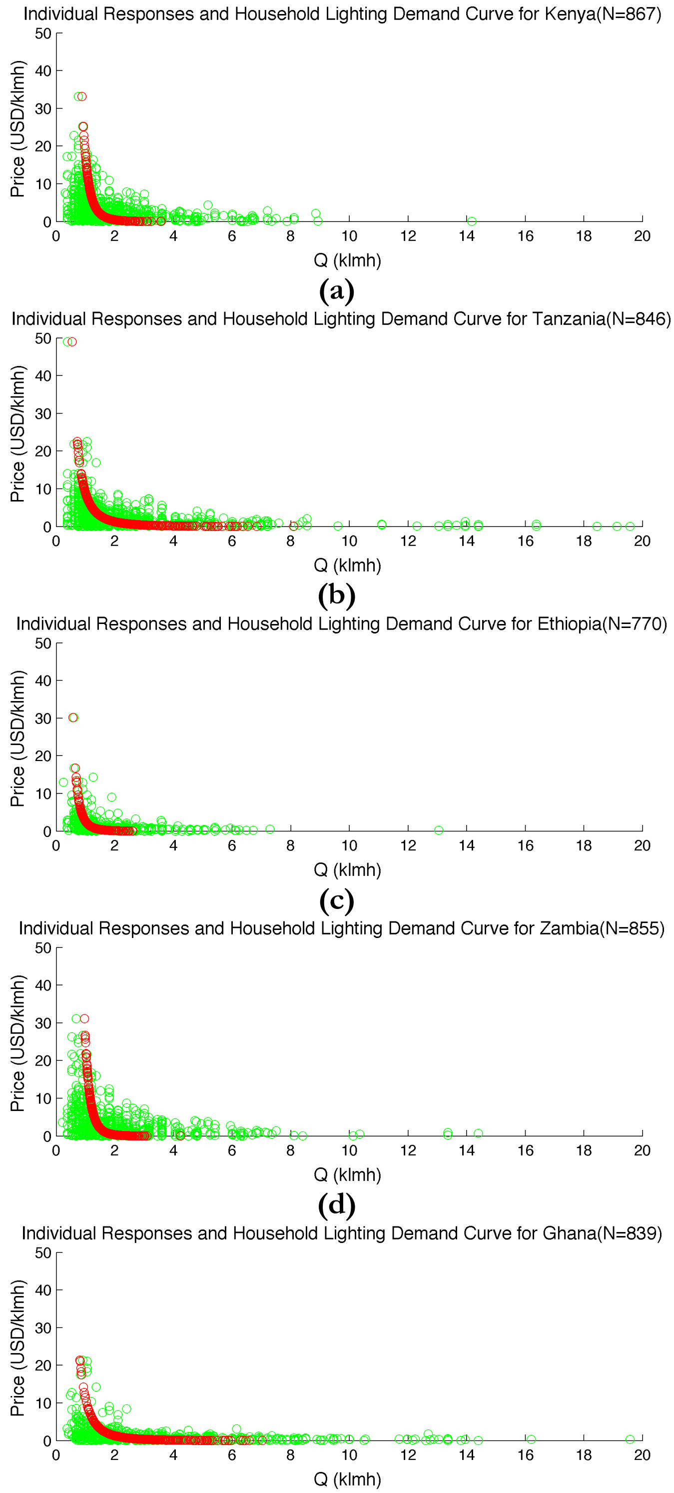


Figure 5: Scatter Plots of Price-Quantity Relationships for Lighting and Derived Demand Curves for Kenya (a), Tanzania (b), Ethiopia (c), Zambia (d) and Ghana (e)

The (relatively) small elasticities found in our analysis are applicable to the low-quantity region of the demand curve. At subsistence levels of consumption, we would expect the elasticities to be low, as there is relatively low scope for demand adjustments to price changes. This helps to explain the estimates for elasticity found in our analysis where the consumption levels in the source data are in a low, narrow range. A comparison between the levels of consumption of lighting in klmh in Yemen is compared to those in each of the five African countries included in the Lighting Africa dataset in Table 4. The consumption levels at the top decile in the Lighting Africa Market Assessment countries are less than the first decile of consumption for urban Yemen households, and within the third decile for rural Yemen households. This is due to the breadth of the Yemeni study's sample, which included many households with petrol or diesel generators as well as other electricity sources, including a variety of public or private grid supplies. We note that the Yemen data cover a fairly wide range of demand and thus represent a composite elasticity at many levels of demand. This breadth provided a great number of "intermediate" P-Q points between those representing households using low-quality lighting fuels like kerosene and those using central grid power, thus accounting for their model's very high R-squared value of 0.75 (Wilson et al., 2010).

Table 4: Lighting Consumption Deciles (klmh/month) for Yemen and Five Countries in Lighting Africa Market Assessment. Note that Yemen data is sourced from Wilson et al. (2010).

Consumption Decile	Yemen Urban	Yemen Rural	Kenya	Tanzania	Ethiopia	Zambia	Ghana
1	47	6.0	0.8	0.8	0.7	0.7	0.9
2	237	11	0.9	0.9	0.8	0.8	1.2
3	381	21	1.1	1.1	0.9	1.1	1.4
4	522	34	1.2	1.2	1.1	1.2	1.8
5	664	55	1.2	1.5	1.1	1.5	2.1
6	844	121	1.5	2.1	1.3	1.8	2.7
7	1,108	238	1.9	2.6	1.8	2.1	3.5
8	1,462	447	2.5	3.2	2.4	2.7	4.5
9	2,037	833	3.6	4.8	3.0	3.6	6.4
10 (max)	3,540	1,947	14	20	13	14	20

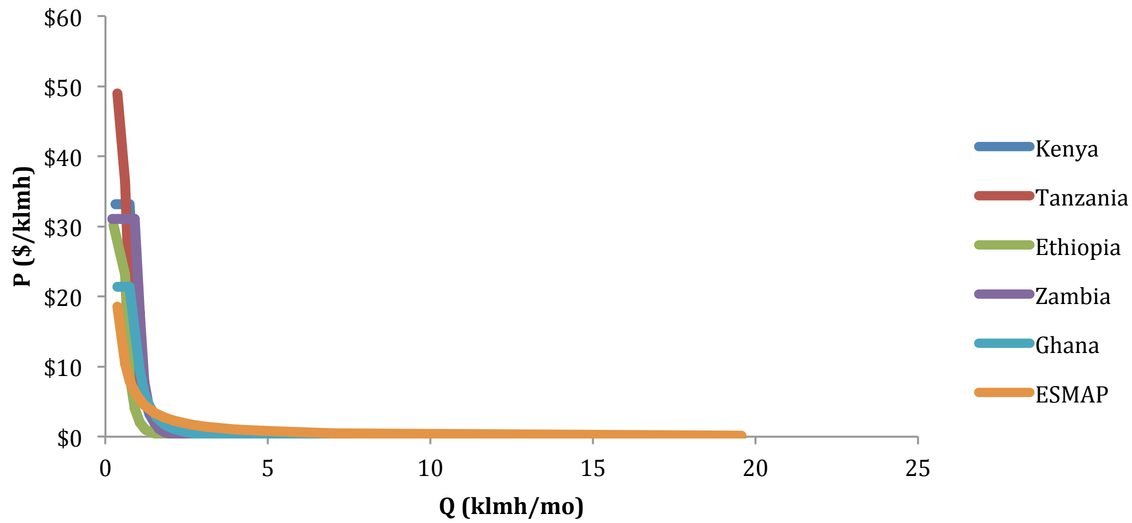
The consequence of the low elasticities modeled at low levels of consumption is an exceedingly low consumer value at higher levels of consumption. At consumption levels in the hundreds or low-thousands of klmh per month, consistent with typical use of electric light, the Lighting Africa-based regression model breaks down, yielding consumer willingness to pay on the order of 10^{-5} USD/klmh to 10^{-10} USD/klmh for each of the five countries. This would suggest that these households would be unwilling to pay for electric light even at heavily subsidized tariffs of less than 0.10 USD/kWh, which in units of lighting with a 75W incandescent bulb is 0.006 USD/klmh. The curve derived from the Yemen model predicts a much more plausible willingness to pay of 0.02 USD/klmh at ~100 klmh/mo, and 0.002 USD/klmh at ~1,000 klmh/mo (Wilson et al., 2010). These are still somewhat low for consumer willingness to pay at these quantities, but this is attributed to the fact that the central grid tariff in Yemen is incredibly low – just 0.02 USD/kWh – far smaller than the central grid tariffs of any of the five countries included in our analysis, presented in Table 5.

Table 5: Central Grid Lighting Costs

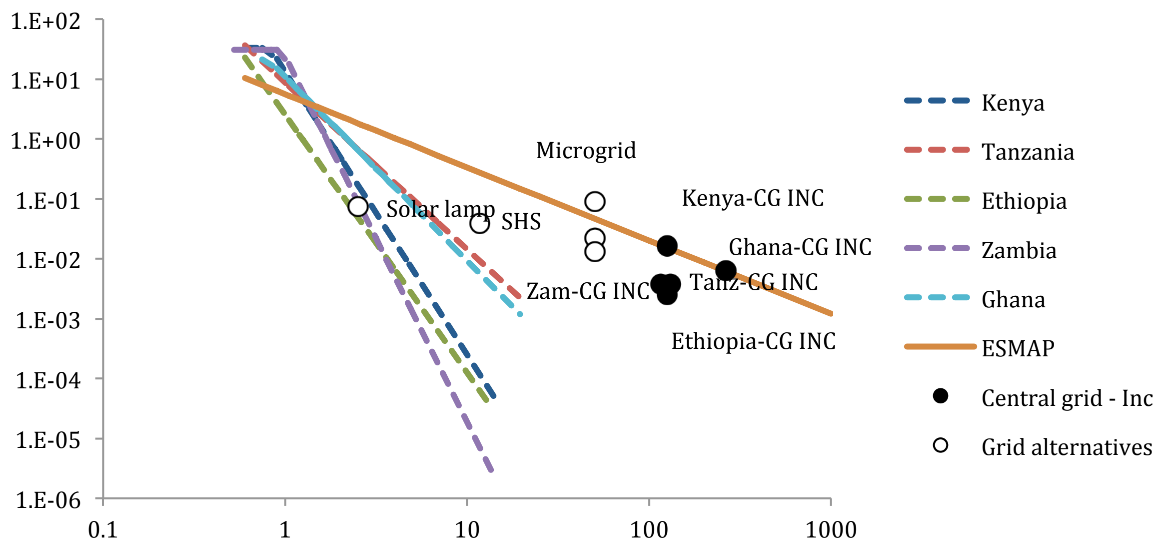
	Kenya	**Tanzania**	**Ethiopia**	**Zambia**	**Ghana**
Central Grid Tariff (USD/kWh)	$0.26	$0.06	$0.04	$0.06	$0.10
Unit Price of Central Grid Lighting (USD/klmh)					
Incandescent	$0.0163	$0.0038	$0.0025	$0.0038	$0.0063
CFL	$0.0041	$0.0010	$0.0006	$0.0010	$0.0016
LED	$0.0028	$0.0007	$0.0004	$0.0007	$0.0011

Table 5 also lists the calculated unit price of lighting in USD/klmh from the central grid assuming usage of a 1,200 lumen light bulb. The wattage for Incandescent, CFL and LED light bulbs at this lumen output are assumed to be 75W, 19W and 13W, respectively.

The demand curves for each country at the regression coefficients shown in Table 3 are provided in Figure 6.



(a)



(b)

Figure 6: Demand Curves obtained by the Lighting Africa Regression Coefficients and the ESMAP Regression Coefficients, on a linear (a) and logarithmic (b) scale.

Figure 6(a) plots the demand curves for each country to the highest measured level of consumption included in the Lighting Africa Market Assessment survey results. The ESMAP curve illustrates the results of the regression found in Wilson et al. (2010), plotted to the highest level of consumption included in the Lighting Africa Market Assessment survey results. The regression results of the Lighting Africa Market Assessment are shown to be much less valid when the model includes higher levels of consumption and is plotted on a logarithmic scale, as shown in Figure 6(b). This depiction of the curves reveals the strong under-valuation of lighting at consumption extending into the hundreds of klmh, which is on the order of 10^{-10} USD/klmh. The unit price of central grid lighting with a 75W incandescent light bulb is also shown at the tariffs for each of the five countries. These unit prices are several orders of magnitude higher than the predicted consumer willingness to pay for the Lighting Africa Market Assessment countries, but are less than the willingness to pay for the ESMAP regression, as expected. The unit prices of the grid alternatives are also provided, and are for the most part not under the Lighting Africa demand curve models.

Because the regressions over the range of values included in the Lighting Africa Market Assessment data are insufficient to yield an elasticity that is valid over as wide a range of consumption as we seek to model (i.e., up to levels of consumption with central grid lighting), we modify the demand curve model to allow for non-constant price elasticity of demand at higher levels of consumption. An intermediate point along the demand curve was chosen to create an inflection point between the "small" elasticity value at low levels of consumption and a "large" elasticity value at higher levels. The inflection point between small and large elasticity was introduced at the 75th percentile consumption level for each country. Note that the significantly higher price elasticity found in the ESMAP model from Yemen is a composite of a relatively small elasticity at low levels of consumption and a higher elasticity at higher levels of consumption.

In order to deal with the unmeasured nature of the larger elasticity value at higher levels of consumption and the uncertainty of the modeled elasticity at lower levels of consumption (recall the low R^2 values from Table 3), our study includes a variety of sensitivity values around the intercept and elasticity parameters for each country. Each sensitivity case was deemed "valid" based on the constraint that the central grid and grid alternatives unit prices fell below the demand curve. The sensitivity cases are described in Table 6.

Table 6: Sensitivity Analysis Scenarios Around Model Intercept and Elasticity

							2x Model Coefficients				2x – 4x Model Coefficients		
Intercept	Model	Model	Model	ESMAP	ESMAP	ESMAP	2x Model	2x Model	2x Model	ESMAP	2x Model	2x Model	ESMAP
Low elasticity	Model	Model	ESMAP	Model	Model	ESMAP	Model	Model	ESMAP	Model	Model	2x Model	2x Model
High elasticity	Model	ESMAP	ESMAP	ESMAP	Model	ESMAP	2x Model	ESMAP	ESMAP	2x Model	4x Model	ESMAP	4x Model
Validity	*Not valid*	*Not valid*	*Not valid*	*Valid*	*Not valid*	*Valid*	*Not valid*	*Valid*	*Valid*	*Not valid*	*Valid*	*Valid*	*Valid*

2.2.3 Consumer Surplus Model

The objective of this analysis is to calculate the maximum consumer willingness to pay for a high-quality grid alternative, and the maximum acceptable level of central grid unreliability. Both outputs are predicated on the assumption that low-quality lighting sources such as kerosene, candles and battery-powered flashlights and lanterns are used as the default alternative when the central grid is unavailable. The high-quality grid alternative intervention posits that consumer surplus may be increased when a high-quality grid alternative, such as a solar lamp, solar home system or micro-grid, is used instead of the unreliable central grid. Of course, the low-quality lighting source is still taken as a back-up to the high-quality grid alternative subject to the alternative's level of reliability.

Consumer surplus is commonly defined as the difference between consumer value and expenditure,

$$CS = \int_0^{\sum_{i=1}^{n} q_c^i} D(q)dq - \sum_{i=1}^{n} p_c^i \cdot q_c^i$$

D(*q*) is the demand function, as defined by the model in the previous section, and p_c^i is the price at which a consumer is purchasing some quantity, q_c^i, of lighting from a particular lighting source. The first half of the expression – the area under the demand curve – is consumer value. This is derived independently of the price of the lighting sources, and is dependent only on the shape of the demand curve model and the total amount of lighting consumed, $\sum_{i=1}^{n} q_c^i$, from the *n* lighting sources being used by the consumer. The second half – expenditure – depends on the price and quantity of the sources used, and is the sum of the expenditure on the *n* lighting sources being used by the consumer.

Consumer surplus from a household connected to the central grid is

$$CS^{CG} = \int_0^{q_c^{CG}+q_c^{LQb}} D(q)dq - (p_c^{CG} \cdot q_c^{CG} + p_c^{LQ} \cdot q_c^{LQb})$$

where p_c^{CG} and q_c^{CG} are the price and quantity consumed for the central grid (CG), p_c^{LQ} is the price of the low-quality (LQ) lighting source, and q_c^{LQb} is the quantity of lighting consumed on the low-quality lighting source as a back-up to the central grid when it is in outage.

Because this analysis compares the hypothetical central grid usage of off-grid customers, a formula was introduced to calculate the projected level of central grid consumption, q_c^{CG}, at each decile of off-grid klmh consumption captured in the Lighting Africa Market Assessment. The formula first calculates the number of low-quality lighting devices that are required to provide a total of klmh equal to each decile of off-grid consumption at a rate of 4 hours of use per day. This number is taken as the comparable number of light bulbs that a consumer at a particular decile of off-grid consumption would use if they were connected to the central grid, shown at each consumption decile in Table 7.

Table 7: Equivalent Number of Lighting Points at Off-Grid Lighting Consumption Deciles

Off-Grid Consumption Decile	Kenya	Tanzania	Ethiopia	Zambia	Ghana
1	1	1	1	1	1
2	1	1	1	1	1
3	1	1	1	1	1
4	1	1	1	1	1
5	1	1	1	1	2
6	1	2	1	1	2
7	2	2	1	2	2
8	2	2	2	2	3
9	2	3	2	2	4
10 (max)	3	4	3	3	5

The low-quality lighting source is used during periods when the central grid is in outage, with quantity q_c^{LQb}. In order to determine outage rates, we used the responses to the Lighting Africa country surveys targeted at grid-connected consumers. There were many fewer grid-connected respondents included in the Lighting Africa Market Assessment surveys compared to the off-grid respondents. The grid-connected respondents were asked to assess the frequency of outages as well as the time of day during which the outages occurred. These responses were used to calculate the average number of days per month during which an outage occurred, as well as the probability that the outage would occur in the evening. Assuming that the duration outage would be 4 hours, the survey data were used to calculate the fraction of a month during which the central grid was not providing power in the evenings. This outage rate is equivalent to the fraction of time during which the consumer is using the low-quality backup. Outage data for each of the countries is provided in Table 8.

Table 8: Central Grid Outage Data

	Kenya	Tanzania	Ethiopia	Zambia	Ghana
Outage days per month	7	6	10	19	9
Evening outage probability	57%	44%	41%	31%	27%
Outage Duration (hours)	4	4	4	4	4
Fraction of usage in outage (ASUI)	12%	9%	13%	19%	8%
n	95	95	90	81	97

The quantities consumed on the central grid, q_c^{CG} and on the low-quality backup, q_c^{LQb} were calculated at each decile of off-grid consumption as follows

$$q_c^{CG} = \frac{(1 - f^{CG}) \cdot n_l \cdot l^{CG} \cdot d \cdot h}{1{,}000}$$

$$q_c^{LQb} = f^{CG} \cdot q_c^{LQ}$$

where f^{CG} is the fraction of the month during which the grid is in outage, n_l is the number of light bulbs powered by central grid electricity as per Table 6, l^{CG} is the lumen output of the light bulbs, d is the number of days per month (30), and *h* is the number of hours per evening that the consumer is using light (4). The numerator must be divided by 1,000 to convert the result from lumen-hours into kilo-lumen-hours. In the equation for q_c^{LQb}, the quantity of low-quality backup lighting consumed, the fraction that the grid is in outage is simply multiplied by the total off-grid lighting consumption that the consumer would normally consume in the absence of the central grid. This ensures that the number of low-quality devices being used to light the home at a particular consumption decile is analogous to the number of light bulbs being used with central grid electricity.

Lighting consumption for the high-quality grid alternatives scenarios, q_c^{HQ}, is calculated identically to the calculation for central grid lighting. The high-quality grid alternatives parameters are provided in Table 9, and detailed calculations and assumptions are provided in Appendix A.2.

Table 9: Grid Alternative Assumptions

Grid Alternative	Unit Price (USD/klmh)	Lumen output (l^{HQ})	Fraction of Usage in Outage (f^{HQ})
Solar lamp	$0.0732	22.5	7%
SHS	$0.0384	105	7%
Microgrid - INC	$0.0889	450	7%
Microgrid - CFL	$0.0222	450	7%
Microgrid - LED	$0.0133	450	7%

The microgrid was assumed to charge a relatively high tariff of 1 USD/kWh, which is converted in Table 9 to units of USD/klmh based on the use of 450 lumen light bulbs with 40W, 10W and 6W consumption for incandescent, CFL and LED options, respectively.

Consumption from the high-quality grid alternatives is defined as:

$$q_c^{HQ} = \frac{(1 - f^{HQ}) \cdot n_l \cdot l^{HQ} \cdot d \cdot h}{1{,}000}$$

where f^{HQ} is the fraction of the month during which the high-quality lighting alternative is non-functional, n_l is the number of high quality grid-alternative devices as per Table 6, l^{HQ} is the lumen output of the light bulbs, *d* is the number of days per month (30), and *h* is the number of hours per evening that the consumer is using light (4). The quantity consumed on the low-quality back-up when the high quality grid alternative is in outage, q_c^{LQb}, is defined as

$$q_c^{LQb} = f^{HQ} \cdot q_c^{LQ}$$

The consumer surplus improvement (i.e., "net" consumer surplus) from the low-quality lighting source consumer surplus to the central grid consumer surplus is,

$$CS_{net}^{CG} = CS^{CG} - CS^{LQ}$$

and

$$CS_{net}^{HQ} = CS^{HQ} - CS^{LQ}$$

for the high-quality grid alternative. Expanding the terms, we find

$$CS_{net}^{CG} = \int_0^{q_c^{CG}+q_c^{LQb}} D(q)dq - (p_c^{CG} \cdot q_c^{CG} + p_c^{LQ} \cdot q_c^{LQb}) - \left(\int_0^{q_c^{LQ}} D(q)dq - p_c^{LQ} \cdot q_c^{LQ}\right)$$

eqn. 1

$$CS_{net}^{HQ} = \int_0^{q_c^{HQ}+q_c^{LQb}} D(q)dq - (p_c^{HQ} \cdot q_c^{HQ} + p_c^{LQ} \cdot q_c^{LQb}) - \left(\int_0^{q_c^{LQ}} D(q)dq - p_c^{LQ} \cdot q_c^{LQ}\right)$$

eqn. 2

where

$$p_c^{LQ} \cdot q_c^{LQ} - p_c^{LQ} \cdot q_c^{LQb}$$

represents the savings on the low-quality lighting source alone. The *net* savings on total lighting expenditures when the consumer is using the central grid or the high-quality grid alternative is defined as,

$$Savings_{net}^{CG} = p_c^{LQ} \cdot q_c^{LQ} - (p_c^{LQ} \cdot q_c^{LQb} + p_c^{CG} \cdot q_c^{CG})$$

eqn. 3

$$Savings_{net}^{HQ} = p_c^{LQ} \cdot q_c^{LQ} - (p_c^{LQ} \cdot q_c^{LQb} + p_c^{HQ} \cdot q_c^{HQ})$$

eqn. 4

For clarity, we substitute equations 3 and 4 into equations 1 and 2 to obtain a clear expression for the increase in consumer surplus from switching a consumer from low-quality lighting sources to the central grid or to a high-quality grid alternative as follows,

$$CS_{net}^{CG} = \int_{q_c^{LQ}}^{q_c^{CG}+q_c^{LQb}} D(q)dq + Savings_{net}^{CG}$$

$$CS_{net}^{HQ} = \int_{q_c^{LQ}}^{q_c^{HQ}+q_c^{LQb}} D(q)dq + Savings_{net}^{HQ}$$

The purpose of the analysis, however, is not merely to calculate the increases in consumer surplus from switching a consumer from low-quality lighting source to high quality grid alternatives or the central grid. Rather, it is to infer whether a consumer would be better served by a central grid with a given rate of outages relative to a high-quality grid alternative with a given price. This analysis can be undertaken in two ways, as follows.

The first mechanism for the comparison is to compute the maximum willingness to pay for the high-quality grid alternative given a fixed central grid outage rate, *ceteris paribus*. The second mechanism is to compute the maximum central grid outage rate the customer would be willing to accept given a fixed price for the high-quality lighting alternative, *ceteris paribus*.

The objective function to solve for the maximum consumer willingness to pay for the grid alternative – i.e., the maximum p_c^{HQ} – can be formulated as,

$$\min_{p_c^{HQ}} CS_{net}^{CG} - CS_{net}^{HQ}(p_c^{HQ})$$

which can be solved in a straightforward closed-form solution as follows:

$$CS_{net}^{CG} - CS_{net}^{HQ}(p_c^{HQ}) = 0$$

$$CS_{net}^{CG} = CS_{net}^{HQ}(p_c^{HQ})$$

$$CS_{net}^{CG} = \int_0^{q_c^{HQ}+q_c^{LQb}} D(q)dq - (p_c^{HQ} \cdot q_c^{HQ} + p_c^{LQ} \cdot q_c^{LQb}) - \left(\int_0^{q_c^{LQ}} D(q)dq - p_c^{LQ} \cdot q_c^{LQ}\right)$$

$$p_c^{HQ} = \frac{CS_{net}^{CG} - \int_{q_c^{LQ}}^{q_c^{HQ}+q_c^{LQb}} D(q)dq + p_c^{LQ} \cdot q_c^{LQb} - p_c^{LQ} \cdot q_c^{LQ}}{q_c^{HQ}}$$

Similarly, to solve for the maximum acceptable central grid outage rate, the objective function can be formulated as,

$$\min_{d^{CG}} \ CS_{net}^{CG}(d^{CG}) - CS_{net}^{HQ}$$

where d^{CG} is the number of days per month *with* electricity from the central grid. The consumer surplus equation above must be converted to be computed on a daily, rather than monthly, basis to allow for the closed-form solution to be solved. This is done by breaking up the monthly central grid net consumer surplus into three terms: (1) a daily central grid consumer surplus term, which is multiplied by d^{CG}, (2) a daily low-quality back-up consumer surplus term, which is multiplied by the number of days *without* central grid electricity, $30 - d^{CG}$, and (3) a daily low-quality consumer surplus term, which is multiplied by the number of days in a month, *30*. Subtracting the third term from the sum of the first two yields the same monthly central grid net consumer surplus result as Equation 2. The closed-form solution to d^{CG} is thus derived as follows:

$$CS_{net}^{CG}(d^{CG}) - CS_{net}^{HQ} = 0$$

$$CS_{net}^{CG}(d^{CG}) = CS_{net}^{HQ}$$

$$d^{CG} \cdot (CS_{day}^{CG}) + (30 - d^{CG}) \cdot CS_{day}^{LQb} - 30 \cdot CS_{day}^{LQ} = CS_{net}^{HQ}$$

$$d^{CG} \cdot \left(\int_{0}^{q_{c-day}^{CG}} D(q)dq - p_c^{CG} \cdot q_{c-day}^{CG} \right) + (30 - d^{CG}) \cdot \left(\int_{0}^{q_{c-day}^{LQb}} D(q)dq - p_c^{LQ} \cdot q_{c-day}^{LQb} \right)$$

$$- 30 \cdot \left(\int_{0}^{q_{c-day}^{LQ}} D(q)dq - p_c^{LQ} \cdot q_{c-day}^{LQ} \right) = CS_{net}^{HQ}$$

$$d^{CG} \cdot \left(\int_{q_{c-day}^{LQb}}^{q_{c-day}^{CG}} D(q)dq - p_c^{CG} \cdot q_{c-day}^{CG} \right) - (30 - d^{CG}) \cdot p_c^{LQ} \cdot q_{c-day}^{LQb} + 30 \cdot p_c^{LQ} \cdot q_{c-day}^{LQ}$$

$$= CS_{net}^{HQ}$$

$$d^{CG} = \frac{CS_{net}^{HQ}}{\int_{q_{c-day}^{LQb}}^{q_{c-day}^{CG}} D(q)dq - p_c^{CG} \cdot q_{c-day}^{CG} + p_c^{LQ} \cdot q_{c-day}^{LQ}}$$

The quantity of lighting consumed on a daily basis during a central grid outage, q_{c-day}^{LQb}, is equivalent to the quantity of lighting consumed in the off-grid low-quality lighting source scenario, q_{c-day}^{LQ}. As such, the terms in the above derivation with these quantities get reduced to zero. The desired variable to solve for is 30 – d^{CG}, which would be the number of days of central grid outage per month.

The results below show each of the computed values for maximum willingness to pay for high-quality grid alternatives (summarized in Figure 9) and maximum acceptable central grid outage rates (summarized in Figure 10) in comparison to the actual values of the price of the high-quality grid alternatives and the actual central grid outage rates for each country.

2.3 Results and Discussion

High-quality grid alternatives as well as the central grid are capable of delivering large increases to consumer surplus in the context of lighting as an energy service. Such claims have been borne out by empirical and theoretical analyses that have advocated for policymakers to undertake strategies that will quickly remove dependence on low-quality lighting sources like kerosene and candles (Choynowski, 2002; Wilson et al., 2010).

Our results show that solar lamps do not offer consumers great benefits relative to the central grid, even with high grid unreliability. However, solar home systems, and especially microgrids, may offer great improvement to consumer surplus relative to the central grids in Kenya, Tanzania, Ethiopia, Zambia and Ghana at their present levels of reliability. In the following discussion of results, we present model outputs for the 50^{th} percentile level of consumption for each country. Full model outputs for all deciles of consumption may be found in Appendix A.3.

2.3.1 Net Savings Increase from Electric Lighting

Simply assessing the value of net savings delivered to consumers, nearly all forms of high-quality electric lighting sources will have a positive effect on consumers' budgets. Regardless of the percentile of consumption, the amortized monthly cost of solar lights and solar systems result in savings relative to low-quality lighting sources in each of the countries included. As shown in Figure 7, monthly net savings from solar lamps and solar home systems are approximately 4 USD in Kenya, Tanzania and Zambia, and are approximately 2 USD in Ethiopia and Ghana. These savings are the dollar savings from lighting the equivalent number of rooms over the course of a month as what each consumer in a given country is lighting with low-quality lighting sources. Savings of 2 – 4 USD per month for the median consumer may seem trivial, but adds up to a substantial fraction of per capita GDP in each of these countries, which, for example, is just 994 USD, 695 USD, 498 USD, 1,540 USD and 1,850 USD in Kenya, Tanzania, Ethopia, Zambia and Ghana, respectively.

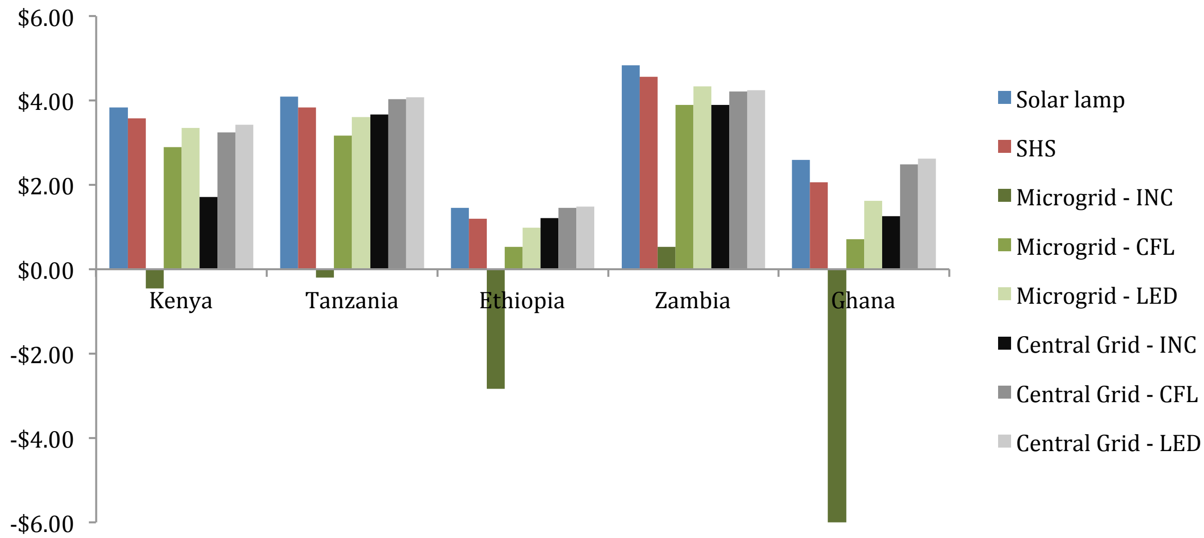


Figure 7: Net Savings (USD/mo.) from Usage of High-Quality Lighting Sources Relative to Low-Quality Lighting Fuels at 50th Percentile Lighting Consumption

Microgrids also yield net savings at the modeled unit price of 1 USD/kWh subject to the caveat that consumers use efficient CFL or LED light bulbs. Microgrid consumers may end up spending more each month to light their homes if they use incandescent light bulbs relative to their expenditures on low-quality lighting fuels. Monthly net savings are approximately 3 – 4 USD in Kenya, Tanzania and Zambia, and are approximately 1 USD in Ethiopia and Ghana.

These figures account for a modeled outage rate of two evenings per month, where the consumer falls back on using low-quality lighting fuels when the high-quality grid alternative is unavailable (e.g. due to microgrid maintenance or insufficient battery state of charge for the solar options).

At the empirically calculated outage rates (ASUI) for each of the five countries (see Table 8 above), the central grid yields net savings comparable to those of the CFL or LED microgrid options. As with microgrids, the central grid savings are subject to the similar caveat as the microgrid, where the savings are best realized by utilizing efficient CFL or LED light bulbs.

Although the observed outage rate for the central grid is higher than the modeled outage rate for the microgrid, the net savings levels are nearly identical for most countries. The effect of the higher outage rate on central grids (which leads to greater expenditure on the low-quality lighting fuel back-up) is offset by the significantly lower tariff on the central grid (see Table 5). Another effect is that it is assumed that households with central grid access will utilize more powerful 1,200 lumen light bulbs, whereas microgrid customers – due to constraints on peak load – will use less powerful 450 lumen light bulbs.

2.3.2 Consumer Surplus Increase from Electric Lighting

High quality grid alternatives and central grid electricity alike are capable of delivering substantial increases to consumer surplus relative to the consumer surplus from using low-quality lighting alternatives. Figure 8 shows these changes at the 50^{th} percentile level of consumption for each country. Consumer surplus was calculated for each lighting source and each decile across a sensitivity analysis corresponding to each of the seven demand curve models listed in Table 6. These models yield a wide range of consumer surplus values, plotted as boxplot ranges in Figure 8. Lower and upper uncertainty edges correspond to the minimum and maximum of the sensitivity values. Due to the large value of the upper sensitivity values, the plots in Figure 8 have been capped at 50 USD so that the median results are visible. The upper sensitivity values not shown are approximately 100 – 150 USD for the SHS and 150 – 200 USD for the microgrid and central grid options.

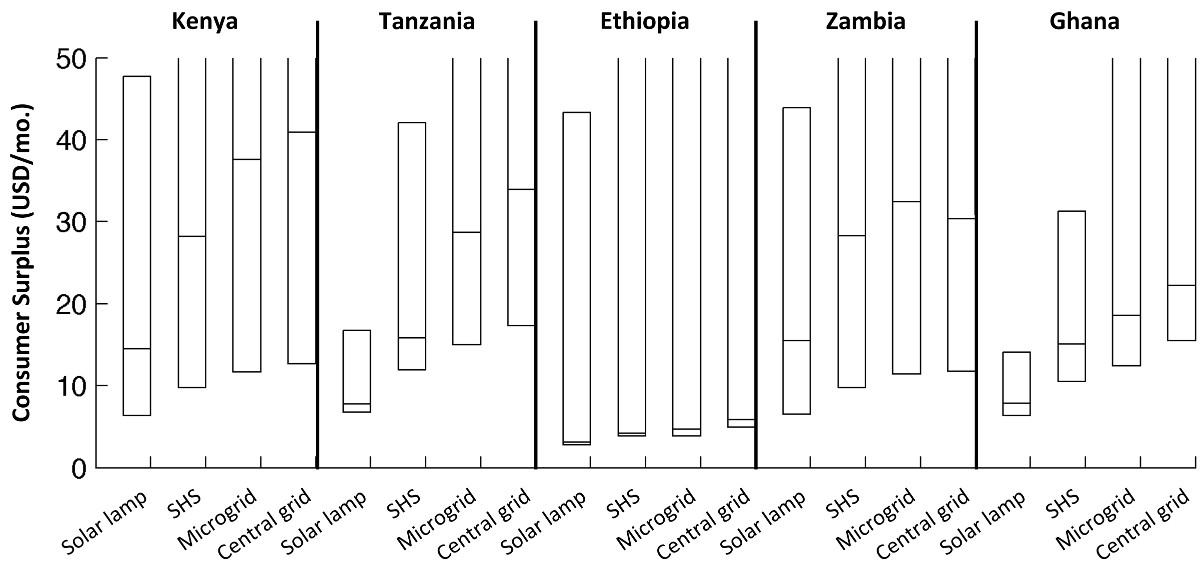


Figure 8: Net Consumer Surplus Change (USD/mo.) from Usage of High-Quality Lighting Sources Relative to Low-Quality Lighting Fuels at 50th Percentile Lighting Consumption

Given the extremely low income of these households, very large consumer surpluses are, in reality, unlikely. The lower-end sensitivity values, however, are more reasonable, with CS values of 6 USD to 12 USD per month for solar lamps and SHS across all countries except Ethiopia, where the lower-end values for solar lamps and SHS are 2 USD to 4 USD. Lower-end sensitivity values for microgrid and central grid options are 11 USD to 18 USD across all countries except for Ethiopia, where they are 4 USD to 5 USD.

These values are higher than those values calculated in a similar study in Yemen, where CS values of 0.25 USD to 5 USD were found across consumption deciles (Wilson et al., 2010). It is worth noting that the high consumer surplus values in our results may be attributed to the very high unit prices paid for by consumers in the Lighting Africa countries – over 20 USD/klmh – at very low consumption levels (<2 klmh/mo.), relative to the Yemen study, where they are under 2 USD/klmh. Furthermore, the 50th percentile households in the Yemen study spent only 2.3 USD/mo. on low-quality lighting fuels, whereas those in the Lighting Africa countries spend 3 to 5 USD/mo. at the 50th percentile.

2.3.3 Maximum Willingness-to-Pay for High-Quality Grid Alternatives

With central grid reliability is taken as an fixed input, we calculate the willingness to pay for a high quality grid alternative at the point at which the consumer surplus delivered by the grid alternative is equal to the unreliable central grid. This is effectively the maximum consumer willingness to pay for these grid alternatives. In nearly all cases, the present level of grid unavailability (see Table 8) is sufficiently low that the prices of the high quality grid alternatives would need to be negative in order to equalize the consumer surplus from the central grid.

In Figure 9 the results of this analysis are shown for each high quality grid alternative in each country at the 50th percentile level of consumption. The analysis was carried out for seven sensitivity levels for the demand model, and three sensitivity levels corresponding to the central grid consumer using an incandescent, CFL or LED bulb at each of the seven demand model sensitivity cases. The only cases where positive WTP values were found were for the use of microgrids in Kenya, (0.03 USD/klmh), microgrids in Ethiopia (0.01 USD/klmh), and microgrids in Zambia (0.07 USD/klmh). The use of microgrids in Zambia was also the only case to yield a median result for the sensitivity cases greater than zero (0.02 USD/klmh). The results suggest that, for a consumer that already has access to central grid electricity at these existing rates of unreliability, it is not beneficial to switch to a high quality grid alternative. The only cases where this may be justified would be in Kenya and Zambia, where it may be worthwhile for consumers to have access to an independent microgrid at a price of over 1 USD/kWh (equivalent to 0.022 USD/klmh with the use of a 450 lumen CFL).

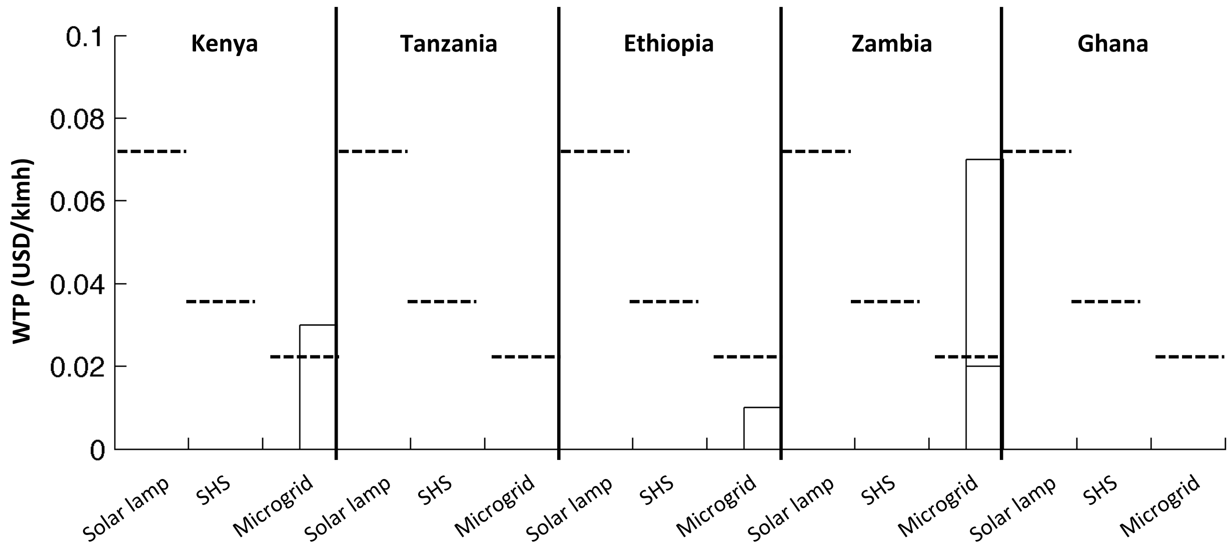


Figure 9: WTP for High Quality Grid Alternatives (USD/klmh) at Actual Levels of Central Grid Outage Rate (ASUI) for 50th Percentile Consumption. Dashed horizontal lines indicate actual prices in USD/klmh for each lighting option, as found in Table 9.

2.3.4 Maximum Acceptable Central Grid Outage Rate (ASUI)

In this analysis, central grid reliability is taken as variable, and price points of high quality grid alternatives are provided as fixed inputs. Reliability of the central grid (ASUI) is adjusted until the surplus it delivers is equal to the surplus delivered by the alternatives. This is effectively the "maximum acceptable ASUI."

The maximum acceptable ASUI for the 50^{th} percentile level of consumption end-user are shown in Figure 10 for each country. The lower and upper edges of the boxplots correspond to the minimum and maximum sensitivity results, and the horizontal line is the median of the results. As with the maximum WTP analysis, the sensitivity analysis was conducted across three central grid lighting cases, and seven sets of demand model parameters. The minimum value reflects the sensitivity case where consumer value from lighting is highest and where incandescent light bulbs are used on the central grid. The maximum value reflects the case where consumer value from lighting is lowest and where LED light bulbs are used on the central grid.

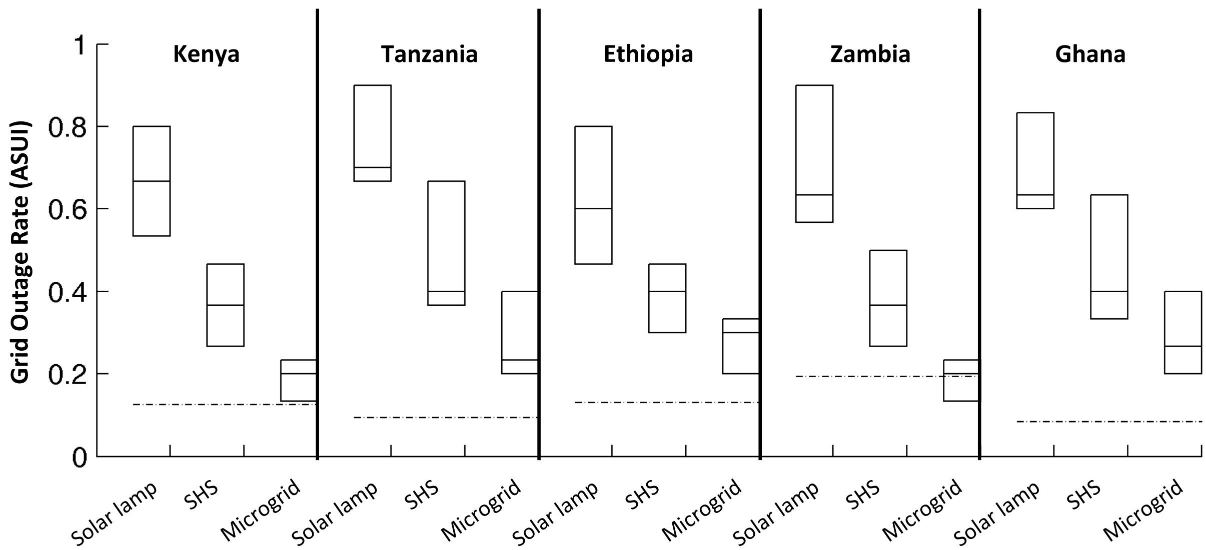


Figure 10: Maximum Acceptable Central Grid Outage Rate (ASUI) for High Quality Grid Alternatives for 50th Percentile Consumption. The dashed horizontal lines correspond to the actual outage rates as calculated by the Lighting Africa Market Assessment responses on central grid reliability – see Table 8. ASUI is measured as a fraction, where 0 indicates that the central grid is never unavailable, and 1 indicates that the central grid is always unavailable.

We find that for each country, central grid ASUI would need to be in excess of 50% in order for solar lamps to deliver the same level of consumer surplus as the central grid. The ASUI threshold falls to 30% - 50% depending on the country for consumer surplus from SHS usage to equal that of the central grid.

For microgrids, central grid ASUI would need to be in the range of 13% to 40%, depending on the country. The lower end of this range is at the actual ASUI in Kenya, which is measured to be 13%. The range also includes the observed ASUI in Zambia, 19%. In agreement with the analysis of maximum WTP, microgrids may be viable "parallel" systems for areas in which consumers in Kenya and Zambia are experiencing outages at 13% and 19% ASUI, respectively.

For areas *not* presently connected to the central grid, these results are useful to assess whether the high quality grid alternatives should be deployed instead of extending the central grid. Not all areas connected to the central grid experience the same ASUI. For example, rural areas in India's Karnataka state experience significantly lower levels of grid availability than urban areas (Harish &

Tongia, 2014). It is possible that newly connected rural areas may be deemed lowest priority for service, and those consumers might be harmed if policymakers choose to extend central grid transmission lines to them rather than promoting high quality grid alternatives.

2.4 Policy Implications

The premise of taking reliable central grid electricity as a certainty can adversely affect consumers waiting for access to modern energy services. With electrification rates of just 19%, 15%, 23%, 22% and 72% in Kenya, Tanzania, Ethiopia, Zambia and Ghana, respectively, (International Energy Agency, 2012) there is the potential to capture massive increases to consumer surplus by utilizing a multi-track approach to electricity access that prioritizes the rapid spread of high-quality grid alternatives while the slow process of expanding and securing the central grid occurs.

First, our analysis shows that consumers can gain significant net savings by switching to high quality grid alternatives such as solar lamps, SHS and microgrids from low quality kerosene and candle-based lighting. Using empirical data on actual levels of low-quality lighting fuel consumption in five countries, this result is shown to be ubiquitous across all levels of lighting consumption. However, this analysis is subject to the caveat that it does not take into account the capital intensive nature of purchasing solar lights and SHS. Capital expenditures are difficult for low-income households to afford because of poor access to secure savings accounts (Banerjee & Duflo, 2007). As such, it is insufficient to simply bring physical access to solar lamps and solar home systems. Financial access must be served as well – through the addition of "pay-as-you-go" (PAYG) technology, a traditional micro-loan, or a "rent-to-own" financing scheme – to make these products affordable to the poor. The explosion of sales of PAYG solar home systems in Kenya as well as other sub-Saharan African countries and India, is testament to the importance of financial access

(Fehrenbacher, 2014). In India, appropriately structured loans from the formal banking sector have been shown to be key factors for increasing sales of solar lighting systems (Harish, Iychettira, Raghavan, & Milind, 2013). Thus, the factors for successfully providing access to high-quality grid alternatives are not just technical. Rather, a concerted effort is necessary to provide access to finance and ongoing after-sales-service.

Second, our analysis shows that significant gains can be made to consumer surplus through the use of high-quality lighting alternatives relative to low-quality alternatives. The shape of the consumer demand curve for lighting strongly influences the resulting amount of consumer surplus. Testing several demand curves with different arc elasticities at different segments of the demand curve provides a range of estimates for consumer surplus. While some consumer surplus estimates were unreasonably high, even the lowest results are supportive of policmakers implementing a multi-track path to electrification rather than solely pursuing central grid extension on the basis that doing so increases consumer surplus relative to low-quality lighting.

Third, our analysis captures the inter-relation between maximum WTP for high-quality grid alternatives and the maximum acceptable ASUI. When the maximum acceptable central grid ASUI is less than or equal to a country's actual ASUI, the WTP for that grid alternative is greater than the actual price of that grid alternative. Thus, at these levels, consumers would be better served by grid alternatives than by the grid itself. We find that the ranges necessary for this to occur are, for the most part, well above actual central grid ASUI. However, the ASUI figures calculated are average figures and do not capture the different rates of unreliability and unavailability that certain geographic areas and certain demographics will experience. For these areas, policymakers should consider a more permanent multi-track approach, where grid alternatives are used not only as an interim solution prior to central grid connection, but also as a parallel, permanent system to capture consumer surplus that would otherwise be lost during periods of unavailability.

2.5 Conclusion

Arguments that merely advocate central grid extension and investment in central grid power stations discount not only the reality of central grid performance in less developed countries – as measured by conventional metrics like SAIDI, SAIFI and ASUI – but further leave out the notion of central grid availability. Availability during evening hours, when lighting is most needed, is not captured in these metrics or arguments, and there is insufficient data to link increased investment in grid capacity or extension to short-term gains in central grid reliability and availability during evening hours. As such, under certain conditions, grid alternatives may be necessary *even after the arrival of the central grid*. There are well-documented cases of central grid extension that do not actually result in much access to electricity; several cases in India have been documented where power does not flow to new rural distribution systems, and, the Government of India's own definition of "access to electricity" omitted the notion of electricity actually being used by households for a village to be considered "electrified" until 1997 (Schnitzer et al., 2014; Chaudhuri, 2007). In Kenya, thousands of households have been found to be within 200 meters of the central grid and yet remain unconnected (Lee, et al., 2014). Under such conditions, central grid extension is not a panacea for the problem of providing the poor with access to modern energy services.

Eliminating usage of low-quality lighting fuels should be a goal in itself, exclusive of merely expanding access to central grid electrification. Advocacy against adoption of high-quality grid alternatives (Bazilian & Pielke, Jr., 2013; Moss, Pielke, Jr., & Bazilian, 2014; Caine, et al., 2014) is a pernicious one that furthers the poverty and harm to health, education, and productivity linked to the use of low-quality lighting fuels (Craine, Mills, & Guay, 2014; Mills, 2012).

With insufficient metrics and insufficient definitions of access to electricity, advocacy for central grid investment is a necessary, but insufficient condition for access to modern energy services. As documented by our research, high-quality grid alternatives have a profound role to play in a multi-track approach to access to electricity.

A Appendix

A.1 Defining Access to Electricity: A Case Example in India

The definition of electricity access is fundamental to government policies to universalize electricity supply for its population.

The evolution of the definition in India is a case in point, illustrating how a conventional definition of electricity access can lead to sub-optimal electricity service. The Indian Government defined "electrification" four times between 1970 and 2003. There was impressive "growth" in electrification from the 1970s to 2000 under a definition that included only physical access to electricity – if any part of a village was provided with electricity from the central grid – even a single water pump on the outskirts – it was considered electrified (Chaudhuri, 2007). This definition no doubt served immediate political aims, but the long-term outcome was duplication of effort as the government returned to many of these areas after 2000 to provide access to electricity under a revised definition (Government of India Planning Commission, 2011). The change to a new definition that included notions of quantity of electricity consumed caused the number of electrified villages to drastically decrease, with the number of un-electrified villages increasing from 86,816 to 154,690 between 2000 and 2007 as those villages that were only nominally served no longer met the definition (Chaudhuri, 2007).

Figure A-1 tracks the chronology of the number of electrified villages over the various definitions used by the Government of India. It was compiled from data found in (Chaudhuri, 2007) and (Government of India Planning Commission, 2011).

At the outset of India's rural electrification efforts in the 1970s, the prevailing definition of an "electrified village" was if any part of the village was provided with electricity by the central grid for any purpose – even a single water pump on the outskirts of the village. In 1990, the number of "electrified" villages stood at 470,838 out of the total 587,258 villages included in the national census, leaving over 116,420 villages un-electrified (Chaudhuri, 2007).

In 1997 the definition was changed slightly to a village where central grid electricity was used for any purpose in its inhabited part. Around the same time, the Ministry of New and Renewable Energy (MNRE) adopted an alternative definition where lighting must be provided to at least 60% of households, regardless of whether it was provided by the central grid or distributed solar. However, this definition was only applied to villages that were declared as being "remote," meaning they would be "impossible" to connect to the central grid. By 2000 the number of "electrified" villages increased to 506,916. At this point, it was estimated that over 80,000 villages were still un-electrified – according to the "central grid" definition – including 18,000 villages declared as being impossible to reach with the central grid (Chaudhuri, 2007).

Electricity access was redefined in the 2003 Electricity Act, which required that a village have just 10% of its houses connected to the central grid in order to be considered electrified. Acknowledging the limited use of this definition for the end users, it evolved to a requirement of delivering 1 unit (kWh) of electricity per day per household under the National Electricity Policy of 2005 (Government of India, 2005). In 2007, the number of electrified villages fell from 506,916 (the 2000 figure) to 439,042 due in part to the new, more stringent definition promulgated in 2005. The number of "electrified" villages fell further during this time simply due to central grid infrastructure falling into disrepair or never having been energized in the first place (Chaudhuri, 2007). This left the number of un-electrified villages at 119,000 by the Ministry of Power's count and 154,690 by the Central Electricity Authority's, the disparity being attributed to the 35,690 un-electrified "remote" villages.

According to India's Twelfth Five Year Plan (2012-2017), 104,496 villages were provided with access to the central grid between 2007 and 2012, bringing the total number of electrified villages to

556,633 out of 593,732. According to the Plan, only 8,299 villages are still un-electrified, but this leaves an additional 28,800 "remote" villages to be electrified through distributed energy under the MNRE (Government of India Planning Commission, 2011).

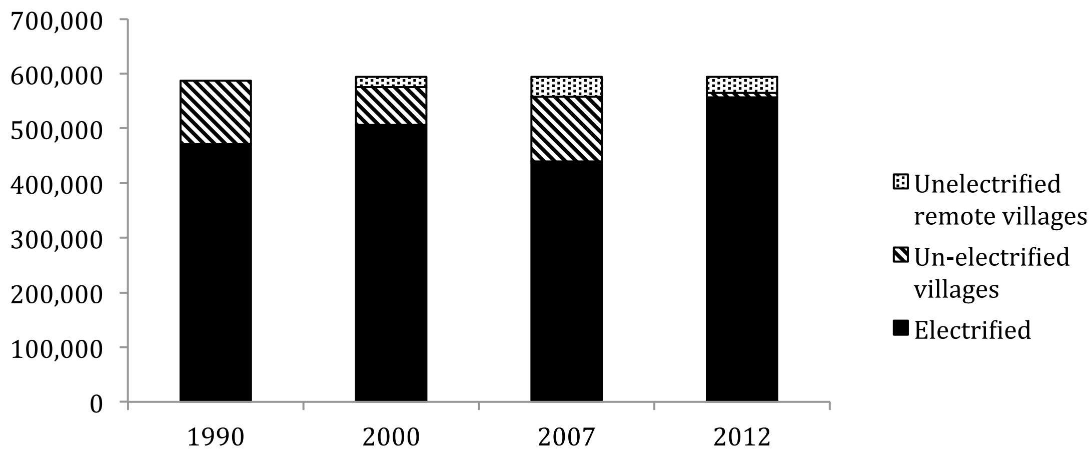


Figure A-1: Number of Electrified and Un-electrified Villages in India, 1990 – 2012

A.2 High Quality Grid Alternative Price Assumptions & Calculations

Table A-1: Solar Lamp Assumptions

	WakaWaka	References	Nokero N200	References
Retail price (USD)	15	Manufacturer	10	Manufacturer
Battery capacity (mAh)	800	(Lighting Global)	1,000	Manufacturer
Battery voltage (V)	3.6	(Lighting Global)	1.2	Manufacturer
Battery type	3xAA NiMH package	(Lighting Global)	1xAA NiMH	(Lighting Global)
Battery replacement cost (USD)	2.59	Assumption	0.86	Assumption
Battery life (years)	2	Assumption	2	Assumption
10-year total cost of ownership (USD)	27.96	Calculation	14.32	Calculation
Lumen output	28	(Lighting Global)	17	(Lighting Global)
Hours of light on day of solar charging	8.8	(Lighting Global)	2	(Lighting Global)

Table A-2: Solar Home System Assumptions

	BFP Connect 600	**References**	**One Degree Solar BrightBox2**	**References**
Retail price (USD)	160	Assumption	125	Assumption
Battery capacity (mAh)	4,000	Manufacturer	7,700	(Lighting Global)
Battery voltage (V)	12	Manufacturer	12	(Lighting Global)
Battery type		Sealed lead-acid	Sealed lead-acid	(Lighting Global)
Battery replacement cost (USD)	25	Assumption	35	Assumption
Battery life (years)	3	Assumption	3	Assumption
10-year total cost of ownership (USD)	243.33	Calculation	241.67	Calculation
Number of lamps	4	(Lighting Global)	2	(Lighting Global)
Total lumen output	300	(Lighting Global)	275	(Lighting Global)
Hours of light on day of solar charging	8	(Lighting Global)	5	(Lighting Global)

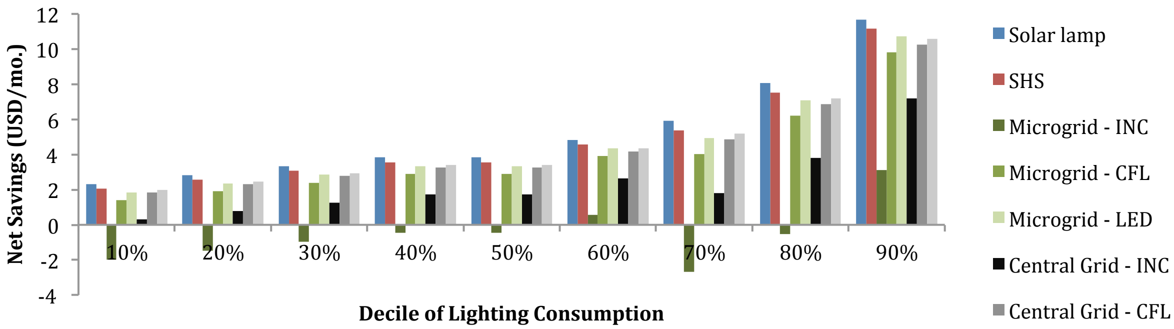
To find the cost of these solar lighting products on a USD/klmh basis, the following formula was used:

$$p = \frac{C}{l \cdot h \cdot 365 \cdot 10} \times 1{,}000$$

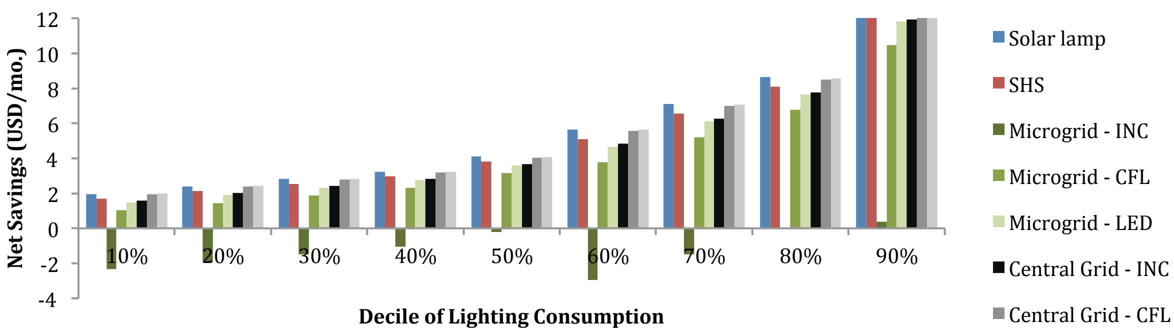
where *p* is the cost of the product in USD/klmh, *C* is the 10-year cost of ownership, *l* is the total lumen output of the product, *h* is the hours of light available from a single day of solar charging, *365* is the number of days in a year, *10* is the number of years over which the calculation is being levelized, and *1,000* is the factor to adjust from lumens to kilo-lumens. The costs were found to be 0.031 and 0.115 USD/klmh for the WakaWaka and the Nokero N200, respectively. Costs for the solar home systems were found to be 0.028 and 0.049 USD/klmh for the Barefoot Power Connect 600 and the One Degree Solar BrightBox 2, respectively. For the purpose of the analysis, the average costs for each category was taken. As recorded in Table 9, the averages are 0.073 and 0.038 USD/klmh for the solar lamp and the solar home system, respectively.

A.3 Full Model Outputs

A.3.1 Net Savings



(a)



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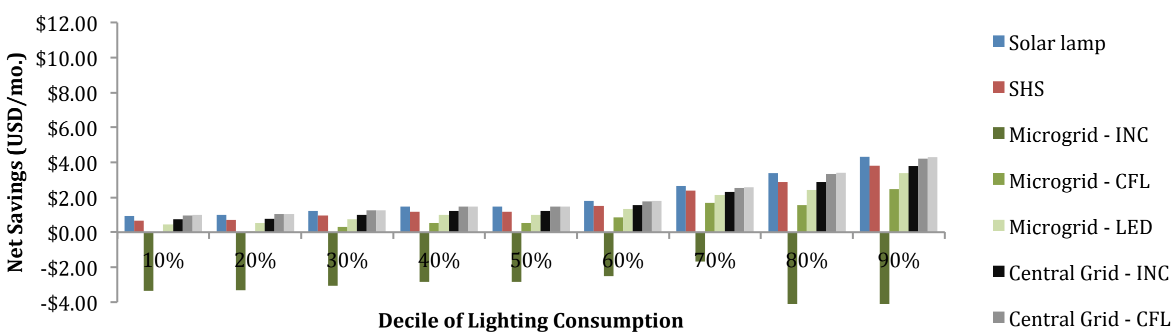

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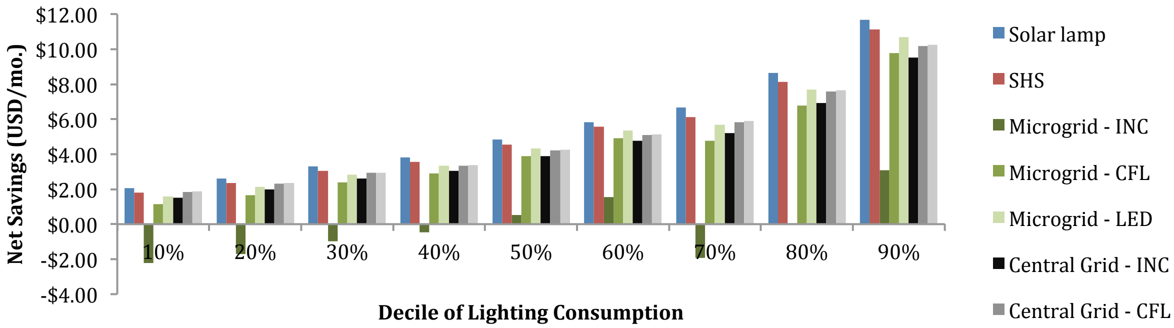
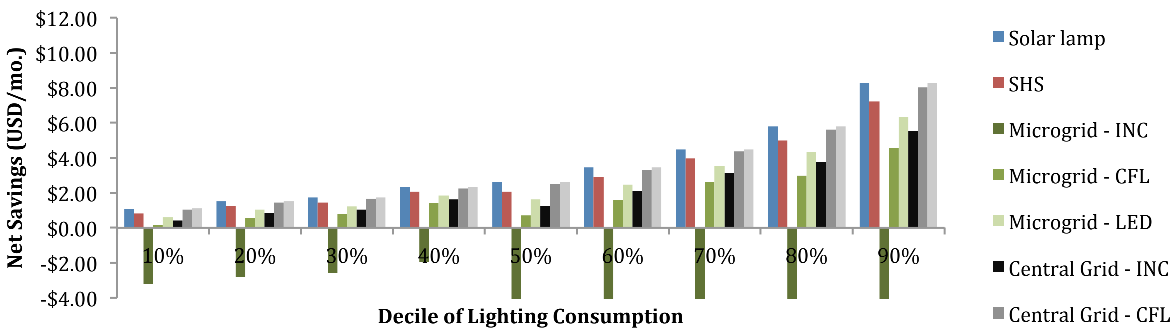


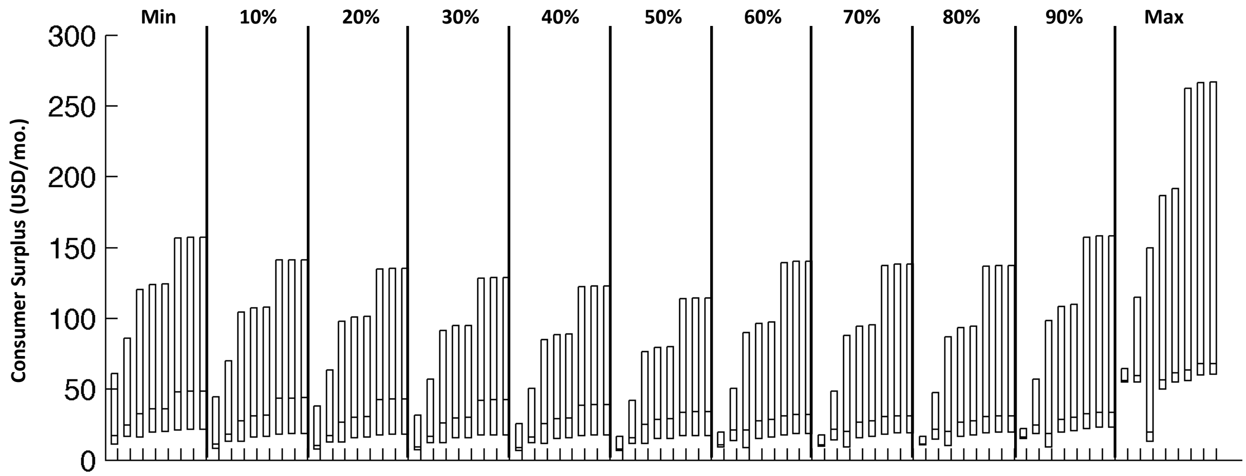
(d)



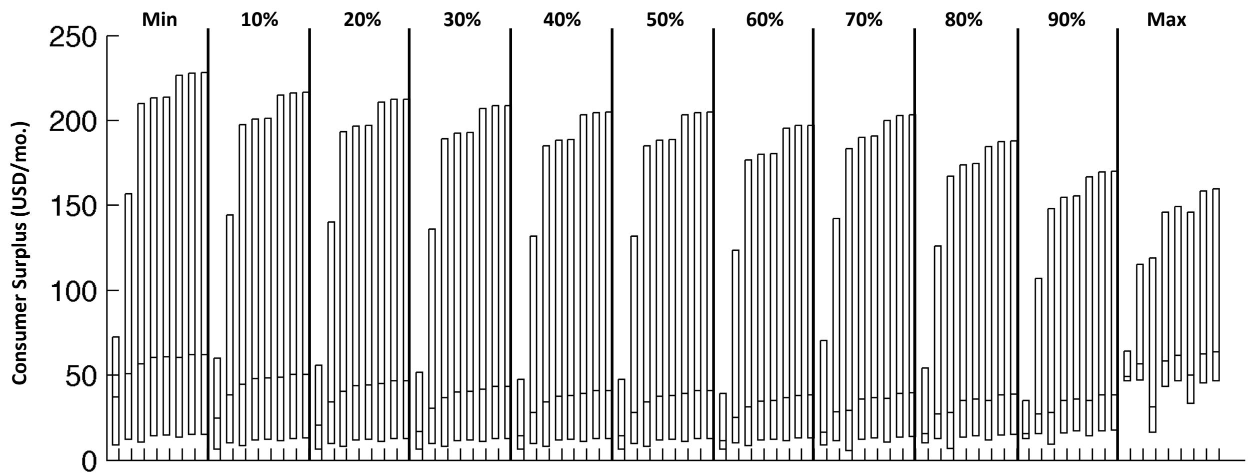
(e)

Figure A-2: Net Savings (USD/mo.) from Usage of High-Quality Lighting Sources Relative to Low-Quality Lighting Fuels at Lighting Consumption Deciles for (a) Kenya (b) Tanzania (c) Ethiopia (d) Zambia (e) Ghana

A.3.2 Consumer Surplus



(a)



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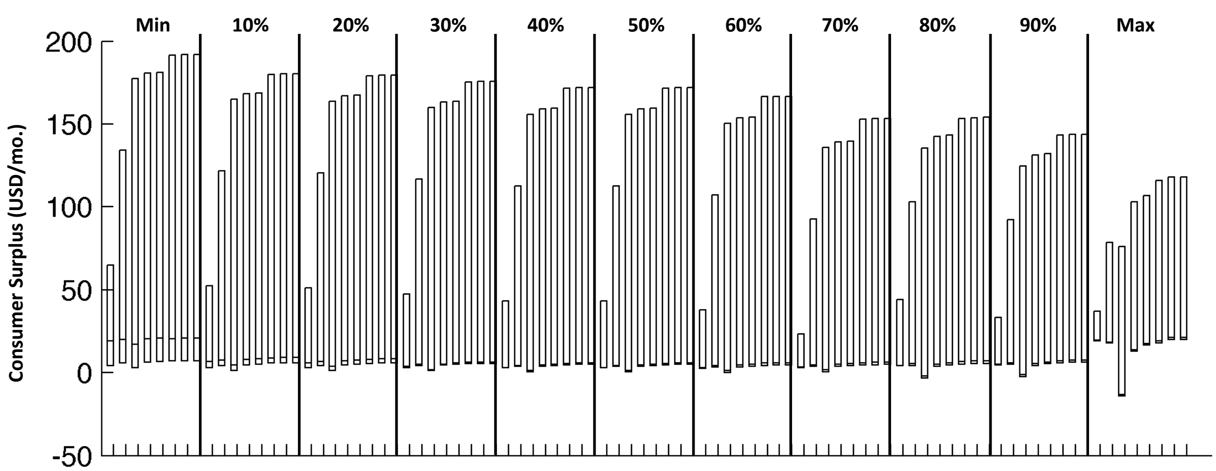
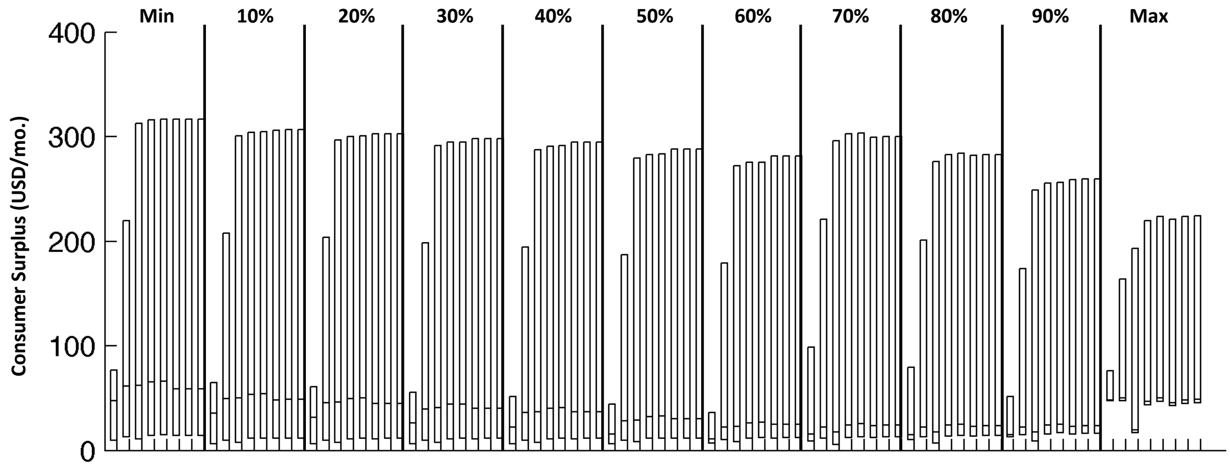


(c)



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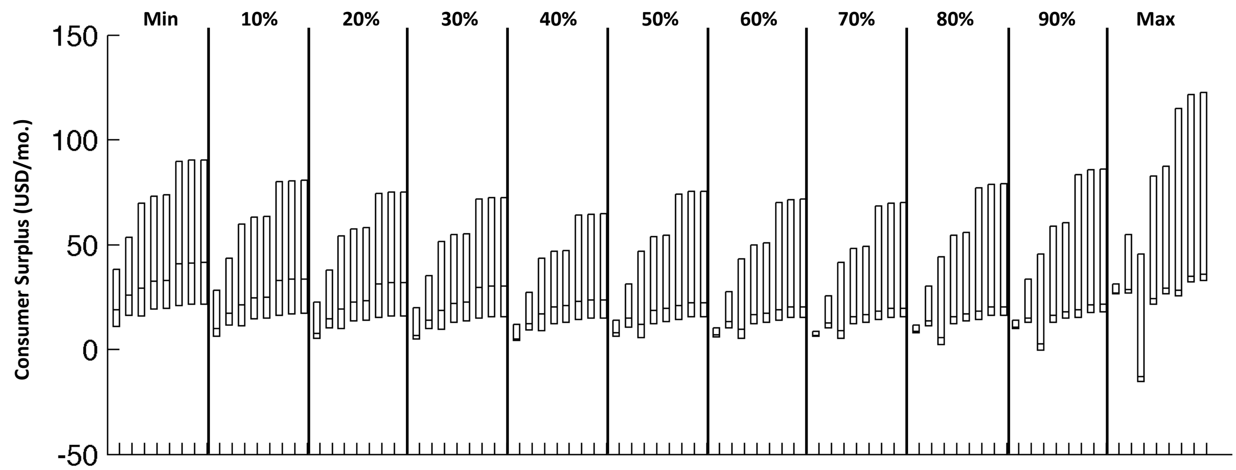
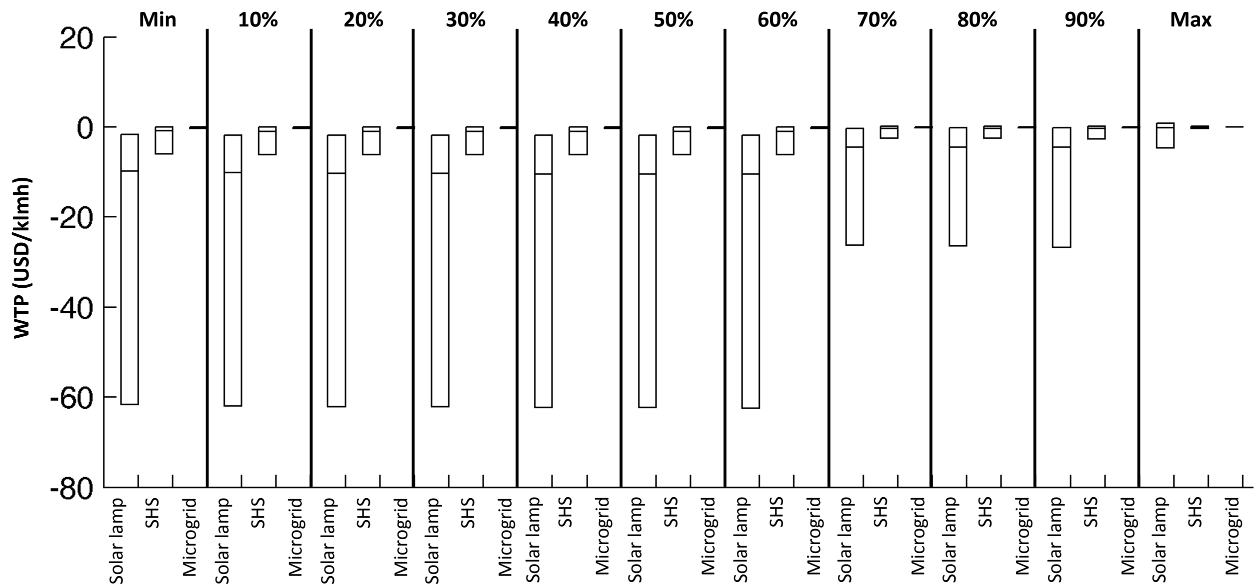


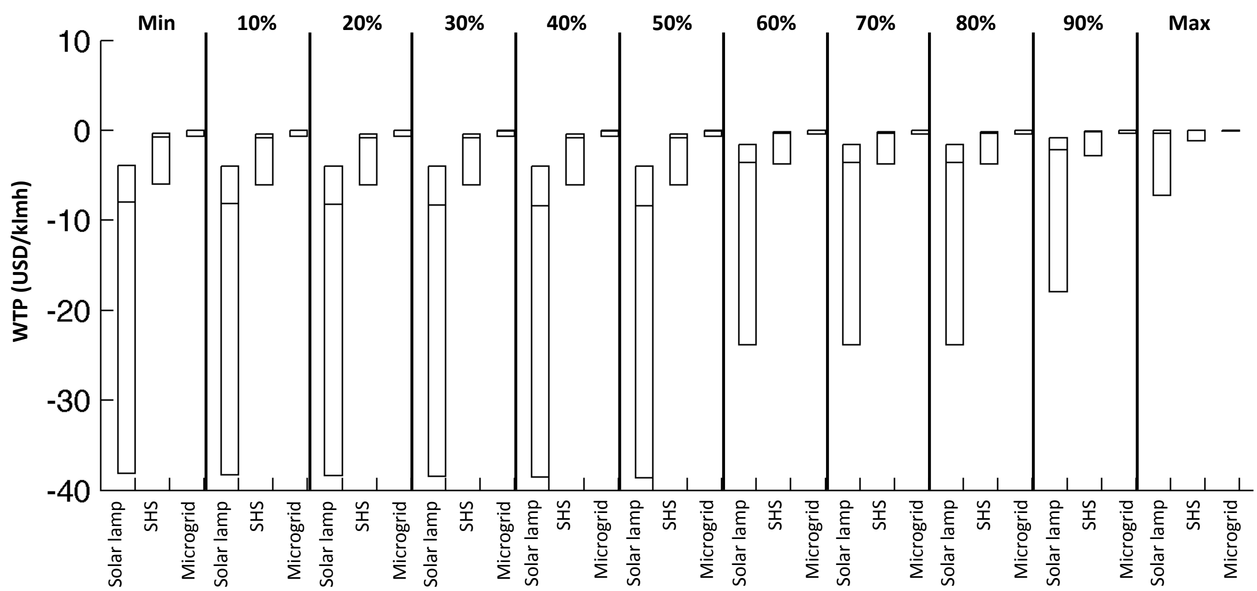
(e)

Figure A-3: Consumer Surplus (USD/mo.) from Usage of High-Quality Lighting Sources Relative to Low-Quality Lighting Fuels at Lighting Consumption Deciles for (a) Kenya (b) Tanzania (c) Ethiopia (d) Zambia (e) Ghana. Results for each lighting option within each decile is ordered, from left to right, Solar Lamp, Solar Home System, Microgrid-INC, Microgrid-CFL, Microgrid-LED, Central Grid-INC, Central Grid-CFL, Central Grid-LED.

A.3.3 Maximum WTP for High-Quality Grid Alternatives



(a)



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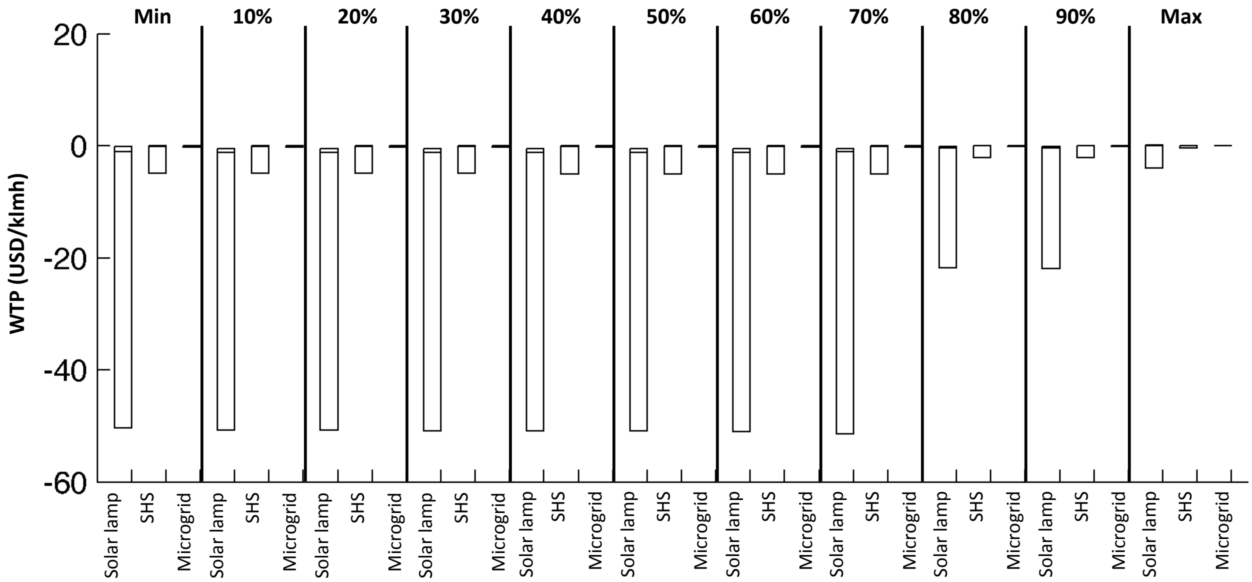
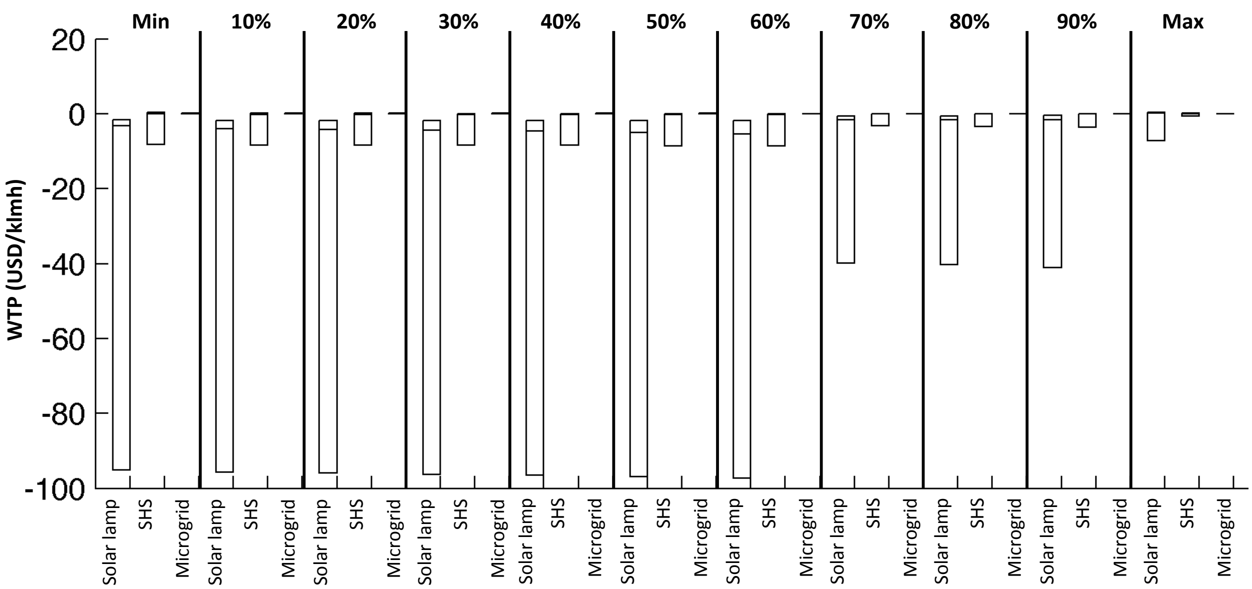

Min
10%
20%
30%
40%
50%
60%
70%
80%
90%
Max
WTP (USD/klmh)
20
0
-20
-40
-60
Solar lamp
SHS
Microgrid

(c)


Min
10%
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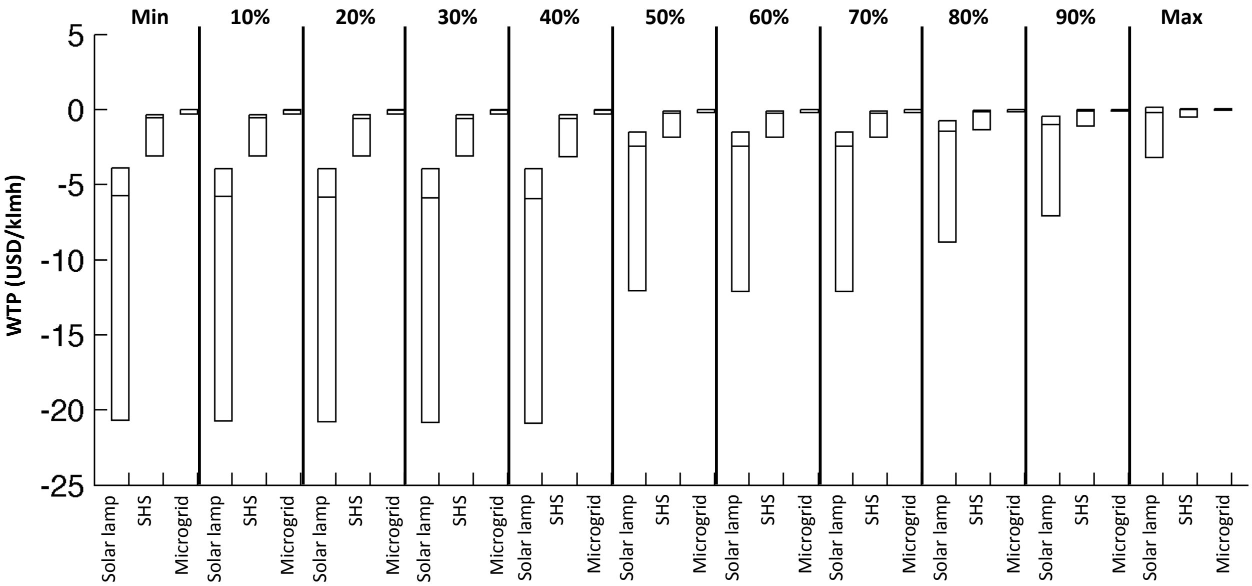
80%
90%
Max
WTP (USD/klmh)
20
0
-20
-40
-60
-80
-100
Solar lamp
SHS
Microgrid

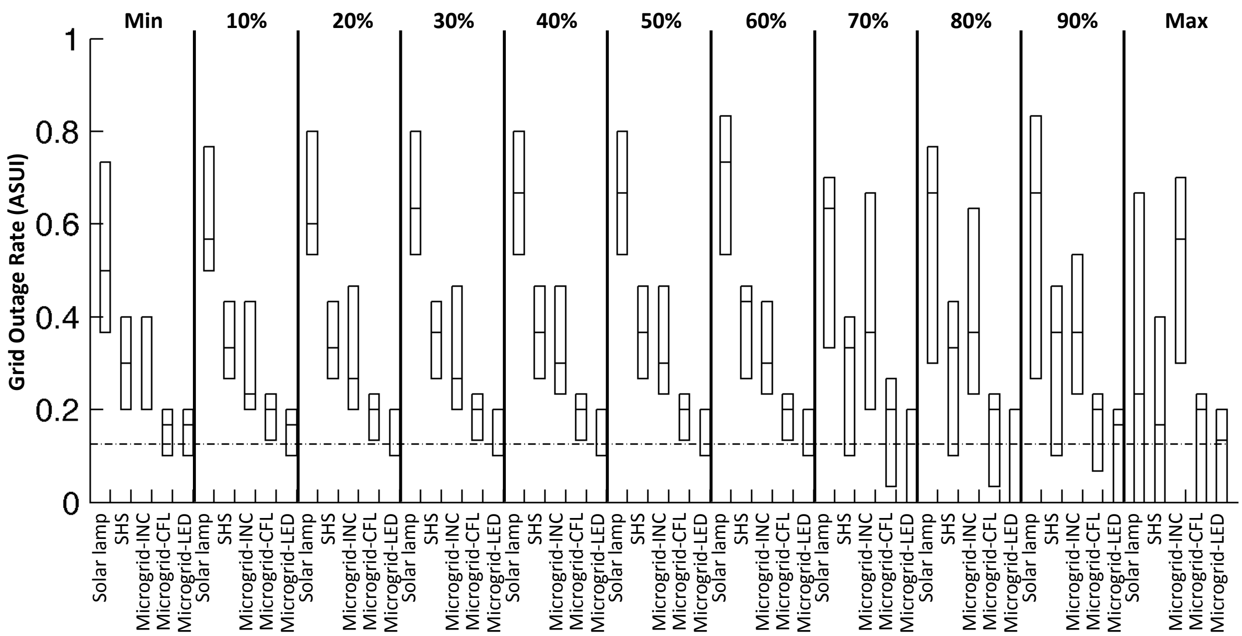
(d)



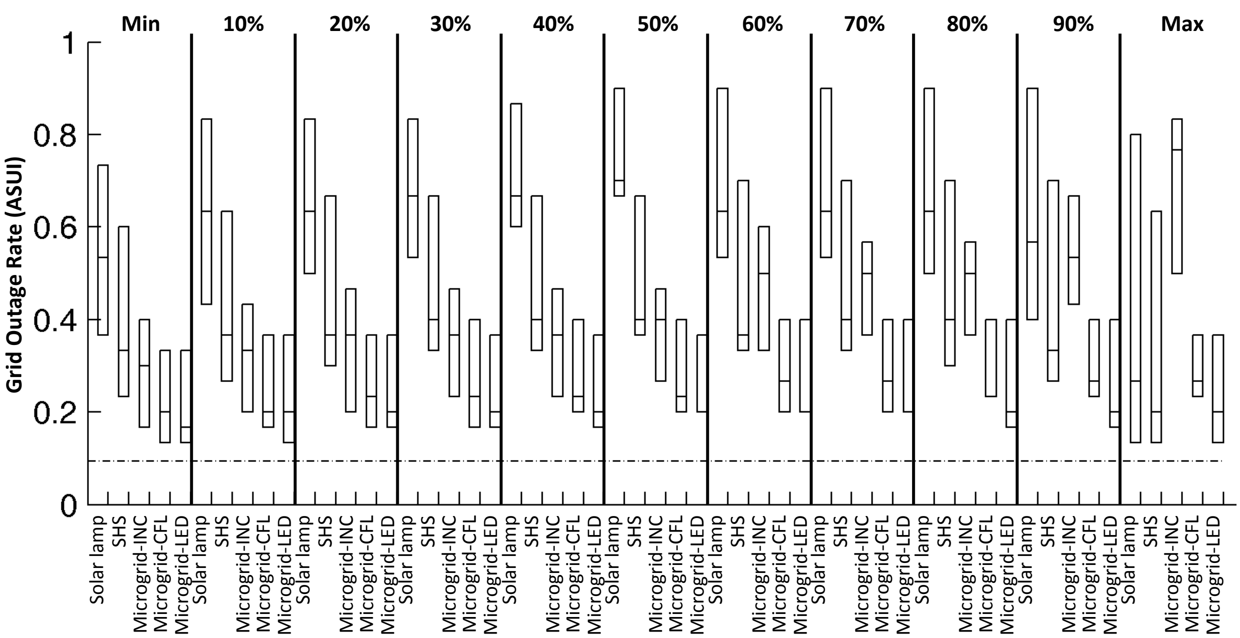
(e)

Figure A-4: WTP (USD/klmh) for High Quality Grid Alternatives at Lighting Consumption Deciles for (a) Kenya (b) Tanzania (c) Ethiopia (d) Zambia (e) Ghana

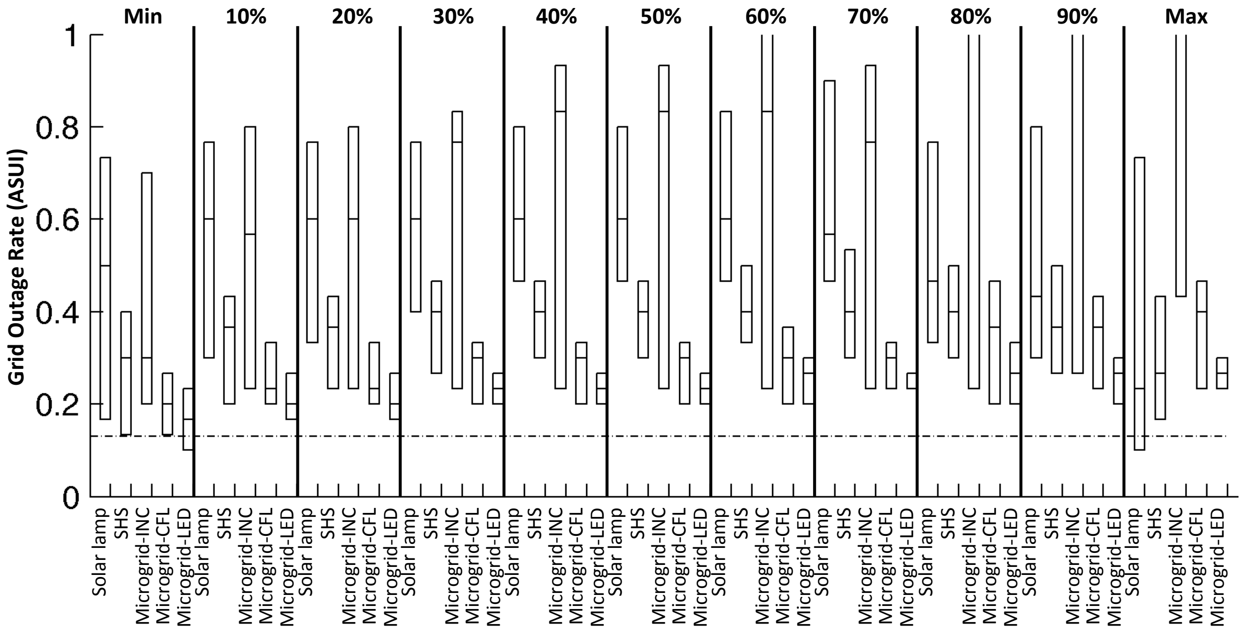
A.3.4 Maximum Acceptable Grid Outage Rate (ASUI)



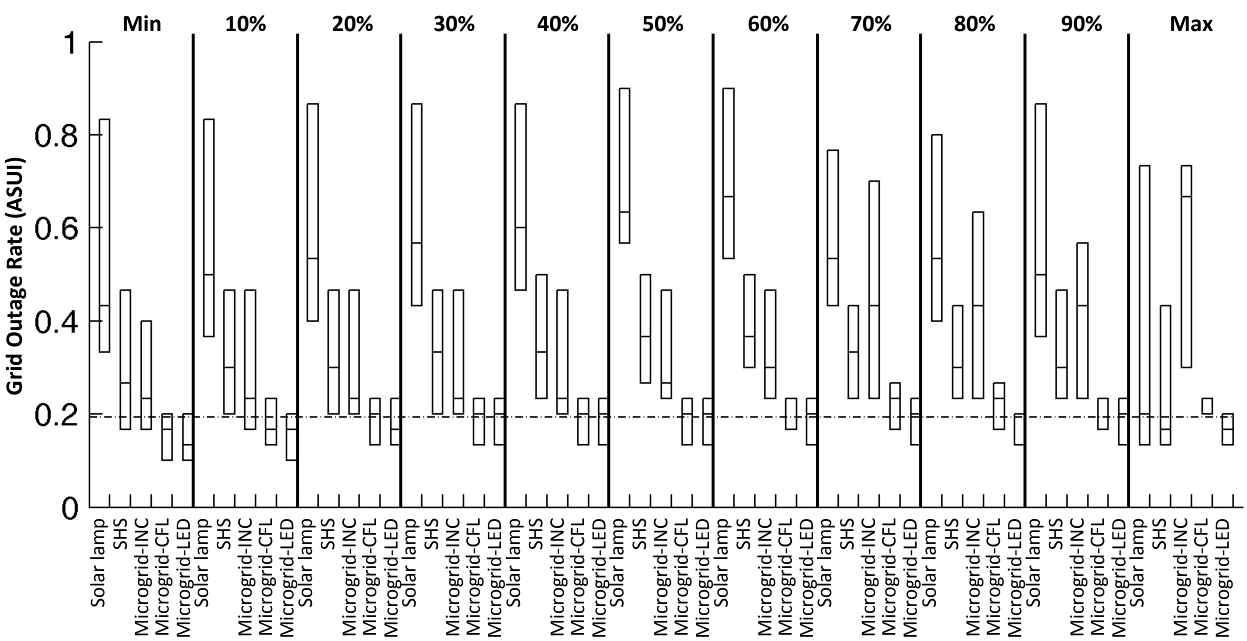
(a)



(b)


Min
10%
20%
30%
40%
50%
60%
70%
80%
90%
Max
Grid Outage Rate (ASUI)
Solar lamp
SHS
Microgrid-INC
Microgrid-CFL
Microgrid-LED

(c)


Min
10%
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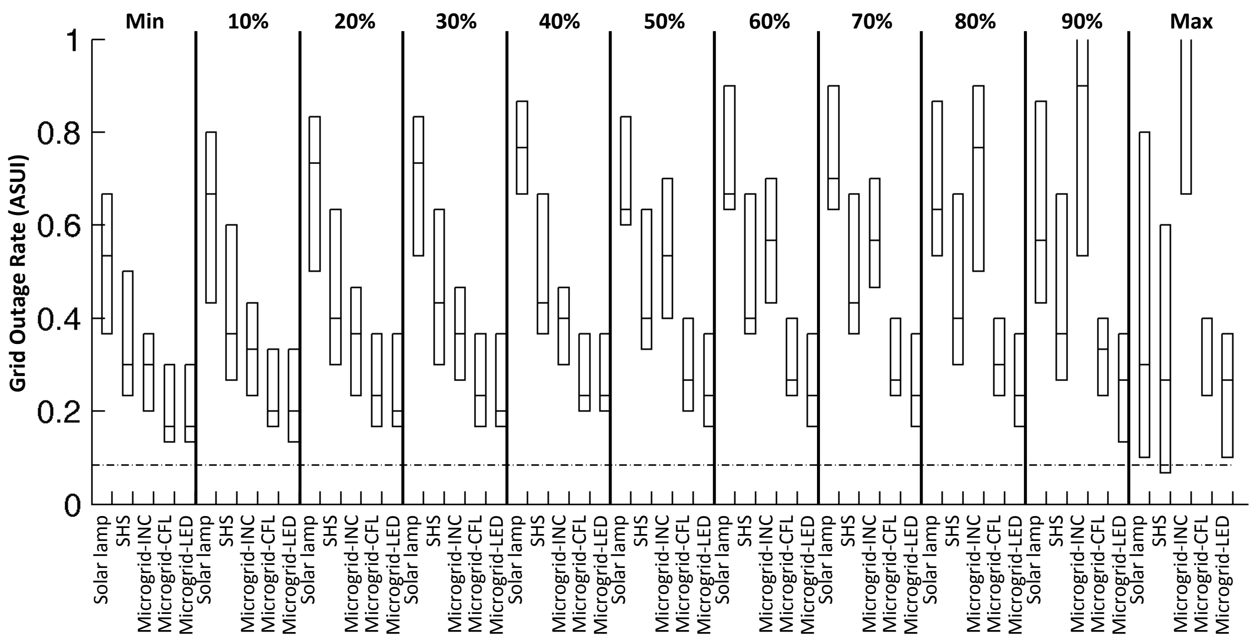
Max
Grid Outage Rate (ASUI)
Solar lamp
SHS
Microgrid-INC
Microgrid-CFL
Microgrid-LED

(d)



(e)

Figure A-5: Maximum Acceptable Central Grid Outage Rate (ASUI) at Lighting Consumption Deciles for (a) Kenya (b) Tanzania (c) Ethiopia (d) Zambia (e) Ghana. The dashed horizontal lines correspond to the actual outage rates as calculated by the Lighting Africa Market Assessment responses on central grid reliability – see Table 8.

Chapter 3: Financial Requirements for Improving Rural Micro-Grid Operations in Haiti

Abstract

All 36 of Haiti's diesel micro-grids operate for far fewer hours than their nominal operating schedules, which are typically three to four hours a night for four to five nights per week. On one closely studied microgrid we find that tariffs are set at levels 10% below operating costs, which prevent them from operating at their scheduled output, and that grid operators do not have sufficient working capital to make up for gaps in untimely customer tariff payments. For this microgrid, we model 23 demand- and supply-side interventions to determine whether operating costs can be reduced to levels below tariffs, and, if so, what the equivalent increase in hours of availability would be. We then model a subset of interventions to simulate the effect of working capital. Replacing incandescent light bulbs with CFLs and using a smaller diesel generator or a hybrid PV-diesel system halves operating costs relative to the existing system and would allow the grid to double its operating hours while yielding a positive return on investment with the existing tariffs. Other demand-side interventions, such as LED light bulbs, load-limiters, and load-shifting, coupled with an appropriately sized diesel generator do not offer as great a level of operational cost savings or as many additional hours of availability as the CFL-replacement intervention.

This paper was written with Daniel Soto, Niranjini Rajagopal, and Jay Apt.

3.1 Introduction

Starting in the mid-1980s, Electricité d'Haiti (EDH), the national utility, provided electricity to 36 municipalities with microgrids. None of these microgrids are connected to neighboring systems, and anecdotal evidence suggests that all of these grids either operate infrequently or are completely nonoperational. A list of the locations and capacities of these microgrids is given in Table 10 and Table 11. System capacities range from 60 – 500 kW, and their locations are distributed fairly evenly throughout the country. A typical microgrid may have dozens or a few hundred customers.

Table 10: EDH Microgrid Development in Grand Nord and Centrale-Ouest Regions, Haiti

Town	Department	Generator Capacity (kW)
Ennery	Artibonite	100
Gros Morne	Artibonite	250
Marmelade	Artibonite	300
Dondon	Nord	150
Pilate	Nord	100
Plaisance	Nord	60
Capotille	Nord-Est	100
Mont Organisé	Nord-Est	175
Ste Suzanne	Nord-Est	80
Anse à Foleur	Nord- Ouest	150
Bassin Bleu	Nord- Ouest	350
Bombardopolis	Nord- Ouest	200
Chansolme	Nord- Ouest	350
Jean Rabel	Nord- Ouest	500
Mole St Nicolas	Nord- Ouest	N/A
Casale	Centrale-Ouest	175
Pointe à Raquettes	Centrale-Ouest	60

Table 11: EDH Microgrid Development in Grand Sud Region, Haiti

Town	Department	Generator Capacity (kW)
Anse d'Hainault	Grand'Anse	150
Dame Marie	Grand'Anse	225
Marfranc	Grand'Anse	300
Pestel	Grand'Anse	85
Anse à Veau	Nippes	100
Baradères	Nippes	100
Grand Boucan	Nippes	100
L'Asile	Nippes	240
Petit Trou de Nippes	Nippes	150
Pte Rivière de Nippes	Nippes	150
Coteaux	Sud	125
Port à Piment	Sud	200
Roche à Bateau	Sud	100
Tiburon	Sud	150
Anse à Pitre	Sud-Est	150
Arnaud	Sud-Est	150
Belle Anse	Sud-Est	100
Côte de Fer	Sud-Est	200
Thiotte	Sud-Est	132

These systems were built by EDH under its mandate to provide rural towns with access to electricity through microgrids. There is an unfortunate dearth of data on these systems. However, we have obtained detailed information about seven projects through site visits conducted by the organization EarthSpark International.

In 2012, EarthSpark International conducted field visits at seven sites: Anse d'Hainault, Dame Marie, Marfranc and Pèstel, in Grande Anse; and Coteaux, Port-a-Piment and Roche-a-Bateaux in Department Sud (Table 12). EarthSpark chose these sites because of their location and relative accessibility. They were not chosen to be a representative sample of all 36 microgrids, but rather in response to interest expressed by the Government of Haiti as candidates for interventions.

Table 12: Status of Microgrids Visited by EarthSpark International in Grand Sud Region, Haiti

Town	Year Installed	No. Customers	Operational Status
Anse d'Hainault	1989	500	As of January 2014, had not been functional since 2010.
Dame Marie	1989	N/A	As of January 2014, had not been functional since 2010.
Marfranc	2005, upgrade in 2011	200	As of March 2013, had not been used since October 2012 due to lack of funds for fuel.
Pèstel	1986, upgrade in 2006	250	Consistent operations, 1986 – 2012. As of March 2013, had not been used since April 2012 due to a transformer failure.
Coteaux	1994	250	Inconsistent operations, see section 2.
Port-a-Piment	2009	210	Inconsistent operations, see section 2.
Roche-a-Bateaux	2008	160	Inconsistent operations due to insufficient tariff collection. Ceased operations in May 2012 due to transformer failure.

We found that each of the microgrids operates rarely, if at all. No customers are metered, and customer billing is based on a fixed monthly tariff as a function of the number of light bulbs or appliances in a home. These monthly tariffs are set at levels that are below operating costs, preventing cost recovery. During any particular monthly billing cycle, cost recovery may be further hindered due to the irregularity of customer tariff payments. Customers may be allowed to make a single payment in one month for charges incurred in the previous three. In tandem, insufficiently priced tariffs and irregular tariff payments prevent the operator from purchasing sufficient fuel to operate at the nominal schedule in the next month. Reduced hours of operation in the next billing cycle are grounds for not collecting tariffs, further driving operations to ever fewer hours. None of the microgrid operators have access to working capital, though EDH or a local politician may at times provide a small amount of fuel, especially during holidays.

The size of the diesel generators relative to the loads they serve results in very high fuel costs and a high maintenance burden. Diesel generators run most efficiently close to their nameplate capacity, as illustrated in Figure 11 and Figure 12 for the generators in Coteaux and Port-a-Piment. Generators are much less efficient at very low levels of output relative to capacity (typically under 30%) due to incomplete fuel combustion commonly referred to as "wet stacking." Wet stacking can also damage the generator if not properly addressed, creating further costs (National Fire Protection Agency, 2013).

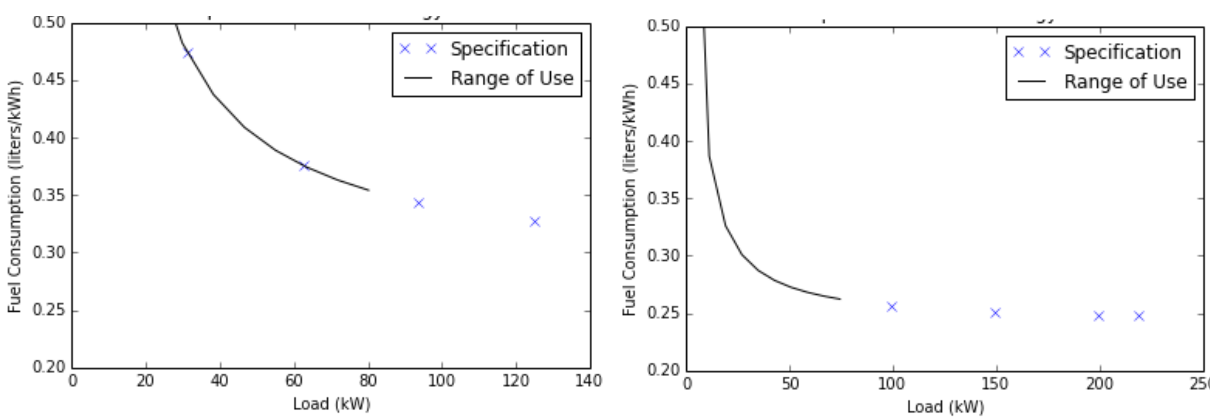


Figure 11: Diesel generator efficiency curve showing fuel use per unit electrical energy delivered for microgrids in Coteaux (L) and Port-a-Piment(R)

Theoretical and practical efforts have been made to resolve problems like these that prevent microgrids from operating reliably. Some analyses have produced least-cost electrification strategies for individual villages or regions. Most of these studies focus on supply-side solutions. For example, some studies find that hybrid renewable-diesel systems can be the most cost-effective options (Khan & Iqbal, 2005; Rana et al., 1998; Schmid & Hoffman, 2004). Others limit their analyses to non-hybrid systems or find that single generation sources rather than hybrids are the lowest cost for that particular area (Kolhe, Kolhe, & Joshi, 2002). Some studies also look specifically at the trade-offs between renewable solutions compared to diesel solutions for stand-alone systems; Mahmoud and Ibrik (2005) found that PV-only systems are lower cost solutions to providing energy access than diesel generators or central grid extension for communities in Palestine.

The outcomes of these analyses are dependent on assumptions about resource availability, fuel costs, capital costs, load factor, load profile, and the assumed discount rate. HOMER (hybrid optimization model for electric renewables, HOMER, 2014) software is one tool for such analyses, and has been used by Khan and Iqbal (2005), Johnson et al. (2012) and Casillas and Kammen (2011). Load factor is defined as the ratio between peak and average load. A meta-analysis of microgrid intervention modeling studies found that "...low load factors...are typifying characteristics of rural electricity..." and that "…systems which are uneconomic at a given load factor may become feasible at a higher load factor" (Kaundinya, Balachandra, & Ravindranath, 2009). Thus, demand-side interventions are also necessary to further improve rural microgrid operations. Casillas and Kammen (2011) examine several demand-side options, such as replacing incandescent light bulbs with CFLs, increasing the efficiency of streetlights, and installing meters. Johnson et al. (2012) is one of very few studies that have examined these types of interventions from multiple stakeholder perspectives. This oft-neglected element of analysis is crucial given the significant roles that communities, governments, NGOs and private actors can play in just one microgrid (Schnitzer et al., 2014).

The poor functioning state of at least a fraction of the 36 microgrids in Haiti – and likely more that have not been documented as thoroughly – presents opportunities for improvement and the provision of much higher quality energy services for thousands of households.

The problems plaguing these grids are not intractable. In this paper, we show that a range of demand- and supply-side interventions can be made to increase the number of operating hours, without needing to increase tariffs. The outlook for these microgrids is further enhanced with the addition of working capital – a component of their business models that ought to have been integral given that customers are allowed to use electricity on credit.[6]

We improve on previous studies by using high-resolution data on household appliance stock and generator output data to accurately model specific demand-side interventions on a single microgrid that we studied in more detail. We also present one-minute time series data and corresponding statistical analyses of total load collected over a period of nearly one year from two microgrids in Haiti to further contribute to knowledge in this under-studied space.

3.2 Coteaux and Port-a-Piment Case Studies

Two microgrids were selected for in-depth analysis, and one for modeling (Figure 12). Site visits to the community micro-grids in Port-a-Piment and Coteaux were made as initial assessments during March and April 2012. Data loggers were installed on the generators at each site to measure microgrid load at a time resolution of one minute for approximately one year. The loggers are accurate to +/- 1% of the current reading.

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[6] We are not aware of any studies assessing improvements to microgrid operations that make reference to working capital, though it is mentioned in passing in reports that focus on the financial viability of commercial microgrid business models (Economic Consulting Associates Limited, 2013; Tenenbaum et al., 2014).

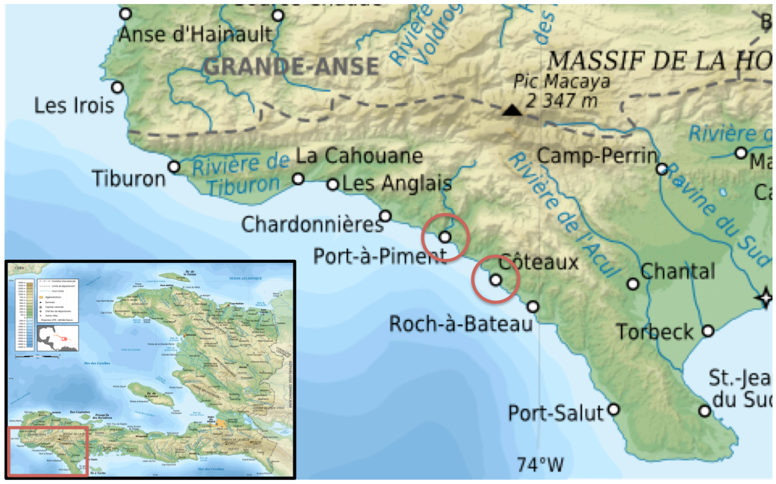

Figure 12: Locations of Coteaux and Port-a-Piment, Haiti. Inset map of Haiti shows area of magnification in highlighted box. (Kaupp, 2009)

Both microgrids are powered by three-phase diesel generators. Detailed information on the microgrid generators and photographs of the generators, distribution system interconnections, and the first connected distribution poles with step-up transformers are provided in Appendix B.1.

3.2.1 Finance and Management

Table 13 provides detailed data on the operations and finances of these two microgrids.

Table 13: Financial and Operational Summary for Two Microgrids in Department Sud, Haiti

	Coteaux	Port-a-Piment[7]
Generator Rating	149 kW	249 kW
Microgrid Nominal Voltage	120 V	120 V
Generator Year of Manufacture	1994	2009
Year Generator Installed	1994	2010
Nominal Schedule	7-10 pm, Su, M, W, F, Sa	6-1 0pm Su; 7-10 pm Tu, Th, Sa
Grid management entity	Volunteers affiliated with Mayor's office and paid EDH technician	Electricitè de Port-a-Piment (EDP)
Monthly Tariff	50 HTG/bulb (USD 1.22)	150 HTG (USD 3.66) plus 50 HTG/bulb (USD 1.22)
Disconnection penalty rule	3 months missed payments	3 months missed payments
Re-connection fee	Arrears	Arrears + 150 HTG (USD 3.66) penalty
Typical Monthly Revenue	25,000 HTG (USD 610)	35,381 (USD 861)
Typical Monthly Costs	60,000 HTG (USD 1,463)	40,385 (USD 985)
Typical Monthly Shortfall	35,000 HTG (USD 853)	5,084 HTG (USD 124)
Typical Monthly Income/Expense Ratio	42%	87%

The majority of operating costs on the Haiti microgrids are diesel fuel purchases. Some microgrids pay small salaries to management personnel, such as a secretary who collects payments and makes purchases, or operations staff, such as a generator house guardian or janitor. Maintenance expenditures are small, but insufficient, as the generators occasionally fall into disrepair and remain non-functional for weeks or months even as a result of minor maintenance requirements such as replacing generator house fuses or engine oil filters.

Compared to the other microgrids visited, the Port-a-Piment microgrid operator keeps the most formal records, and seems to execute operational practices such as billing, connection requests, and addressing non-payment more reliably than the others. Figure 13 shows the monthly expenses and accounts receivable for the Port-a-Piment microgrid from November 2009 to March 2012. As is

[7] Revenues and costs are calculated as actual averages based on Port-a-Piment microgrid secretary's records from November 2009 – March 2012. Given the recorded expenditures, it is suspected that the micro-grid operated much more frequently during this time than during the March 2012 - March 2013 timeframe over which we logged the output of the Port-a-Piment generator.

apparent, accounts receivable sums are typically below expenses, indicating that tariffs are set to levels that are below cost recovery.

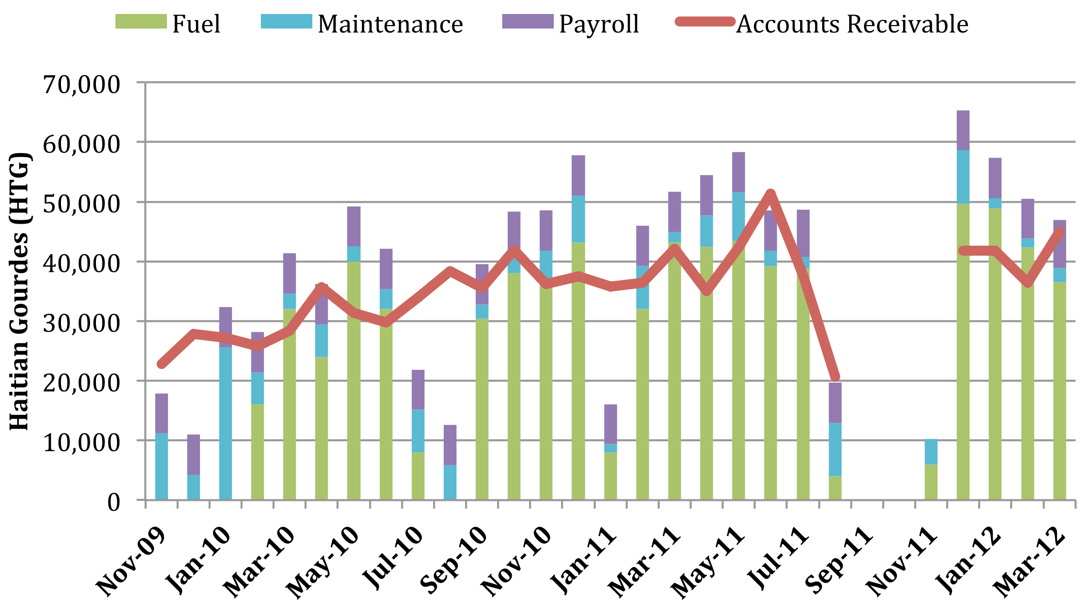

Figure 13: Time-series of Port-a-Piment Micro-Grid Accounts Receivable Income and Expenditures, November 2009 – March 2012[8]

3.2.2 Microgrid Operations Analysis

In Coteaux, the grid is scheduled to run 7-10 PM every day except for Tuesday and Thursday. In Port-a-Piment, the grid is scheduled for 7-10 PM on Tuesday, Thursday and Saturday, and 6-10 PM on Sunday. The Coteaux generator is equipped with a counter that records the number of hours it has run. The counter had logged 8,522 hours since it was installed 18 years before our observation on May 11, 2012. This is an average of 9 hours per week, compared to the scheduled 15.

[8] The figure shows a few periods in which accounts receivable far exceeded expenditures and many periods in which expenditures exceed income by 30 - 60%. This is likely due to a peculiarity in the accounting procedure used by the grid operators. As mentioned previously, customers are allowed to make aggregated payments – that is, making a single payment for the current month as well as the previous two, three or four months. The grid operator records in his accounts receivable ledger each of the previous months being paid for in those months, rather than payments of zero in those months, and a large payment in the most recent month. In other words, the accounts receivable line in Figure 4 does not show actual income (cash flow). Actual income is, in actuality, far more inconsistent, and likely matches the peaks and troughs of the expenses more closely.

We measured the power output of both microgrids over the periods shown in Figure 14. In total, the data logger recorded for 238 of the 325 days it was installed on the Coteaux site, and 275 of the 338 days it was installed on the Port-a-Piment site. The greyed-out sections of the time-series indicate the periods during which the data logger's batteries were depleted.

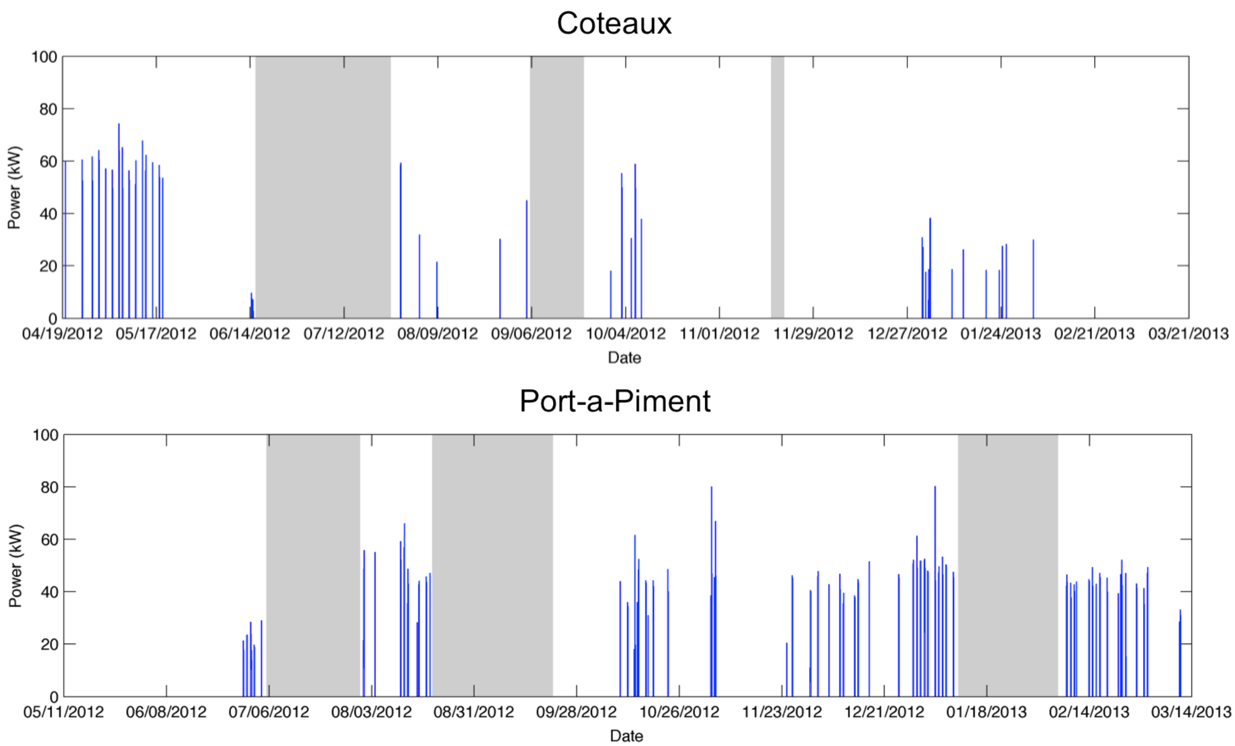

Figure 14: Coteaux Load Profile, 5/11/2012 – 3/14/2013; and Port-a-Piment Load Profile, 4/19/2012 – 3/21/2013

The microgrids operate much less frequently than their nominal schedule, and when they are operational total load is significantly less than the rated capacity of the generators. The highest peak load on the Coteaux microgrid was 80 kW out of an available 149 kW, and 75 kW on the Port-a-Piment microgrid out of an available 249 kW. Average load in Coteaux was 37 kW, and 41 kW in Port-a-Piment for the duration during which they were being monitored. As discussed above, running diesel generators at such low load ratios is very fuel inefficient (Figure 11) and increases maintenance requirements, further increasing operational costs.

There are several instances of the grids being run for brief periods of time – less than 15 minutes – usually during the day. These are typically associated with maintenance. Removing periods during which the microgrids were operating for less than 15 minutes, the microgrid in Coteaux was operational for 66 days during the times that the data logger was active, and for only 28 days in Port-a-Piment – or 28% and 10% of logged days, respectively. These can be compared to the nominal operating schedule of 71% of days for Coteaux (260 days a year) and 57% for Port-a-Piment (208 days a year). In terms of hours, the Coteaux and Port-a-Piment microgrids ran for just 131 and 54 logged hours, respectively.

When the microgrids are operational, they typically operate for fewer hours than what is scheduled. The average duration for microgrid operations is just under two hours on both grids compared to scheduled run-times of three to four hours.

Given their brief run-times on most operating days, the intra-day load changes are minor over the course of the operations. Figure 15 shows load profiles for the approximately two hours of operation on a typical day on each microgrid. Appendix B.2 includes a more detailed analysis of the load profiles.

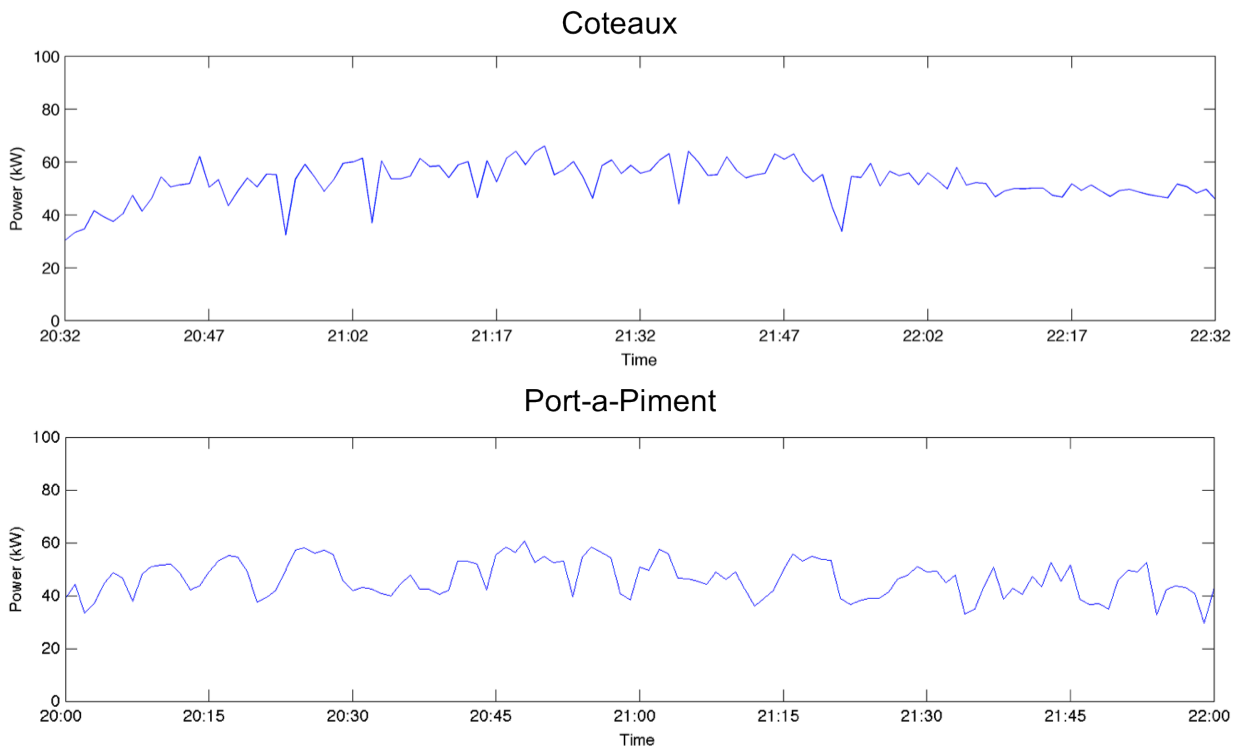

Figure 15: Coteaux Microgrid One-Minute Load Profile from 8/11/2012 and Port-a-Piment Microgrid One-Minute Load Profile from 4/24/2012

In addition to intra-day loads being similar, inter-day loads are also similar. Figure 16 shows a 24-hour hourly load curve with distributions of the hourly average load during each hour of the day for all days in the Port-a-Piment sample.

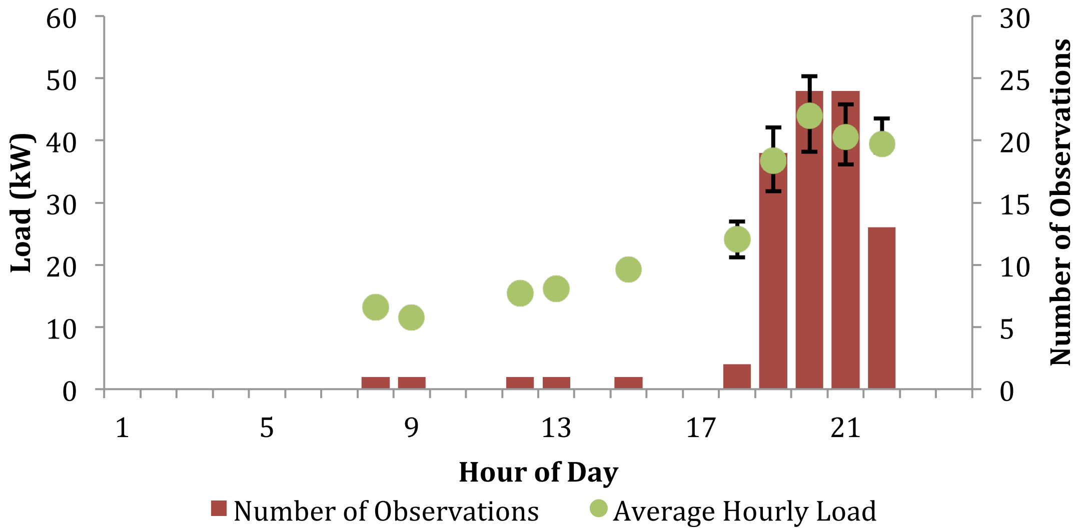

Figure 16: Hourly Average Load on the Port-a-Piment Microgrid for All Days, N=28. A 50 kW load is approximately 20% of the maximum capacity of the generator. Whiskers around the average hourly load indicate the 25th and 75th percentile load where there was more than one observation.

The Port-a-Piment microgrid runs most frequently in the evening, as is evident by the small number of observations for hours prior to 7 PM. There are many hours of the day during which the Port-a-Piment microgrid was never recorded as operating. During the evening hours when the microgrid was operating, the average load did not vary much from one day to the other.

Despite sparse data collection, the data reveal a few strong trends. Intra- and inter-day comparisons of load reveal strong consistencies, and the full load profiles shown in Figure 14 validate the commonly held belief in Haiti that these systems rarely function.

3.3 Modeling Approach

In order to assess the five demand-side interventions listed in Table 14, a demand model of appliance stock and appliance usage was created. The output of the demand model is an aggregated one-year load profile for the entire community of Port-a-Piment. The demand model can therefore be used as a tool to develop a baseline load profile representing the actual load profile in each town, or as a simulation tool to model different appliance efficiency and scheduling interventions.

Corresponding generation-side interventions were modeled for each set of demand-side interventions by using the load profile as an input into HOMER microgrid modeling software. The sample space in HOMER included a diesel generator with specifications similar to the generator sited at the Port-a-Piment microgrid in Haiti, as well as smaller, appropriately sized generators. Photovoltaic systems with battery storage were included as generation options, but small-scale wind turbine systems were not. HOMER optimizes generation resource size and dispatch on the basis of levelized cost of electricity (LCOE) for a given set of assumptions about the load curve, resource availability and cost, and capital costs.

Results from the demand- and supply-modeling were used as inputs to a financial model to assess the efficacy of the interventions. In the case of the microgrids in Haiti, the capital costs of the system were paid for by the national government. We chose to have the model take into account the cost of capital for both load-side interventions and supply-side interventions. In this way, it is possible to assess both a subsidized approach to these interventions that strive to lower operating costs, and an unsubsidized approach to implementing the interventions that could be taken on by a private-sector energy services company (ESCO) that bears the cost of capital and would look for a return on its investment.

A total of five demand-side and three generation-side interventions were considered, listed in Table 14.

Table 14: Generation- and Demand-Side Interventions Modeled

Generation-Side Interventions
Appropriately sized diesel generator
PV-battery only
PV-battery-diesel generator hybrid

Demand-Side Interventions
Replace incandescent light bulbs with CFLs
Replace incandescent light bulbs with LEDs
Replace CFL light bulbs with incandescent bulbs
Limit household loads to 100W
Scheduled iron usage

3.3.1 Demand Model

A microgrid customer load survey was fielded in both Coteaux and Port-a-Piment by the NGO EarthSpark International between November 2012 and January 2013. In total, 101 surveys were fielded in Coteaux and 151 in Port-a-Piment. Five businesses were included in both locations, and the remaining respondents were households. The surveys revealed what types of loads customers used and the number and size (in Watts) of each.[9]

The results of the survey were used as inputs into the demand model. The demand model stochastically populates a stock of consumer loads for any number of consumers, *N*, with identical distributions of number and size of loads as the survey sample.

Validation of the simulated appliance stock in the demand model was achieved by comparing the sample distribution of consumer maximum load (the sum of the product of appliance quantity and appliance size for each appliance) to the simulated distribution with a Mann-Whitney-Wilcoxon test. The result of the test indicates that the null hypothesis (that independent samples in the sample distribution and simulated distribution are from identical distributions with equal medians) cannot

[9] The survey was implemented by EarthSpark International using the Columbia University Modi Research Group formhub tool running on Android tablets. The survey tool is available for download, modification and re-use at https://formhub.org/dan/forms/Microgrid_survey_20120903.

be rejected at the 5% significance level. Figure 17 compares the distribution of maximum loads between the sample (*N*=151) and simulated (*N*=1,000) distributions for Port-a-Piment. The simulated results are nearly identical to the survey data.

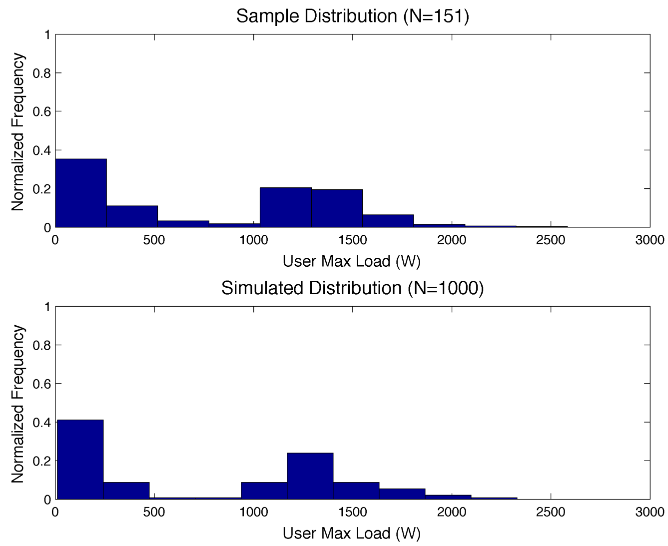

Figure 17: Normalized Histograms of Sample and Simulated Consumer Maximum Load in Port-a-Piment

Once the appliances stock is populated, the demand model specifies energy usage rates for each appliance at each hour of the day. This approach is similar to that used in Paatero and Lund (2006), which presents a simple "bottom-up" load model where 24-hour load profiles are constructed from survey data on individual household appliance stock and usage in Finland. Figure 18 shows the 24-hour load profile constructed from the Port-a-Piment demand model for $N = 210$ consumers. No free parameters were used in this aspect of the model; the resulting 24-hour load profiles were generated solely by the statistical information from the load surveys and the appliance time-of-day usage rates derived from Paatero and Lund (2006). Further details about this aspect of the demand model and the usage rates derived from Paatero and Lund (2006) are provided in Appendix B.3.

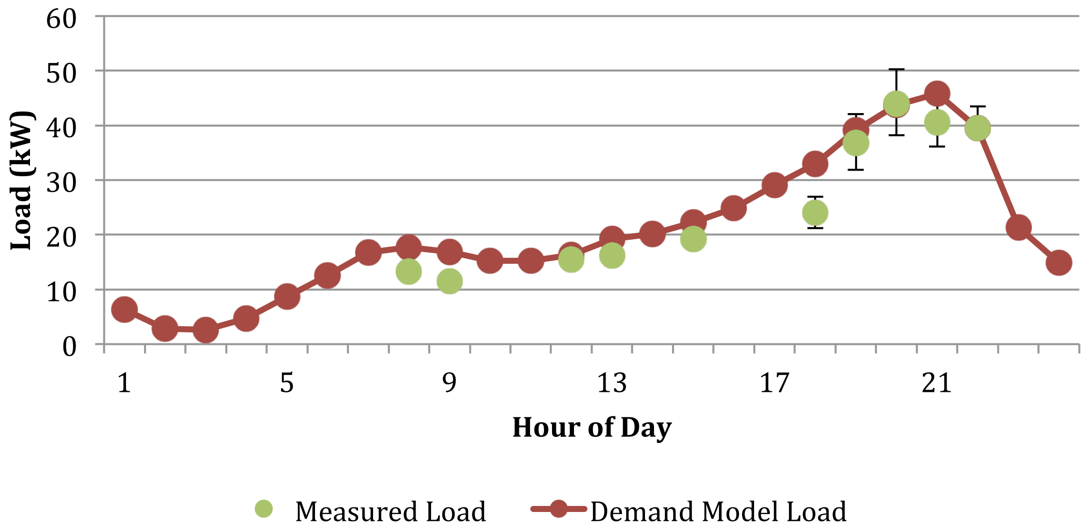

Figure 18: Comparison of Hourly Average Load on Port-a-Piment Microgrid with Simulated Average Hourly Baseline Load

The 24-hour load profiles were then evenly spread across the duration of a year for the proportional number of days that each microgrid could have run based on their measured output from March 2012 to March 2013. This is equivalent to 37 days for Port-a-Piment. A duration window and start-time were stochastically chosen for each day from the measured distribution of these variables on each microgrid. The output of this process is a baseline one-year load profile for each microgrid that is statistically similar to the measured profiles with respect to load magnitude, number of operating days, and operational durations.

The simulated number and corresponding consumption of each appliance on the Port-a-Piment microgrid is specified in Table 15.

Table 15: Simulated Loads in Port-a-Piment Baseline Scenario (*N*=210 households)

Appliance	Total Quantity	Annual Energy (kWh)	Percent of Energy (%)
Incandescent light bulb	421	2,918	69.5
CFL light bulb	520	629	15.0
Radio	93	179	4.3
Iron	112	149	3.6
Floor Fan	13	110	2.6
TV	61	88	2.1
Ceiling Fan	4	39	0.9
Vertical refrigerator	9	35	0.8
Chest refrigerator	9	35	0.8
Blender	27	7	0.2
Tube fluorescent light	4	5	0.1
DVD player	89	3	0.1
Laptop	1	0	0.0
LED light bulb	0	0	0.0

Given that the vast majority of operating hours are in the evening, it is not surprising that lighting accounts for approximately 85% of the load. Appliances used for entertainment account for a considerable load. Irons are the third most-owned appliance, which may come as a surprise to some. However, anyone who has visited Haiti can verify that clean, pressed clothing is a social norm that pervades all social and economic classes throughout the country. Dry cleaners are common in urban areas, and in rural areas without electricity, charcoal-holding irons are found in nearly every household.

3.3.1.1 Intervention modeling

Demand-side interventions were modeled by making changes to the quantity of appliances, their consumption (in Watts), or their scheduled usage.

Two energy-efficient lighting interventions were simulated by replacing the existing 421 incandescent light bulbs with CFL or LED light bulbs. This was modeled by replacing the stock of incandescent light bulbs with light bulbs with lower levels of consumption at the equivalent level of lumens. Another lighting-based intervention was designed to test the counter-intuitive hypothesis that replacing the 520 existing CFL light bulbs on the microgrid with incandescent bulbs would improve the efficiency of the existing diesel generator by increasing the load, thereby creating cost savings.[10]

Load limiters are often cited as a "best practice" for microgrid operators that must contend with demand that often exceeds supply (Harper, 2013). While the microgrids in Haiti are not capacity constrained, load limiters would be beneficial if the existing over-sized generators were replaced with smaller-scale systems. The utilization of load limiters precludes the need to maintain a high operating reserve, as peak demand can be easily managed. Load limiters were modeled in a very straightforward manner: all customers were given a 100 W peak load limit. The limit of 100 W was chosen because it is approximately equal to the average customer load of 95 W in the CFL-replacement intervention scenarios. Given that most customers utilize their electricity service only for lighting, this load limit does not significantly diminish available energy services. It is not meant to be illustrative of a more sophisticated, "smart" load limiting system with programmable demand-side management rules. Rather, it functions more closely to a simple fuse or circuit breaker, which is a common technological solution found on many rural microgrids (Harper, 2013).

Irons are common households appliances in Haiti. In most households, they are the single largest load, consuming more instantaneous power than all other appliances summed together. It was hypothesized that restricting iron usage to a specific day of the week would reduce peak demand on days where ironing was prohibited, and increase demand on days where it is permitted. Such a load curve could more efficiently use the existing, over-sized generators on days where ironing is allowed. The introduction of a second, smaller generator would then be used to more efficiently serve the load on non-ironing days.

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[10] Assumptions for lighting loads at equivalent lumen-output levels are shown in Appendix B.4.

3.3.2 HOMER Modeling

The baseline load and each intervention load curve were used as inputs to HOMER. HOMER models generation systems from a specified search space and a set of global assumptions. The search space contains a variety of sizes and quantities of generation inputs such as diesel generators, PV arrays, inverters and batteries specified by the user. Each load curve was first modeled with a single diesel generator with characteristics that correspond to the actual diesel generator installed on the Port-a-Piment microgrid.[11] The output of this scenario is the baseline result provided to the financial model described below to obtain baseline financial and performance metrics from which to compare the interventions.

Each intervention demand model load curve was then modeled with three search space variants in HOMER corresponding to diesel generators only, PV-battery systems only, and PV-battery-diesel hybrid systems. The search space for each load curve was refined until HOMER found the optimal generation system for each variant. HOMER optimizes for the least-cost energy supply. In the case of the diesel generator and PV-battery systems, this was an appropriate metric, and resulted in the least-cost system as measured by LCOE and operating cost. For hybrid systems, the least-cost hybrid system was chosen on a basis of annualized operating cost for systems of up to 50% renewable penetration. This constraint is necessary because choosing the least-cost system on the basis of LCOE would result in a 100% diesel option, and choosing the least-cost system on the basis of annualized operating expense would result in a 100% PV-battery system. 24 HOMER models were run, representing a matrix of four generation configurations (existing generator, plus the three alternatives) and six annual load curves (baseline load, plus the five demand-side intervention loads).

[11] Specification sheets with fuel consumption data for each generator were found from the manufacturers' websites. (FG Wilson; Kohler Power Systems, 2012)

Global assumptions for all scenarios were: 6% discount rate; 20-year project lifetime; cost of diesel fuel of $0.92 per liter[12]. A very high level of operating reserve was specified for the models. This is a common constraint that is used in HOMER to account for the variation of one-minute load that occasionally reaches much higher levels than the average hourly load. In the case of Port-a-Piment, the measured annual peak one-minute load is 75 kW. This is 67% higher than the peak hourly load, which is 45 kW. Thus, the operating reserve was set to 67% for all HOMER simulations except for the load curves corresponding to the load-limiter demand-side intervention.

HOMER provides tools for sensitivity analyses. Sensitivity analysis was included for the "minimum load ratio" variable of the existing microgrid diesel generator. The minimum load ratio is a property of the diesel generator, defined as the instantaneous load divided by the rated capacity of the generator. This variable greatly affects the results of our simulations because of the low measured load on these microgrids. The 249 kW diesel generator that serves an average load of 42 kW in Port-a-Piment consistently operates at a load ratio of approximately 20%. Setting the minimum load ratio that a generator is capable of efficiently servicing in HOMER to 30% would result in very high amounts of excess electricity being produced – and therefore much higher fuel costs. Physically, the 30% minimum load ratio means that the diesel generator is using as much fuel to serve any load under 75 kW as it would to serve a 75 kW load. A 10% minimum load ratio would allow the generator to serve loads at the level of Port-a-Piment's consumption much more efficiently. Given the wide range of financial outcomes from changing this variable, the sensitivity analysis included a 10% "low" and 30% "high" minimum load ratio to complement the chosen 20% ratio.

[12] This cost was calculated as the average unit price paid by the Port-a-Piment operations committee in 2012 from their records.

3.3.3 Financial Modeling

The outputs of the HOMER models were used as inputs to a financial model that also captured assumptions on the demand-side interventions. The model calculates several metrics for each generation- and demand-side intervention, described below.

3.3.3.1 Capital Cost and Annualized Capital Cost

The capital cost of an intervention is the initial cost of the intervention. HOMER provides the capital cost of generation-side interventions as an output. The capital costs for the demand-side interventions are based on realistic estimates for the equipment required for the intervention, such as CFL or LED light bulbs. Annualized capital costs are found using the familiar formula,

$$AC = PV \times \frac{r}{1-(1+r)^{-n}}$$

where PV is the present value of the costs, r is the real discount rate and n is the lifetime of the intervention.

As discussed previously, the EDH microgrids in Haiti receive capital equipment from the Government of Haiti or NGOs. This analysis includes capital costs to examine the attractiveness of a given intervention not only from the perspective of the operator, but also from the perspective of the donor of capital. Annualized capital cost that includes the time-value of money enables the calculation of a return (or loss) on investment in the hypothetical case that an investor would provide the capital rather than the government or an NGO.

3.3.3.2 Annualized Operating Cost and Operating Cost Savings

HOMER calculates annualized operating cost (OpEx) for generation-side interventions and includes fuel, O&M, capital replacement costs and salvage revenues at end-of-life. This analysis also calculates annualized replacement costs for each demand-side measure, which is the total annualized OpEx for these interventions. Given that replacement costs occur in the future, the present value

(*PV*) of these future costs must first be calculated. The *PV* of the replacement costs of the demand side intervention over the project lifetime is

$$PV = \sum_{n_R=1}^{N} \frac{FV}{(1+r)^{n_R \cdot n}}$$

where *FV* is the replacement cost of the intervention, *r* is the real discount rate, *n* is the lifetime of the intervention, and n_R is the number of replacements over the project lifetime. The annualized cost is the result of passing the *PV* into the annualized capital formula.

Operating cost savings for a particular intervention is simply equal to the intervention scenario operating cost subtracted from the baseline operating cost.

3.3.3.3 Cost recovery

Cost recovery is equivalent to the ratio of revenue to annualized operating expenditures.

$$Cost\ Recovery = \frac{Annual\ Revenue}{Annualized\ OpEx}$$

Revenue is constant across all scenarios, as the number of operating hours is constant across all scenarios and revenue is a function of microgrid availability, not kWh consumed. Thus, intervention scenario cost recovery increases as OpEx savings from the intervention increases.

3.3.3.4 Affordable annual hours of availability

The number of affordable annual hours of availability is computed using a formula similar to the affordable annual kWh. All demand intervention scenarios are modeled with the same number of operating hours as the baseline scenario, which in the case of this modeling exercise was 100 hours for Port-a-Piment. The annualized OpEx divided by the number of operating hours results in the unit hourly cost of operating the microgrid. Dividing annual revenue by this unit cost results in the affordable number of hours that the grid can be operated for:

$$Affordable\ annual\ hours = \frac{Annual\ Revenue}{Annualized\ OpEx \big/ Annual\ hours\ operating}$$

When compared to the number of affordable annual hours found in the baseline scenario, this important metric shows the number of additional or reduced hours of availability of the microgrid as a result of a particular combination of demand- and generation-side interventions. An intervention's affordable annual hours will be greater than the baseline affordable hours if the hourly operating cost of the intervention scenario is less than the hourly operating cost of the baseline scenario. Because the number of hours of operation is constant across all scenarios, this is equivalent to stating that the intervention affordable hours will be greater than the baseline if the intervention generates operational cost savings.

3.3.3.5 Net profit and Return on Investment

Useful for evaluating the interventions from the perspective of an investor, net profit is defined as the difference between total revenue and total cost. Related to net profit, return on investment (ROI), is the ratio of net profit to the investment capital.

3.4 Results

3.4.1 Baseline results

In Port-a-Piment, the total annual load in the baseline scenario is 4,197 kWh. The demand model for Port-a-Piment simulates 37 days over the course of a year with power. The total number of hours for which the grid is operating is 100 hours distributed across the 37 days with power, compared to the 54 hours distributed across 28 days with power recorded by our data logger. The modeled microgrid, like the observed one, operates for just 15% of the 676 hours for which it is scheduled to operate across 208 days of the year. With 210 customers on the Port-a-Piment grid, the corresponding revenue collected from the customer base at 15% availability is $1,364 annually.

At the 20% minimum load ratio for the existing diesel generator, the annualized operating expenses of the Port-a-Piment microgrid are $1,524. The income-to-expense ratio is therefore 90%, in excellent agreement with the 89% cost recovery ratio calculated empirically based on the Port-a-Piment microgrid operator's records for 2009-2012. At 10% and 30% minimum load ratio, the cost recovery is 99% and 68%, respectively. This gives strong credence to the use of a 20% minimum load ratio in the HOMER modeling exercise. The levelized cost of electricity is $0.36/kWh. At these levels, the affordable number of kWh is calculated to be 3,757 kWh per year, which corresponds to 90 affordable hours of operation per year at an average load of 42 kW. Baseline results are provided in Table 16.

Table 16: Baseline Results

Revenue	Annualized operating cost	Cost recovery	Load (kWh)	Hours of operation	OpEx per kWh	OpEx per hr
$1,364	$1,524	90%	4,197	100	$0.36	$15.24

3.4.2 Intervention results

As discussed in Section 3.2 above, each of the five load curves resulting from the demand-side interventions were simulated in HOMER with three supply-side intervention options in addition to the existing generator. The results of the HOMER modeling underscore the significant over-sizing of the existing generator in Port-a-Piment. The sizing of the supply interventions for each load curve is provided in Table 17. Annualized operating cost savings are shown as positive numbers, and cost increases are shown as negative numbers. The table is organized first by demand intervention, and then by supply intervention.

Table 17: HOMER Model Output: Summary of Intervention Sizing and Economics

Demand Intervention	Supply Intervention	Generator capacity (kW)	PV capacity (kW)	Battery capacity (kWh)	Inverter capacity (kW)	Annualized Operating Cost Savings	Capital Cost
None	Appropriately-sized genset	80	0	0	0	$423	$40,000
None	PV-battery	0	4	360	80	$212	$148,000
None	Hybrid	60	4	432	20	$532	$138,400
CFL	Existing generator	249	0	0	0	-$128	$1,435
CFL	Appropriately-sized genset	40	0	0	0	$866	$21,435
CFL	PV-battery	0	2	144	40	$746	$68,235
CFL	Hybrid	40	1	144	5	$881	$55,735
LED	Existing generator	249	0	0	0	-$356	$8,222
LED	Appropriately-sized genset	35	0	0	0	$703	$25,722
LED	PV-battery	0	2	144	35	$595	$70,522
LED	Hybrid	25	1	216	10	$758	$73,922
Incandescent	Existing generator	249	0	0	0	-$297	$157
Incandescent	Appropriately-sized genset	120	0	0	0	-$161	$60,157
Incandescent	PV-battery	0	5	504	120	-$509	$213,957
Incandescent	Hybrid	80	3	360	40	-$350	$151,157
Load-limiters	Existing generator	249	0	0	0	-$315	$2,100
Load-limiters	Appropriately-sized genset	25	0	0	0	$690	$14,600
Load-limiters	PV-battery	0	2	144	25	$792	$55,400
Load-limiters	Hybrid	15	2	216	10	$745	$63,800
Iron rescheduling	Existing generator	249	0	0	0	$0	$0
Iron rescheduling	Appropriately-sized genset	65	0	0	0	$435	$32,500
Iron rescheduling	PV-battery	0	4	288	65	$457	$120,100
Iron rescheduling	Hybrid	45	2	360	20	$553	$114,500

An appropriately sized generator for the baseline load (i.e., no demand-side intervention) is just 80 kW – much smaller than the 249 kW generator currently installed. A PV-only system would require just 4 kW of modules, but a fairly significant 360 kWh of battery storage, and an 80 kW inverter. The small solar array size is appropriate due to the sparse operating schedule of the microgrid, where several days' worth of energy produced by the array can gradually charge the storage system until it has been filled with sufficient energy for a single day's load. The hybrid option for the baseline load splits the load between a 60 kW diesel generator and a 20 kW inverter.

Relative to the baseline, most interventions are net improvements as measured by cost savings. As previously discussed, we assess the interventions from two perspectives: first under the operator's "status quo" in which they do not have access to working capital, and second under a new regime where working capital is made available. This second regime is evaluated from the perspective of an investor seeking to earn a return on its capital investment in the interventions, whereas the first regime assumes that the necessary up-front capital is donated by the government or NGO.

3.4.2.1 Status quo operator perspective: up-front capital is donated and no working capital is available

From the current operator's perspective, the ideal system is the one that will provide the greatest number of additional hours, which is equivalent to the system with the greatest OpEx savings and lowest hourly operating cost. In the case of Port-a-Piment, the demand-side intervention of replacing incandescent light bulbs with CFLs in combination with a supply-side intervention of a hybrid generation system ranks first – providing 123 additional hours of availability. The CFL intervention with an appropriately-sized generator ranks a close second, with 118 additional hours provided. The increase to approximately 220 affordable hours of operation with either of these interventions is significant, but is still far from the nominally scheduled 676 annual hours of operation.

Figure 19 shows the space of additional or reduced annual hours of availability for each intervention, separated by generation-side interventions, as well as their hourly operational cost in $/hr. The most attractive interventions are furthest to the right within each generation-side section. Those measures whose hourly operational costs are below the baseline system cost of $15.24 – indicated by a horizontal dashed line – provide additional hours of availability, as is expected from the relationship defined by the formula for additional/reduced hours in Section 3.3.3.

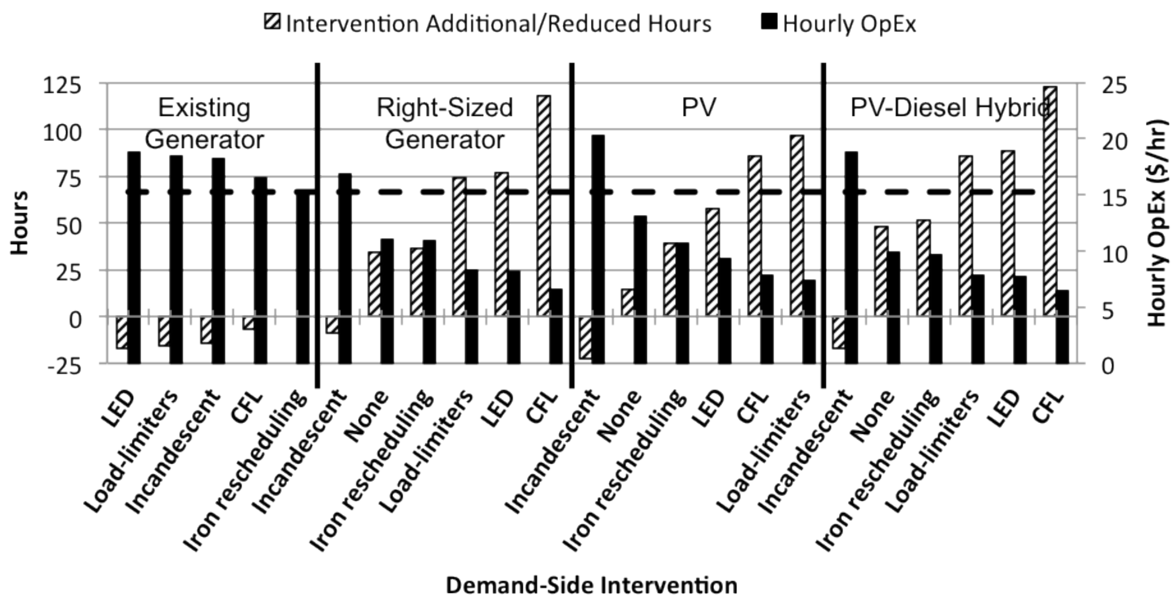


Figure 19: Intervention Additional/Reduced Hours and Hourly Cost of Microgrid Operation, by Generation-Side Intervention[13]

For the demand-side interventions that were considered, two were based on improvements to end-use efficiency: converting all incandescent light bulbs to CFLs and LEDs. The rescheduling of iron usage to one day a week was hypothesized to increase the load on those days to a sufficiently high load ratio on the existing generator to reduce costs below the baseline level. The "incandescent" intervention of replacement of the existing CFL light bulbs to incandescent lights was hypothesized to improve microgrid operations on the existing generator by increasing the load ratio to a more efficient level.

As indicated in the figure, neither of the interventions hypothesized to reduce operating costs on the existing generator by increasing the load were successful. The incandescent intervention results in 15 fewer available hours per year, and the rescheduling of irons results in no change. The incandescent-only intervention does not fare well on any of the other generation options, a result that underscores the importance of energy efficiency in these systems. The iron rescheduling

[13] The reason why there is no "None" demand-side intervention with the existing generator is because that is the baseline scenario, which is represented in Hourly OpEx by the horizontal dashed line, and provides zero increased hours of operation above itself.

intervention does not result in a peak that is sufficiently high to include the existing generator in the operation of the microgrid with a smaller generator for days where ironing is prohibited.

3.4.2.2 Investor-operator perspective: financial return on up-front capital is necessary and working capital is available

While uncommon in Haiti, it is possible – though has not yet been done – for a private, for-profit enterprise to invest the capital required to improve microgrid operations. Such arrangements are much more common in India, and the regulatory frameworks of countries like Cambodia, Tanzania, and Mali support them as well (Schnitzer et al., 2014; Gaye, 2008; Economic Consulting Associates Limited, 2013; Deshmukh et al. 2013). Such an arrangement is not unlike the energy services company (ESCO) model, where the company provides the necessary capital investment for an energy efficiency intervention and receives a fixed return based on the resulting cost savings (Nadel & Geller, 1996). For an investment in the generation system, the arrangement is essentially an independent power producer (IPP) model, in which the investor provides the necessary capital for the generation intervention.

The intervention modeling assessed from the status quo operator's perspective was based on a fixed amount of revenue equivalent to an estimate of what was collected to accurately reflect the grid operator's inconsistent tariff collection. The investor-operator perspective assumes that working capital is available to provide liquidity for fuel and maintenance expenditures despite irregular customer tariff collection. We assume that this allows the microgrid to operate at its nominal operating schedule, or even a more ambitious schedule where electricity is provided from 7 – 10 PM for all 365 days of the year.

Given that the CFL-replacement demand-side interventions were far superior to the other demand-side interventions, the investor-operator perspective was assessed with only this intervention on the demand side. Each of the alternative supply options was modeled with the CFL replacement. A summary of the intervention results is presented in Table 18. The first group of three supply interventions corresponds to the nominal operating schedule that totals 676 annual hours of operation, while the second group corresponds to the more aggressive 365-day schedule, which totals 1,095 hours of annual operation.

Table 18: HOMER Model Output: Summary of Investor Intervention Sizing and Economics

Annual Hours of Operation	Supply Intervention	Generator capacity (kW)	PV capacity (kW)	Battery capacity (kWh)	Inverter capacity (kW)	Annualized Operating Cost	Annualized Capital Cost
676	Appropriately-sized genset	40	0	0	0	$3,577	$1,975
676	PV-battery	0	15	216	40	$675	$8,444
676	Hybrid	30	10	216	10	$2,127	$6,731
1,095	Appropriately-sized genset	40	0	0	0	$5,885	$1,975
1,095	PV-battery	0	20	360	40	$704	$11,391
1,095	Hybrid	20	20	216	10	$3,370	$7,602

As expected, the PV capacity of these interventions is much larger than that of the interventions modeled for the status quo operator, and battery capacity increases as well. The capital costs for the PV-only and hybrid systems for the nominal schedule that would provide 676 hours of operation are $96,000 and $79,000, respectively, which are each about 40% higher than the capital costs of the PV-only and hybrid systems for the systems capable of providing just 220 hours. The capital costs for the PV-only and hybrid systems to power the 365-day schedule that would provide a total of 1,095 hours are $129,000 and $89,000. The marginal capital cost for the hybrid system capable of powering the grid for the 365-day schedule relative to the nominal schedule ($10,000) is much smaller than the marginal capital cost for the system capable of powering the grid for the nominal schedule relative to the status-quo schedule ($23,000). Comparing the marginal capital costs to the marginal increase in hours available, it is shown that there is increasing marginal return in the number of hours provided for the capital cost of the hybrid systems. There is decreasing marginal return in the number of hours provided for the capital cost of the PV-only system.

Figure 11 compares the combined annual operating cost and annualized capital cost for each intervention to the nominal scheduled revenue and the pro-rated revenue generated by increasing the operating duration to 365 days. Profit is shown as the difference between the annual revenues generated and the total annualized costs for each scenario. The annual profit is used to calculate the ROI, which is represented by the red dots plotted against the right-hand-side y-axis in Figure 20.

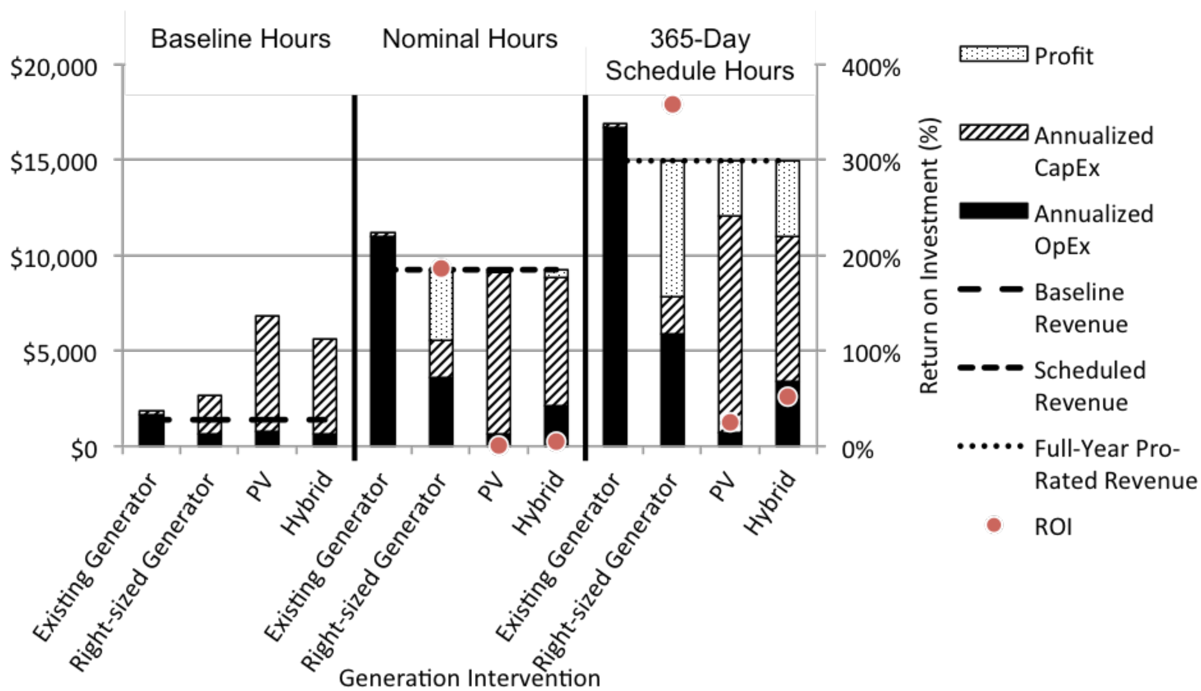


Figure 20: Generation Interventions with CFL Replacement Profit/Loss and ROI, by Schedule

The horizontal dashed lines indicate the revenues collected at each of the schedules presented – the baseline of 100 hours, the schedule of 676 hours, and the 365-day evening schedule of 1,095 hours. The annual revenue to be collected at the scheduled number of hours is $9,220. Pro-rated to 1,095 hours, the annual revenue would be $14,936. The pro-rated revenue is equivalent to a per-customer monthly fee of $5.92, compared to the scheduled $3.66 fee. While this $2.26 increase is non-trivial for a low-income household, it is still much less than the typical monthly expenditures on kerosene and candles households must take on when electricity is not available. In a nearby town without a microgrid, the average household spends $10 per month on kerosene and candles to have light every night (Schnitzer et al., 2014).

As is evident in Figure 20, each of the systems that replace the existing generator at either the nominal schedule or 365-day schedule are capable of serving these schedules profitably. For both the nominal schedule and the 365-day schedule scenarios, the appropriately-sized generator proves to be the most profitable option. The appropriately-sized generator option is the only intervention that is also profitable under the 365-day schedule without pro-rating the revenue above the nominally scheduled revenue (i.e., without an increase in the monthly tariff). At the pro-rated level of revenue on the 365-day schedule, the profit and ROI are $7,080 and 358%, respectively. Without pro-rating the revenue, and maintaining the current tariff of $3.66 per customer per month, the profit and ROI are $1,360 and 69%, respectively.

3.5 Conclusion

As is the case in Haiti, many microgrids throughout the world succeed or fail not due to capital costs, but because of high operational costs, inconsistent tariff collection and insufficient working capital (Schnitzer et al., 2014; Johnson et al., 2012). From the objective of creating operational cost savings, PV-based systems are ideal, but diesel generation still has a role to play, especially when loads are effectively managed to avoid low load ratios.

Operators of the existing microgrids in Haiti that do not have access to working capital can roughly double the operating hours affordable under existing tariffs by implementing inexpensive demand-side interventions such as replacing incandescent light bulbs with CFLs and by appropriately sizing the generator or installing a hybrid system. The demand-side interventions considered are necessary, but insufficient on their own to deliver increased hours of operation. Generation-side interventions are typically successful at lowering operating costs to cost-recovery levels, but the "incandescent" cases underscore the danger that these light bulbs pose to systems designed to primarily provide electricity in the evening.

It may be possible for a commercial microgrid operator to achieve positive return on investment under the assumption that working capital can smooth irregular tariff payments. As is the case with the status quo operator scenario, the microgrid operator can keep costs as low as possible with the nominal operating schedule or a more ambitious 365-day schedule by utilizing an appropriately-sized diesel generator to serve a customer base that uses efficient appliances like CFL light bulbs. The high ROI that can be achieved by an investor is likely sufficient to also cover the additional cost of a commercial interest rate on the working capital, which was not modeled.

Another option to solve the issue of irregular tariff payment is a technological – rather than financial – solution. Many central grids and microgrids have implemented pre-pay metering systems, which resolve the issue of implicitly extending credit to consumers by allowing them to make irregular post-paid tariff payments (Harper, 2013; Tewari & Shah, 2003). However, these systems are not a panacea. They have a significant capital cost that ranges from $60 - $120 per meter, with back-end management and vending systems that can cost over $30,000 (Conlog, 2010). Furthermore, the logistics and technical and management capacity required for successful implementation of these systems may be beyond what is available to small-scale, volunteer-based microgrid operators. That said, a lower-cost, less-complicated pre-payment metering system could be a viable alternative to working capital capable of resolving the mismatch between the timing of tariff payments and microgrid expenses.

B Appendix

B.1 Generator Specifications and Microgrid Photographs

B.1.1 Coteaux

Table B-1: Coteaux Microgrid Generator Specifications

Manufacturer	**Kohler**
Model	150RF0ZJ71
Serial Number	322978
Year Of Manufacture	1994
Rated Power	156 kVA
Rated Active Power	125 kW
Rated Power Factor	0.8
Rated Voltage (p-p/p-n)	380/220 V
Phases	3
Frequency	50 Hz
Rated Current (Per Phase)	237 A

Figure B-1: The Coteaux generator

Figure B-2: The Coteaux micro-grid interconnection (L). The first distribution pole of the Coteaux microgrid (R).

B.1.2 Port-a-Piment

Table B-2: Port-a-Piment Microgrid Generator Specifications

Manufacturer	FG Wilson
Model	P220HE2
Serial Number	FGWNAV03ENM100154
Year Of Manufacture	2009
Rated Power	249 kVA
Rated Active Power	199 kW
Rated Power Factor	0.8
Rated Voltage (p-p/p-n)	220/127 V
Phases	3
Frequency	60 Hz
Rated Current (Per Phase)	653 A

Figure B-3: The Port-a-Piment generator

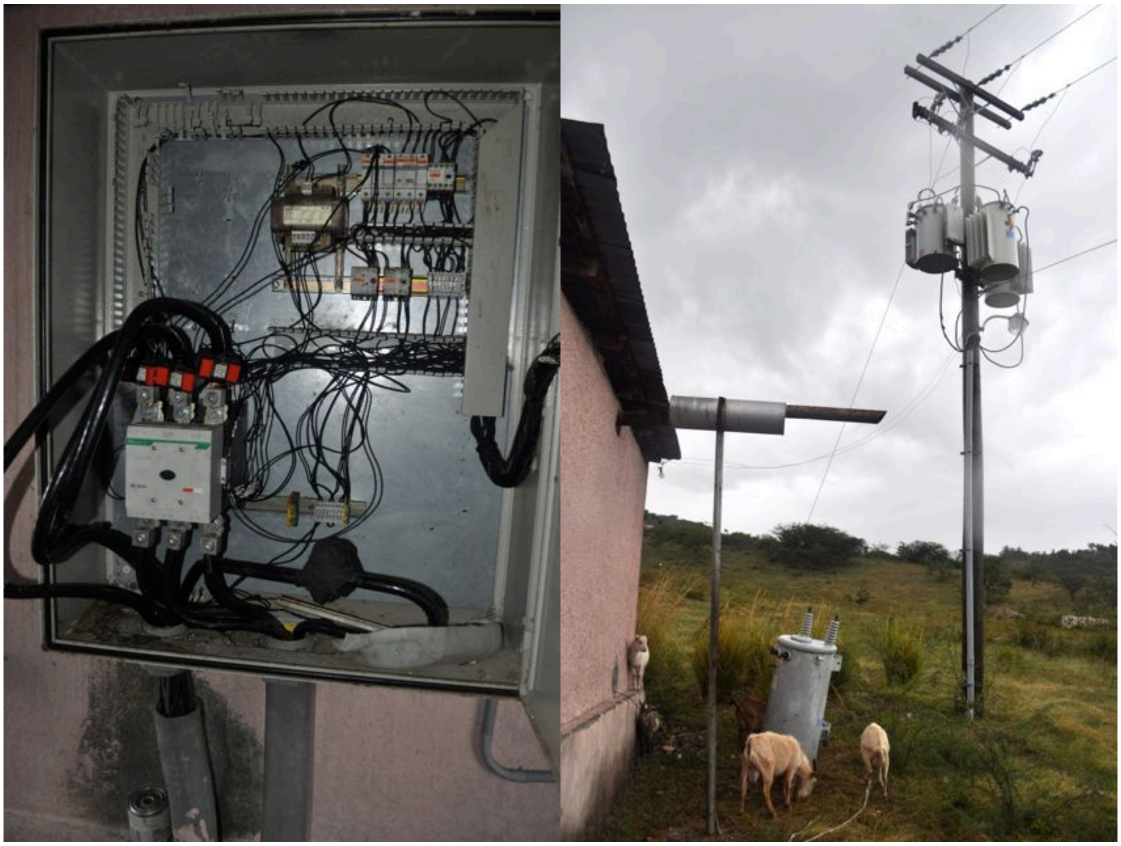


Figure B-4: The Port-a-Piment microgrid interconnection (L). The first distribution pole of the Port-a-Piment microgrid (R).

B.2 Load Profile Analysis

Figure B-5 provides histograms of one-minute change in load for the Port-a-Piment grid on a typical day. The data peak sharply at <1 kW (or ~1% change), with 32% of observations falling into this bin. 48% of one-minute changes are negative, and 52% are positive. The widest negative and positive deviations, which occur less than 1% of the time, are 37% and 45% of load, or 19 and 14 kW, respectively. The consistent load suggests that households leave their loads plugged in and switched on at all times, waiting for the microgrid to be activated, and continuing to use them throughout the duration of operations.

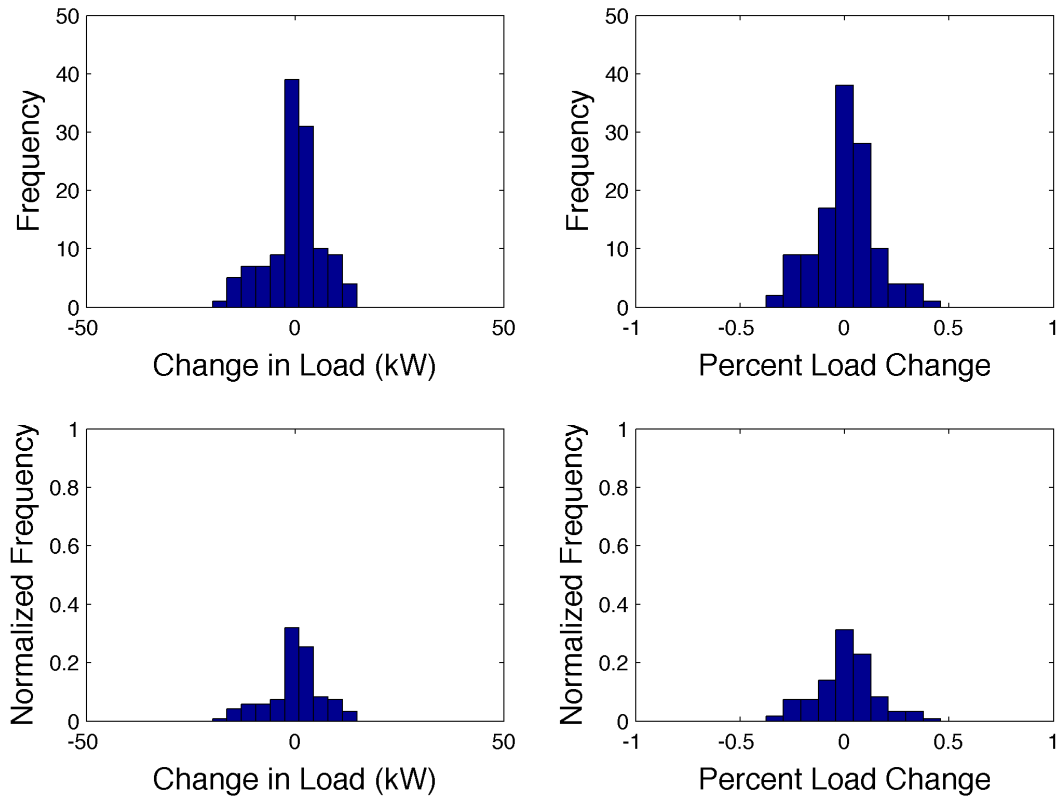


Figure B-5: Histograms of One-Minute Change in Load in Port-a-Piment on 4/24/2012

Figure B-6 and Figure B-7 show the number of days the microgrids were operational and the number of days of missing data from each month for Coteaux and Port-a-Piment, respectively. According to the nominal schedules, there should be approximately 20 operating days per month in Coteaux and 16 in Port-a-Piment.

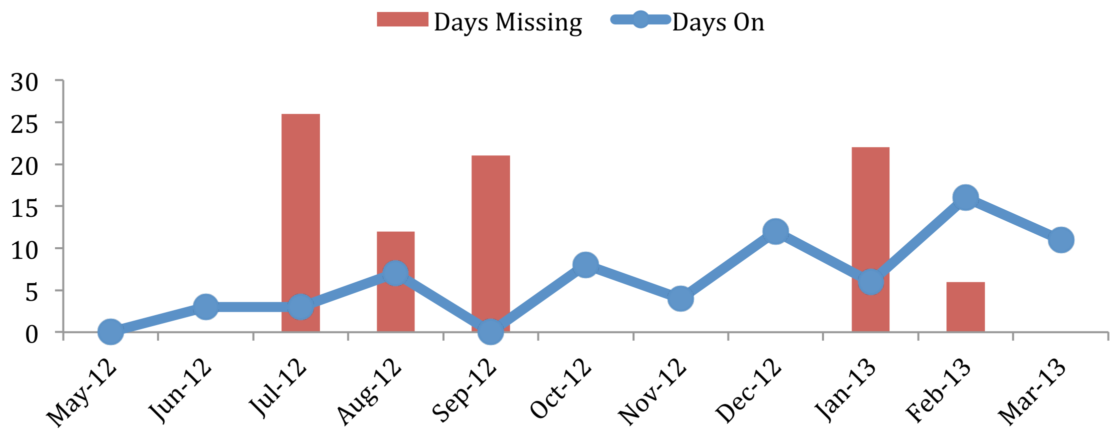


Figure B-6: Coteaux Microgrid Logged Days Operational and Days of Missing Data

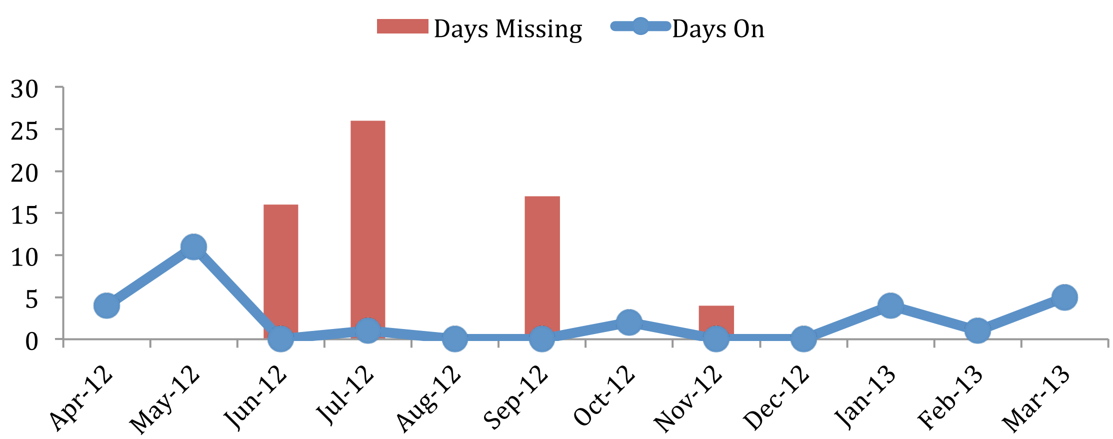


Figure B-7: Port-a-Piment Microgrid Logged Days Operational and Days of Missing Data

B.3 Further Detail on Demand Model

The transition from household appliance stock (number of appliances per household and power consumption per appliance) to a load profile requires assumptions about the rates of use of the appliances within the household. This was achieved by using the framework modeled in Paatero and Lund (2006). For each of the 14 appliances found in the Haiti surveys, we map them to the most similar appliances found in the dataset from Finland (Paatero & Lund, 2006), as shown in Table B-3.

Table B-3: Appliance Mapping from Haiti Appliances to Those Found in Paatero and Lund (2006)

Haiti Appliance	Corresponding Appliance from Paatero and Lund (2006)
Incandescent, CFL, Tube Fluorescent or LED Light Bulb	Lighting
Vertical or Chest Refrigerator	Refrigerator
TV	First TV
Portable DVD Player	Second TV
Radio	Radio
Iron	Printer
Ceiling or Floor Fan	Lighting
Mixer	Microwave
Laptop	PC

Paatero & Lund (2006) does not specify usage rates explicitly, but rather specifies the power consumption of each appliance, the daily frequency of use, the average duration of each usage "cycle," and the probability of usage for each hour of the day. We use these parameters to specify hourly usage rates, which can also be defined as the percentage of time the appliance is being used at each hour of the day – or in other words, the total energy used by the appliance at each hour divided by its power consumption.

The resulting hourly appliance usage rates, or appliance schedule, for the appliances found in households in Haiti are shown in Table B-4 and Table B-5. The tables are separated for readability.

Table B-4: Appliance Schedule for Households in Haiti (1)

Hour of Day	Incandescent	CFL	Tubelight	LED	Vert fridge	Chest fridge	TV	DVD
1	0.093	0.093	0.093	0.093	0.338	0.338	0.047	0.007
2	0.030	0.030	0.030	0.030	0.338	0.338	0.023	0.003
3	0.030	0.030	0.030	0.030	0.338	0.338	0.014	0.002
4	0.075	0.075	0.075	0.075	0.338	0.338	0.012	0.002
5	0.160	0.160	0.160	0.160	0.338	0.338	0.014	0.002
6	0.238	0.238	0.238	0.238	0.338	0.338	0.025	0.004
7	0.320	0.320	0.320	0.320	0.338	0.338	0.041	0.006
8	0.337	0.337	0.337	0.337	0.338	0.338	0.048	0.007
9	0.310	0.310	0.310	0.310	0.338	0.338	0.065	0.009
10	0.274	0.274	0.274	0.274	0.338	0.338	0.062	0.009
11	0.274	0.274	0.274	0.274	0.338	0.338	0.062	0.009
12	0.292	0.292	0.292	0.292	0.338	0.338	0.075	0.011
13	0.355	0.355	0.355	0.355	0.338	0.338	0.075	0.011
14	0.373	0.373	0.373	0.373	0.338	0.338	0.078	0.011
15	0.410	0.410	0.410	0.410	0.338	0.338	0.094	0.013
16	0.446	0.446	0.446	0.446	0.338	0.338	0.125	0.018
17	0.521	0.521	0.521	0.521	0.338	0.338	0.156	0.022
18	0.603	0.603	0.603	0.603	0.338	0.338	0.156	0.022
19	0.739	0.739	0.739	0.739	0.338	0.338	0.156	0.022
20	0.820	0.820	0.820	0.820	0.338	0.338	0.187	0.027
21	0.883	0.883	0.883	0.883	0.338	0.338	0.156	0.022
22	0.765	0.765	0.765	0.765	0.338	0.338	0.125	0.018
23	0.389	0.389	0.389	0.389	0.338	0.338	0.094	0.013
24	0.266	0.266	0.266	0.266	0.338	0.338	0.062	0.009

Table B-5: Applianc Schedule for Households in Haiti (2)

Hour of Day	Radio	Iron	Ceil Fan	Floor Fan	Mixer	Laptop
1	0.100	0.003	0.093	0.093	0.000	0.017
2	0.050	0.002	0.030	0.030	0.000	0.008
3	0.029	0.001	0.030	0.030	0.000	0.005
4	0.025	0.001	0.075	0.075	0.000	0.004
5	0.029	0.001	0.160	0.160	0.002	0.005
6	0.054	0.002	0.238	0.238	0.003	0.009
7	0.088	0.003	0.320	0.320	0.003	0.015
8	0.102	0.003	0.337	0.337	0.004	0.017
9	0.140	0.005	0.310	0.310	0.004	0.023
10	0.134	0.004	0.274	0.274	0.004	0.022
11	0.134	0.004	0.274	0.274	0.004	0.022
12	0.161	0.005	0.292	0.292	0.004	0.027
13	0.161	0.005	0.355	0.355	0.004	0.027
14	0.167	0.006	0.373	0.373	0.004	0.028
15	0.201	0.007	0.410	0.410	0.006	0.034
16	0.267	0.009	0.446	0.446	0.009	0.045
17	0.334	0.011	0.521	0.521	0.010	0.056
18	0.334	0.011	0.603	0.603	0.010	0.056
19	0.334	0.011	0.739	0.739	0.009	0.056
20	0.401	0.013	0.820	0.820	0.008	0.067
21	0.334	0.011	0.883	0.883	0.006	0.056
22	0.267	0.009	0.765	0.765	0.003	0.045
23	0.201	0.007	0.389	0.389	0.001	0.034
24	0.134	0.004	0.266	0.266	0.000	0.022

24-hour household load profiles are created by multiplying the schedules in Table B-4 and Table B-5 by each household's appliance stock parameters – the number of appliances per household and the rated power of each appliance. The entire microgrid 24-hour load profile, such as the one shown in Figure 18, is simply the sum of the household load profiles.

B.4 Light Bulb Assumptions

Table B-6: Modeled CFL and LED Light Bulb Consumption (W)

Incandescent consumption (W)	Equivalent CFL consumption (W)	Equivalent LED consumption (W)
40	10	6
60	15	10
75	18	13
100	25	17

Chapter 4: The Commercial Viability of Remote Microgrids in Developing Countries: A Case Study in Haiti

Abstract

Situated at a level of energy service availability between solar home systems and central grids, microgrids are emerging as a scalable model for rural electrification. However, their potential to scale is contingent on their commercial viability. Earlier work has begun to assess the commercial viability of microgrids based on a comparison of total levelized unit energy costs to customer tariffs. Assuming appropriate tariffs, two arguments have emerged against the case for commercial microgrids: 1. User-specific costs on microgrids are high, which make them unsuitable for pay-as-you-go tariffs; and 2. Low-income customers are too poor to make consistent payments for electricity for microgrid operators to earn cost recovery (Economic Consulting Associates Limited , 2013). The operation of a rural microgrid in Haiti shows that neither argument is generally applicable. Anonymized consumption and payment data from customers' smart meters for ten months of operations was analyzed to assess these claims. I found that pay-as-you-go payments were sufficient for user-specific costs to be recovered within 5 years for 78% of users, and 3 years for 57% of users. I also found that the frequency, quantity and magnitude of user payments are sufficient to provide regular cash flow to the utility.

4.1 Introduction

Under the International Energy Agency's World Energy Outlook "Energy for All" Scenario, an additional approximately 50M people per year above the business as usual scenario must be provided with access to electricity for universal electricity access to be attained by 2030 (International Energy Agency, 2012). It is projected that approximately 20M people per year will gain access to electricity through micro-grids, requiring some ~$10B of annual investment. While it is assumed that government and multilateral sources of financing will contribute significantly to financing microgrid electrification, private investors will be crucial. Whether microgrids can generate returns on commercial investment – and to what extent – will determine the extent to which the necessary levels of investment are made in microgrids. If microgrids prove to be unprofitable, investment will stall and millions of households will continue to be served by low quality fuels.

Despite the nascent status of commercial microgrid ventures, some arguments are already being made against their viability. Regardless of whether a venture is commercially oriented or not, there is widespread agreement that tariffs must be set to levels that exceed costs. While this point is presumably obvious, there are many cases where doing so is forbidden due to a "uniform national tariff" as required by a national regulator. Such tariffs force all electric utilities – be they central grid or microgrid, public or private – to serve electricity at the same tariff, irrespective of their cost (Tenenbaum et al., 2014).

Assuming appropriate tariffs, two arguments have emerged against the case for commercial microgrids: 1. The cost structure of microgrids is unsuitable for pay-as-you-go tariffs; 2. Low-income customers are too poor to make consistent payments for electricity for microgrid operators to earn cost recovery (Economic Consulting Associates Limited , 2013).

The argument against the commercial viability of microgrids based on cost structure focuses on pay-as-you-go prepaid tariffs because there is widespread agreement that prepayment for microgrid electricity service for low-income customers is a best practice (Harper, 2013; ESMAP, 2000). Pre-payment of the "pay as you go" variety, where users' account balances are drawn down on a kWh usage basis, has been an effective tool for expanding access to electricity on central grids in less developed countries since at least the early 1990s when it was implemented in South Africa (Tewari & Shah, 2003).

As a revenue model, pay-as-you-go has been the key to the vast growth of mobile telephony in less developed countries (Economic Consulting Associates Limited , 2013). This is due in part because the *user-specific* fixed cost for providing mobile phone service is very low. A telecom provider does not need to invest in allocating network bandwidth for any specific customer; if a customer purchases a mobile phone and then rarely uses it, the bandwidth s/he would be using can be used freely by any other customer. This quality of mobile telephony is what enables its financial viability while serving low-income customers without a service contract.

On the other hand, if user-specific fixed costs are high, infrequent or low consumption by a particular user creates a loss; the investment for serving that user will take so long to be repaid that it is financially unviable to serve the customer. While speculative, there have been claims that microgrids have high user-specific fixed costs and that many users will be low or infrequent consumers of electricity (Economic Consulting Associates Limited , 2013). In tandem, these are said to prevent commercial viability.

It is reasonable to expect that microgrids would have high user-specific costs. In addition to home wiring, a meter, and the service drop from the distribution system, rural remote microgrids may require dedicated utility poles and distribution cable to reach a specific customer. The extent to which user-specific poles and cabling is necessary is dependent on the geographic dispersion of the customers served under the microgrid and the expected customer loads. At its most extreme, a highly dispersed site could require each individual customer to have several poles and extensive cable length to be reached by the power generation system. On the other hand, a dense site would not require user-specific poles and feeder cable. That is, in a dense site, each pole and each length of cable is necessary to serve not one customer, but the entire site. In such a configuration, the distribution system is much more like mobile telephony network bandwidth, where the distribution circuit one customer would be using can be used freely by any other customer.

The contrast between a densely populated microgrid with low user-specific costs and a more dispersed site with high user-specific costs is illustrated in Figure 21. As is visible in the low-density site, certain customers require dedicated utility poles and lengths of cable to be reached. In the high-density site, no single user requires a dedicated utility pole for service, and each pole and length of cable is a shared system asset.

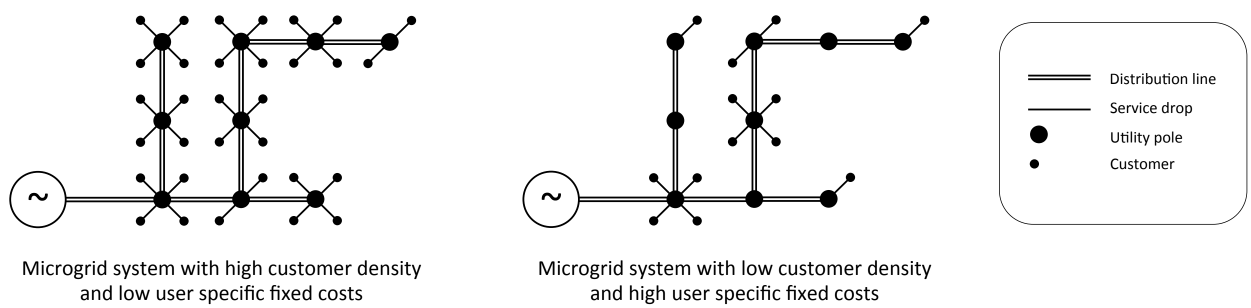


Figure 21: Illustration of Customer Density Effect on User-Specific Fixed Cost

The difference between system shared and user-specific fixed cost components is illustrated in Figure 22. System shared fixed cost components include the generation system and the distribution system. User-specific fixed cost components include service drop hardware, the service drop cable, the electricity meter, and internal home wiring and grounding.

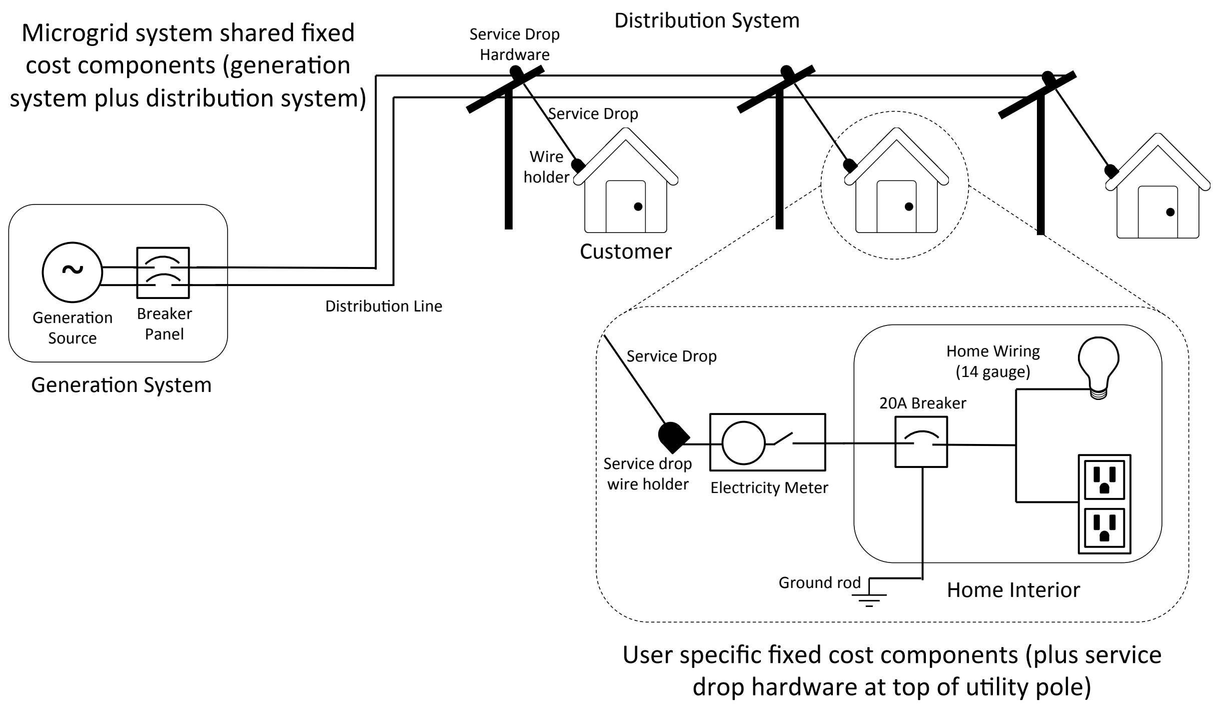


Figure 22: Illustration of System Shared Fixed Costs and User-Specific Fixed Costs

The data analyzed from the EarthSpark microgrid in Haiti provides empirical data to directly compare the results extracted from a model of microgrid costs in India (Chaurey & Kandpal, 2010). In this related analysis, the levelized costs of a rural electrification solar home system approach are compared to a microgrid approach. They conducted sensitivity analysis on the number of customers, their geographic dispersion, their loads, and the cost of the microgrid distribution system. For the 18W per customer load case, where customers are scattered over a 1 km stretch of distribution network, this work found that a minimum of 180 customers (or a density of 180 customers per km) is required for the cost of the microgrid to drop below that of solar home systems. For a larger, 4 km distribution system, a minimum of 270 customers (or a density of 67 customers per km) is required for the cost of the microgrid to drop below that of solar home systems. For the 36W per customer load case, those numbers fall to 100 customers (or a density of 100 customers per km) and 150 customers (or a density of 36 customers per km), for the 1km and

4km distances respectively. The levelized cost of the solar home systems at either load level was estimated to be approximately $0.67/kWh. User-specific costs including service drops and home wiring are estimated to be $45 and $90 for the low and high load cases, respectively. At the minimum tariff level of $0.67/kWh and these assumed levels of monthly consumption, it will take the microgrid utility 31 months to recover the user-specific cost of $45 or $90 for the low and high load cases.

However, while illustrative, the Chaurey & Kandpal (2010) study does not assess either the ability of customers to pay the cost-recovery tariff of at least $0.67/kWh, nor the likelihood of their consuming the modeled demand of 2.1 or 4.3 kWh/mo. for the low and high load cases, respectively, at this price. If customers are in reality consuming half as much electricity as what has been modeled, it could take over five years for user-specific costs to be recovered – which many private microgrid developers would find unacceptable.

The experience of EarthSpark International in Haiti in its development of a rural, remote microgrid suggests that microgrids may be commercially viable, and provides some degree of agreement with the general conclusions of Chaurey & Kandpal (2010). The user-specific fixed costs of the EarthSpark microgrid are low, as it is serving a relatively dense rural town with a density of 110 households per km of distribution line. We present data from over six months of operations of this microgrid that show that the frequency and volume of pay-as-you-go electricity payments are sufficient to earn back the user-specific fixed costs in a reasonable period of time for commercial viability.

4.2 EarthSpark Microgrid Summary

The EarthSpark microgrid is located in Les Anglais, Haiti. There are approximately 5,000 total households in Les Anglais, but there are only ~500 located in the densely populated "centre ville" or town center. Average household income in the centre ville is approximately 100 USD/mo. Thus far, EarthSpark has connected 54 households and businesses to its microgrid, but there are plans to expand service to all households and businesses in the centre ville by September 2014.

In October 2013, EarthSpark installed smart prepaid meters on all customer connections. The remote, high-resolution data collection enabled the analysis necessary to assess individual customer payment trends. Data from the time period October 13th, 2013 – May 8th, 2014 were used for this analysis.

Customers are connected on one of three possible tariff classes. Each tariff class corresponds to a particular load limit, measured in Watts. The smart meters enforce the load limit by automatically disconnecting a customer if their usage exceeds the limit. Once they have reduced their load to be below the limit, the meter will reconnect the next time it closes the circuit to check the load. Prepaid account balances are tracked by the meters. This is done by subtracting the energy used by the customer multiplied by his tariff rate from the previous balance every minute.[14] The parasitic load of the smart meter (which is less than 1 W) is not included in the energy usage reading. Tariff levels are $0.50/kWh for a 600W load limit, $1.00/kWh for a 120W load limit, and $1.50/kWh for a 30W load limit. There is also a $2.00/kWh tariff level for a 12W load limit, but no customers are on this tariff level. There is no explicit demand charge, though a progressively-priced up-front connection fee ensures that users who might only consume 30W-peak would not sign up for the 600W-peak tariff level. The connection fees are $25, $30, $50, and $75 for the 12W, 30W, 120W and 600W load limit levels, respectively.

When a customer wants to add funds to her balance, she makes a payment (cash or mobile money) to a local vendor. The vendor selects the user's account from a point-of-sale interface that is wirelessly synced with the smart metering system, and enters the payment information. Upon

14 For a detailed account of the technical specifications and functionality of the metering system, see (Buevich et al., 2014)

submission of the payment, the customer's balance will increase, and immediately turn her electricity back on if she had run out of credits. The credits sold are deducted from the vendor's balance. When a vendor runs low on his credits, he can purchase more from the microgrid operator (EarthSpark International).

Table 19 summarizes the data for each tariff class. There are 44 customers on the 30W $1.50/kWh class, 9 on the 120W $1.00/kWh class, and just one on the 600W $0.50/kWh class. Total monthly payments over the course of the 41 weeks included in this analysis are $2,069, with $1,034 – almost exactly 50% – paid by the 600W $0.50/kWh class customer. This customer also accounts for 72.3% of total energy consumed, while the $1.00/kWh and $1.50/kWh class customers account for 10.8% and 16.9% of energy consumed, respectively. Monthly average customer payments for the $1.00/kWh customers are approximately twice as high as the $1.50/kWh customer payments, at $4.40 per customer vs. $1.90 per customer per month. Average customer monthly energy use is accordingly approximately three times as high for the $1.00/kWh customers compared to the $1.50/kWh customers, at 4.56 kWh per customer vs. 1.24 kWh per customer per month.

Table 19: Les Anglais Microgrid Payments and Energy Use, by Tariff Class[15]

Tariff Class (USD/kWh)	Number of Customers	Total Payments per Class (USD)	Monthly Average Customer Payment (USD/mo.)	Total Energy Consumed per Class (kWh)	Monthly Average Customer Energy Use (kWh/mo.)	Percent of Energy Consumed
$0.50	1	$1,023	$108.42	2,042	214	72.3%
$1.00	9	$296	$4.40	305	4.56	10.8%
$1.50	44	$739	$1.90	477	1.24	16.9%
Total/Mean	***54***	***$2,069***	***$4.29***	***2,824***	***5.74***	

Table 20 presents the chronology of customers added to the microgrid by tariff class. 38 customers were on the microgrid in October 2013, and an additional 16 were added in January 2014.

15 Data recorded 10/13/2013 – 8/1/2014

Table 20: Les Anglais Microgrid Number of Customers Added over Time, by Tariff Class

	Tariff Class (USD/kWh)			
Month of Connection	**$0.50**	**$1.00**	**$1.50**	**Total**
October 2013	1	3	34	38
January 2014	0	6	10	16

The user-specific fixed costs are limited to home wiring and the distribution system service drop to the home. The itemized costs are presented in Table 21. The total user-specific fixed cost is $95.48.[16] EarthSpark charges a connection fee that varies with the tariff class, as noted in Table 3. Net user-specific fixed costs are $65.48, $45.48 and $20.48 for the 30W, 120W and 600W load limit levels, respectively.

[16] This cost is similar to the costs estimated in Chaurey & Kandpal (2010) for user-specific costs for microgrids in India. Their analysis modeled user-specific costs between $45 and $90, depending on the number of outlets and light sockets per household.

Table 21: Les Anglais Microgrid User-Specific Fixed Costs[17]

	Unit price	Quantity	Total Price
Home wiring			
Pull Chain Socket	$3.66	2	$7.32
Outlet	$5.50	1	$5.50
Home wiring	$0.22	50 ft.	$11.00
Breaker box	$11.12	1	$11.12
Misc.	$4.00	1	$4.00
Meter	$25.00	1	$25.00
Ground rod	$5.95	1	$5.95
Ground rod connector	$1.89	1	$1.89
Subtotal			*$71.78*
Service drop			
Wedge clamps	$1.77	2	$3.54
Nylon wire holder	$3.59	1	$3.59
Compression connector	$0.57	1	$0.57
Service drop wiring	$0.32	50 ft.	$16.00
Subtotal			*$23.70*
Total			***$95.48***
Connection fee (30W)			-$30.00
Connection fee (120W)			-$50.00
Connection fee (600W)			-$75.00
Net cost (30W)			***$65.48***
Net cost (120W)			***$45.48***
Net cost (600W)			***$20.48***

In the following section, we present the results of an analysis of the EarthSpark smart meter data to assess whether this fixed cost can be recovered. We also assess the claim that microgrid customer payment is too low and too infrequent to provide sufficient cash flow for commercial viability.

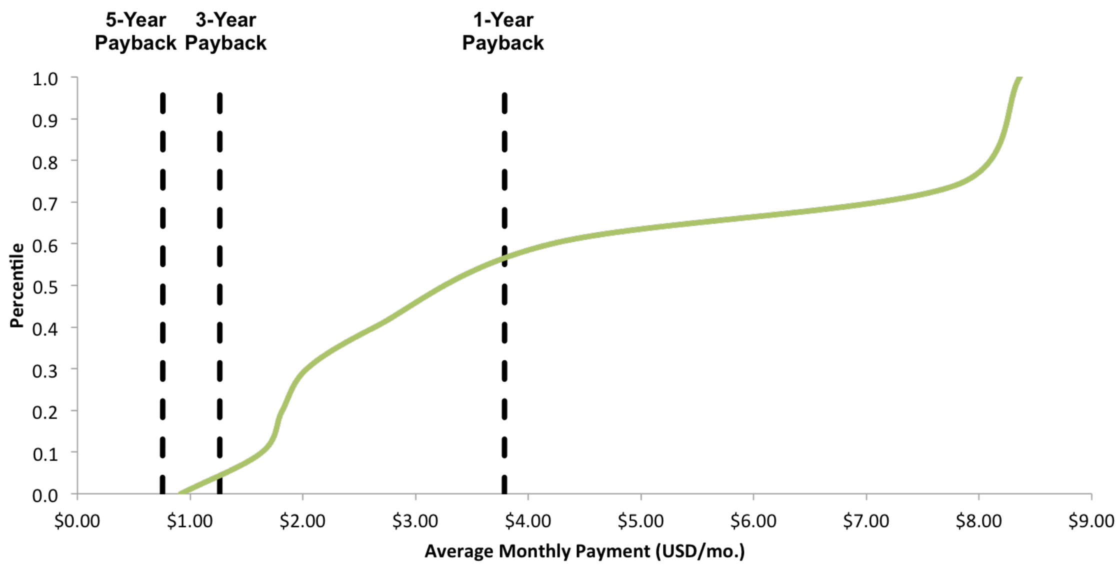
[17] The user-specific fixed cost for each tariff class is the same. Each user, regardless of tariff class, is provided with two pull-chain light sockets, one duplex outlet and a 20A breaker box. Additional sockets and outlets are purchased directly by consumers and as such are not counted in the fixed cost.

4.3 Results

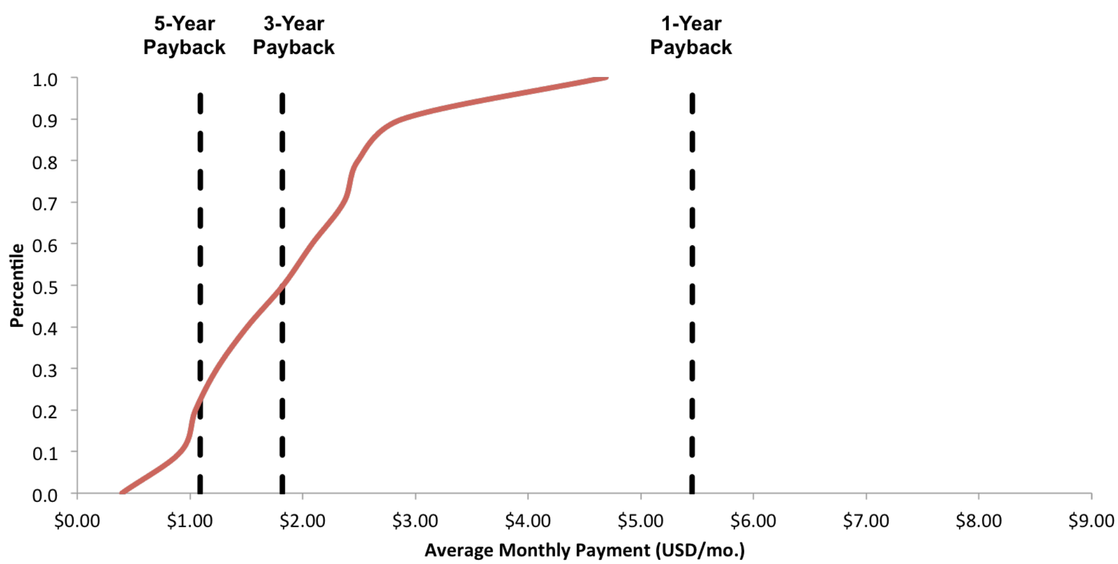
4.3.1 The cost structure of microgrids is *not* unsuitable for pay-as-you-go tariffs

The blanket assumption that microgrids do not have favorable cost structures for pay-as-you-go tariffs is not consistent with the experience that EarthSpark has had thus far on its microgrid in Haiti. The relatively high household density of Les Anglais, at 110 customers per km of distribution line, means that almost all of the grid assets are shared. There is no single pole or length of distribution cable that is necessary to reach just one customer. The user-specific costs are truly only those incurred to connect a user to the distribution system. In the global context, is the EarthSpark grid in Haiti an exception, or the norm in this sense? There is insufficient empirical data on microgrid projects globally to compare the density of the EarthSpark microgrid to other microgrids in a meaningful way. However, the theoretical findings of Chaurey and Kandpal (2010) point to densities of 36 to 180 customers per km resulting in commercial viability. A group of 11 communities with 972 households in the Potosi region of Bolivia electrified by NRECA International range in density from 15 to 60 households per km, with most in the 30 to 40 household per km range (NRECA International, 2013).

Figure 23 shows the distribution of average monthly pre-payments for electricity on the 120W load limit ($1.00/kWh) and 30W load limit ($1.50/kWh) tariff classes. The 600W load limit ($0.50/kWh) tariff class was excluded because there is just one customer, and, as presented in Table 1, this customer makes payments of approximately $110 per month. This customer's net connection fee is just $20.48, which was recovered well within his first month connected to the microgrid.



(a)



(b)

Figure 23: Distribution of Average Monthly Payments for Electricity for (a) 120W $1.00/kWh Customers (*N*=9) and (b) 30W $1.50/kWh Customers (*N*=44). Vertical dashed lines indicate equivalent monthly user-specific fixed costs within labeled payback time. These amounts are $3.79/mo., $1.26/mo. and $0.76/mo. for 1-, 3- and 5-year paybacks for 120W load limit ($1.00/kWh) customers, and $5.46/mo., $1.82/mo. and $1.09/mo., for 30W load limit ($1.50/kWh) customers.[18]

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[18] Monthly payback requirements for 5-year, 3-year and 1-year periods for each tariff level are calculated by dividing the net connection costs in Table 21 by 60, 36 and 12 months.

On the 120W load limit ($1.00/kWh) tariff, a greater fraction of users will pay back their user specific fixed costs sooner than on the 30W load limit ($1.50/kWh). Four of the nine users on this tariff level make average monthly payments greater than the $3.79 per month necessary for earning back their user-specific fixed cost within a year. Another four of the remaining users make sufficient monthly payments to pay back these costs within three years, and the remaining user will make sufficient payments to pay back the costs within five years. None of the customers on the 30W load limit ($1.50/kWh) tariff can pay back their user-specific costs within a year. 50% of them can pay back their user-specific costs within three years, and 73% will make sufficient monthly payments to pay back these costs within five years. That leaves 27% of users for which it will take the utility at least five years to simply earn back the user-specific fixed cost required to connect them to the microgrid. As a percentage of all users, only 22% will take at least five years to pay back their user-specific cost.

These data suggest that a microgrid operator can not only charge the high tariffs necessary for cost recovery on the shared assets, but can also recover user-specific costs on a pay-as-you-go basis within a reasonable time period. While there will be a fraction of users who may be unprofitable to serve, the cost burden of connecting them is likely worth the upside potential that these users may consume electricity at a greater rate in the future.

4.3.2 Low-income customers are *not* too poor to make consistent payments for electricity

The concern that the number of payments over a given time period will be unpredictable and erratic due to the low-income and variable income streams of microgrid customers is not an issue on the Les Anglais microgrid. The relatively high number of customers has essentially smoothed out variance in specific customers' payments. This "law of large numbers" effect can be seen in Figure

24, where the total number of payments and monthly revenue are shown to be relatively constant from October to December with 38 customers and from January onwards with 54 customers.[19]

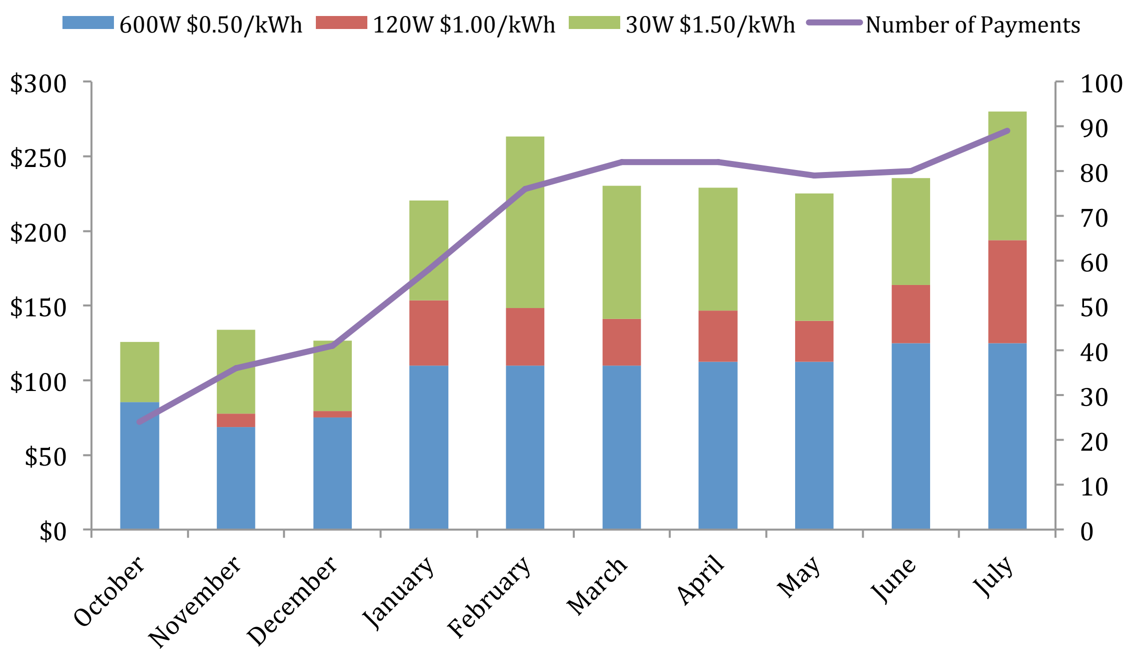

Figure 24: Les Anglais Microgrid Revenue and Number of Payments per Month

During January through July, the months with all 54 customers connected, total average monthly revenue is $240. The average number of customer payments per month is 78. Monthly payments are dominated by the sole customer on the 600W load limit ($0.50/kWh) tariff, whose payments account for roughly half of revenue in any given month. Inter-month variability in both total revenue and number of payments is very small.

A more detailed view of payment trends for the lower-consumption, higher-tariff users is provided in Figure 25, Figure 26 and Figure 27.

19 These data extend to July 27th, 2014.

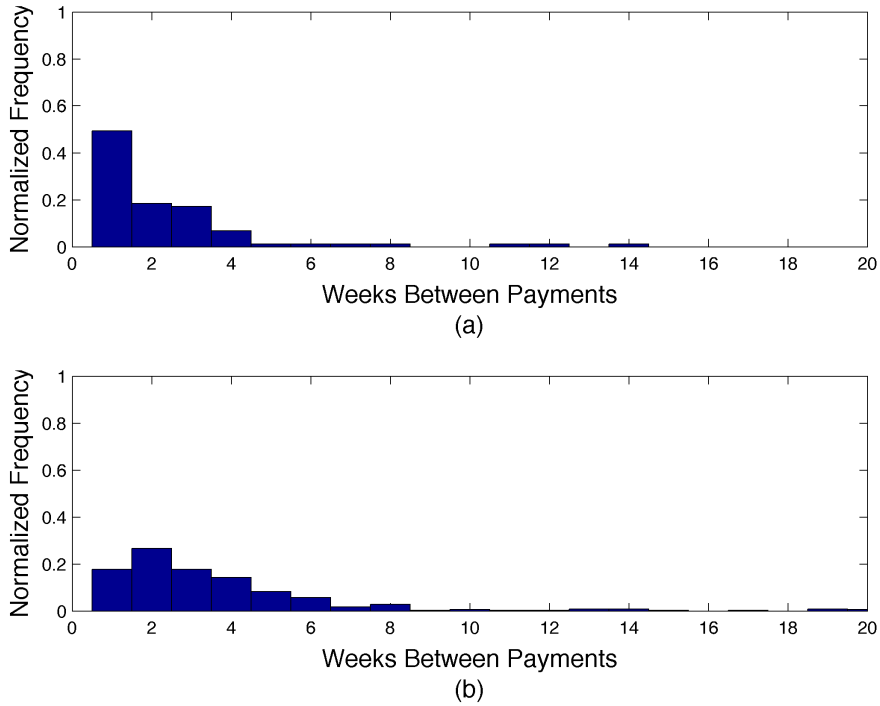

Figure 25: Normalized Histogram of Customer Payment Frequency for (a) 120W $1.00/kWh Customers (*N*=96 payments by 9 customers) and (b) 30W $1.50/kWh Customers (*N*=394 payments by 44 customers)

Figure 25 shows the proportions of customer payment frequency, as measured by weeks between consecutive payments by the same customer. Approximately 50% of consecutive customer payments by 120W load limit ($1.00/kWh) tariff customers are made in a week following a week where a payment was made, and approximately 40% of consecutive payments are made after one or two weeks of no payments. The remaining 10% of payments are made less frequently.

Approximately 50% of consecutive customer payments by 30W load limit ($1.50/kWh) tariff customers are made either in a week following a week where a payment was made, or after one week of no payments. The distribution of payments that are less frequent falls on a tail that is much longer and fatter than the 40 HTG tail. No customer on either class has ever made two payments in the same week.

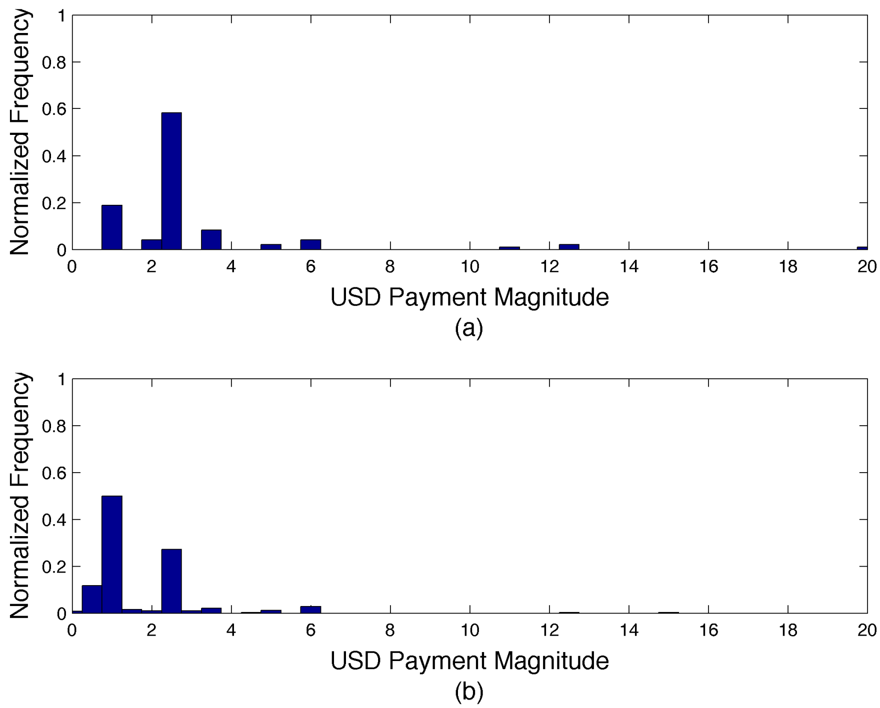

Figure 26: Normalized Histogram of Customer Payment Size for (a) 120W $1.00/kWh Customers (*N*=96 payments by 9 customers) and (b) 30W $1.50/kWh Customers (*N*=394 payments by 44 customers)

As is visible in Figure 26, most payments from the 120W load limit ($1.00/kWh) customers and the 30W load limit ($1.50/kWh) customers fall at either 50 HTG (1.25 USD) or 100 HTG (2.50 USD) amounts. The gap between the two amounts is explained by the denomination of Haitian Gourde notes.

It is notable that the 120W load limit ($1.00/kWh) customers, who are likely to be wealthier, make many more payments at the 100 HTG denomination (60%) than at 50 HTG (20%), whereas the 30W load limit ($1.50/kWh) customers make more payments at the 50 HTG denomination (50%) than at 100 HTG (30%). Payments at other denominations for either tariff class are relatively rare.

An additional data point for assessing customers' ability to pay is the duration between reaching a zero account balance and "topping up" the account. Figure 27 shows histograms of these durations in hours for the 120W load limit ($1.00/kWh) customers and the 30W load limit ($1.50/kWh) customers.

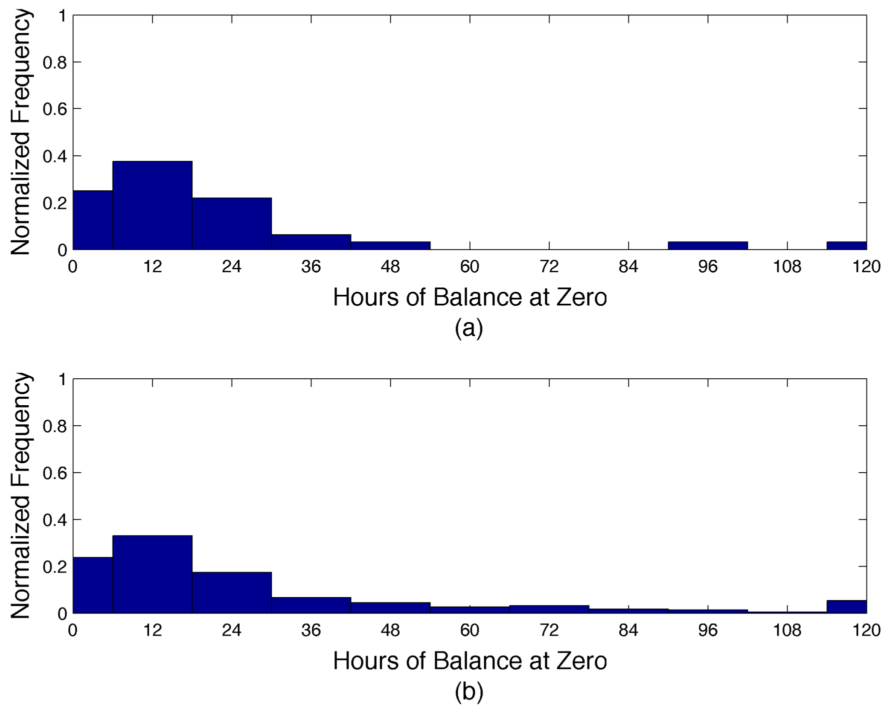

Figure 27: Normalized Histogram of Hours of Balance at Zero for (a) 120W $1.00/kWh Customers (*N*=32 occurrences by 9 customers) and (b) 30W $1.50/kWh Customers (*N*=224 occurences by 44 customers)

As shown in Figure 27, a household will not choose to remain without electricity for very long. Most "top-ups" occur within 24 hours of the account balance falling to zero. 78% of instances are topped up within 24 hours for the 120W load limit ($1.00/kWh) tariff customers, and 67% for those on the 30W load limit ($1.50/kWh) tariff. Figure 28 shows a time-series of a representative customer's hourly account balance, where it is apparent that the customer does not wait long from reaching a zero account balance to topping up his balance. Gaps in the graph are missing data.

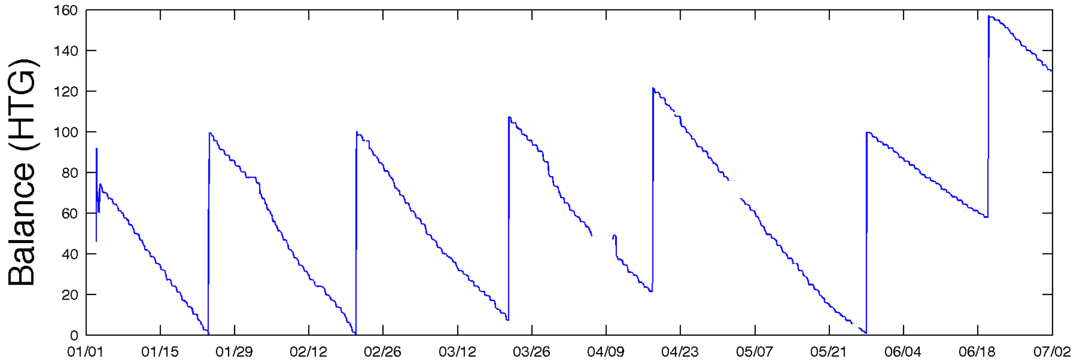

Figure 28: Hourly Account Balance Time-Series for a Representative Customer on the 30W Load Limit ($1.50/kWh) Tariff, 1/2/2014 – 7/2/2014. X-axis ticks appear at two-week intervals.

The relatively small number of hours at zero balance for all customers agrees with the findings of Soto et al. (2012). In their analysis of a microgrid serving 38 households in Mali primarily with lighting, it was found that 66% of households kept a non-zero balance more than 90% of the time, and all customers kept a non-zero balance more than 40% of the time. We find in Haiti that 88% of households keep a non-zero balance more than 90% of the time, and all customers keep a non-zero balance more than 70% of the time. Similar to Soto et al. (2012), we find that customers that maintain a non-zero balance nearly 100% of the time are both high and low expenditure customers, (Figure 29). Further, our findings corroborate the experience in Mali, where those with non-zero balances for lower fractions of time (<90% of the time in the EarthSpark case) tend to have lower monthly expenditures. These findings are useful insofar as they underscore the importance of pre-paid or "pay as you go" metering. With pre-payment, customers make payments when it suits them, and, while electricity is a household priority, it is not something that is always needed or affordable.

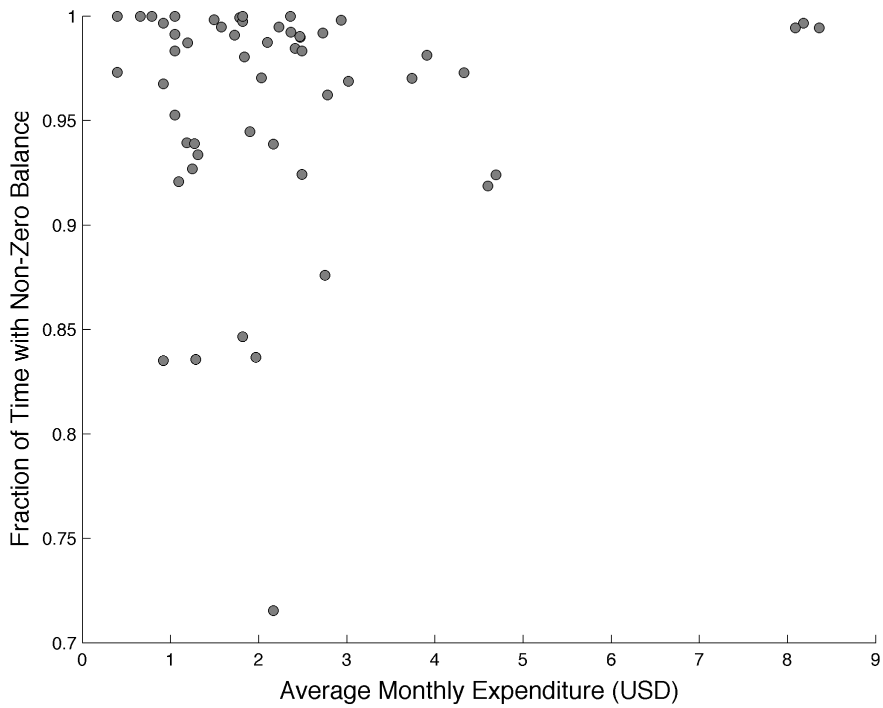

Figure 29: Scatterplot Comparing Monthly Expenditures to Fraction of Time with Non-Zero Balance. Each point represents a household.

4.4 Consideration of Total System Costs

This analysis omits an analysis of the degree of the appropriateness of the tariffs with respect to total non-user-specific fixed and variable costs. This issue is critical, and is one that plagues micro-grid developers throughout the world.

On the Les Anglais microgrid, the \$0.50 - \$2.00/kWh tariffs being charged are estimated by EarthSpark to be sufficient for recovering the levelized generation and distribution costs of the system. However, it is not uncommon for rural microgrid electricity costs to approach \$0.50 - \$1.00/kWh. The ECA report commissioned by the IFC provides case study data for several microgrids' costs and tariffs. The average residential tariff for Cambodian microgrids was \$0.71/kWh in 2005 – 2006. Breakeven costs were estimated to be \$0.46/kWh. In Sri Lanka tariffs are estimated to be \$0.56/kWh on off-grid hydro-power microgrids. The microgrids are subsidized, and costs are estimated to be \$0.37/kWh. Tanzania Carbon X Masurura solar PV mini-grid project charges an equivalent tariff of $0.60/kWh on an estimated $0.30/kWh LCOE. Mozambique, with 30 diesel mini-grids and one micro-hydro grid operated by Western Power, faces much higher costs. This is attributed to the unusually high cost of diesel fuel, attributable to the difficult terrain that makes transport costs extremely high. The actual costs of these microgrids is estimated to be ~$2.50/kWh, yet the utility charges only ~$0.35/kWh (Economic Consulting Associates Limited , 2013).

Another issue germane to cost recovery on the fixed and variable costs of a micro-grid is the presence of a "uniform national tariff." As articulated in (Tenenbaum et al., 2014), such a tariff may prohibit a micro-grid developer from charging any tariff other than the nationally-mandated tariff. The commercial viability of a micro-grid in this context is therefore unlikely, unless there is a dependable mechanism for a subsidy to make up the cost differential between the actual costs and the national uniform tariff.

An alternative framing of this issue is the comparison of total asset costs per customer to the desired maximum payback period. This type of calculation is perhaps most suitable for renewable-based systems with a high ratio of user-specific fixed costs to system shared fixed costs, as well as low variable costs. As framed in Muench & Aidun (2014), micro-grid developers and solar home system vendors alike may consider total asset costs and the minimum revenue required on a per-customer basis to break even within the desired payback period to reveal an appropriate tariff. Their representative figures are $350 per customer and 36 months for the payback period. With consumption of 3 kWh per customer per month, the micro-grid developer would need to charge $3.30/kWh to recover asset costs within three years.

However, while such a calculation is straightforward, it does not take into account the value of leveraging the asset by making a relatively low equity investment and taking on substantial long-term, low-interest debt financing. This type of financing arrangement is typical of larger-scale power projects throughout the world, and was utilized effectively in the United States from 1936 – 1981 under the expansion of its central grid into rural areas by the Rural Electrification Administration (United States Department of Agriculture, 1982).[20] The arrangement is useful in these cases because the cost of debt is lower than the required IRR on equity. In the REA case in the United States, the debt itself was originally subsidized at interest rates of 2% to 5%, though it transitioned in the 1960s towards a model where the REA simply provided loan guarantees while the loan itself was furnished by Wall Street firms. In the case of off-grid electrification in developing countries, similar leverage would allow for a much lower tariff than the one calculated in Muench & Aidun (2014) to yield full cost recovery on the *equity investment* in a relatively short amount of time while spreading out cost recovery on the remaining asset cost to debt service over the remaining lifetime of the project.

4.5 Conclusion

The cost structure of microgrids is not inherently unfavorable to commercial viability at reasonable customer densities. While user-specific costs are likely higher than those of mobile telephony providers, a combination of up-front user connection fees, appropriate tariffs and project financing that leverages concessional debt can ensure payback (especially for equity investors) for most customers within a reasonable timeframe.

Misconceptions of consumer ability-to-pay and poor understanding of spending habits of low-income households in general and in the off-grid electrification context specifically, have prevented project developers and retailers of off-grid solutions from obtaining financing (United Nations Foundation, 2012). One objection presented by financiers to financing requests for off-grid projects is the credit-worthiness of the end-users. The ideal collateral to project finance for an off-grid power project would be a firm power-purchase agreement (PPA) to minimize risk to the utility.

[20] Between 1970 and 1980, it was not uncommon for rural United States generation projects to be leveraged with 93% to 97% debt, and 65% to 70% debt for distribution projects (United States Department of Agriculture, 1982).

However, a utility cannot obtain such a contract from every member of the off-grid community – nor can it enforce such contracts even if it did. Instead, a microgrid developer may point to the consistency of household payments for kerosene before the arrival of electricity, and to data on payment magnitude and frequency provided by this study and others such as (Soto, et al., 2012).

Further, there is a need for concessional debt[21] to become more available to finance these off-grid projects. Highly leveraged projects could flourish in places with low electrification rates like Africa or India through similar cheap debt mechanisms provided by modern, global equivalents of the United States REA, such as the International Renewable Energy Agency (IRENA), the Global Environmental Fund (GEF), and in-country Rural Electrification Agencies with backing from the World Bank. Critically, however, the modern, private sources of capital have yet to recognize the bankability of these rural electrification projects because they don't perceive the end-users as being "credit worthy." While it may not be feasible to obtain PPAs from every member of the community, the cumulative effect of their payments is such that cash flow may be sufficiently regular and large enough to pay back project costs.

Future investigations may consist of the development of a more sophisticated risk-based pro-forma financial model. Such a model can utilize key parameters of payments, such as frequency, payment and duration of time at zero account balances. In the case of the EarthSpark grid in Haiti, a steady stream of $1.25 or $2.50 payments for pre-paid electricity from both low- and moderate-usage customers, with payments most often being made every week or every other week was found. Other cases will undoubtedly vary from these findings, but project developers should be sure to include such parameters into their modeling efforts to dispel criticism from financiers who may otherwise dismiss the project as being inherently risky.

[21] Debt is considered to be "concessional" when its terms are more forgiving than typical market terms. For example, low or below-market interest rates, payment-free grace periods, or financing terms that are longer in duration than those found from most commercial sources are examples of such terms. Non-traditional or limited debt security (i.e., non-collateralized debt) may also be considered as a term for such concessional loans.

Chapter 5: MICROGRID BEST PRACTICES: INSIGHTS FROM SEVEN CASE STUDIES

Abstract

A small number of guides and reports on rural electrification and microgrids delineate "best practices." We examine these best practices through the lens of seven case studies of microgrid developers in India, Malaysia and Haiti. Our data collection process consisted primarily of in-person interviews with six of the seven microgrid developers, and site visits to 17 of their microgrids to interview microgrid operators and field staff. Through factor analysis, we take the best practices from the literature as a starting point, and provide insights from the case studies to highlight specifically how each "best practice" contributes to a microgrid's success or failure. We describe 11 best practice areas that fall under four categories. Under Strategic Planning: market assessment, technology choices, and public policy and legal issues; under Operations (Commercial): cost recovery requirements, tariff design, frequency of tariff collection, and likelihood of customer payment; under Operations (Technical): demand-side management and maintenance & safety; and under Social Context: enabling income generating activities and community involvement. We find that the applicability of best practices is strongly affected by the business model and goals of the microgrid developer. Microgrid business models fall under three categories: fully-subsidized, partially subsidized, and for-profit. The goals of each business model type vary, but in the seven case studies included in our study, we find that political mandate, community empowerment, and return on investment are each coupled with the aforementioned business model types, respectively.

As such, best practices under particular areas dominate for particular business models and are often case specific, rather than broadly applicable.

This chapter was written with Deepa Shinde Lounsbury, Juan Pablo Carvallo, Ranjit Deshmukh, Jay Apt and Daniel M. Kammen. It is a modification of an excerpted chapter from our report, which was published as Schnitzer, D., Lounsbury, D. S., Carvallo, J. P., Deshmukh, R., Apt, J. & Kammen, D. M., "Microgrids for rural electrification: A critical review of best practices based on seven case studies," United Nations Foundation, 2014.

5.1 Introduction

Recent research on rural electrification has used case studies as guides for analyzing successes, failures and lessons learned for programs promoting access to modern energy services and the goals of the United Nations Sustainable Energy for All initiative (Sovacool, 2013; Bazilian, et al., 2012). Fewer works have focused solely on gleaning insights from case studies of microgrids specifically, though existing guides and reports on rural electrification delineate "best practices" in microgrid planning, operations and maintenance (Alliance for Rural Electrification, 2011; Ashden India Sustainable Energy Collective, 2012; ESMAP, 2000; Martinot et al., 2002; Harper, 2013; Sovacool, 2012).

Taken independently, best practices and case studies each provide a limited degree of depth. Taken together, case studies can add useful examples that clarify and enrich the knowledge embedded in best practices. Case studies can also underscore the practical challenges that prevent best practices from being implemented, and can highlight the relative importance of some best practices as compared to others. Taking the output from seven case studies of microgrid developers' experiences in India, Borneo and Haiti, we find that the best practices found in the microgrid literature do not always lead to successful outcomes. The case studies provide a more nuanced view that does not necessarily contradict the best practices, but rather gives useful examples of how such practices evolve in the field.

Detailed case studies based on in-person interviews and field visits to microgrid developers in India, Malaysia, and Haiti may be found in our report, "Microgrids for rural electrification: A critical review of best practices based on seven case studies" published in 2014 by the United Nations Foundation under its Sustainable Energy for All banner (Schnitzer et al., 2014). Through the lens of these case studies, we reexamine the recommendations in the existing microgrid literature on best practices while taking into account developers' varying objectives, which range from delivering societal benefits to delivering profits to shareholders. In doing so, we obtain a new set of lessons learned, which incorporate the unique challenges and opportunities that arise in the real world. Our objective in publishing this analysis is to improve the likelihood of success for developers who face the unpredictability and idiosyncrasies of the real world on a daily basis.

5.2 Case Studies

Seven microgrid developers were included in this research, located in India, Malaysian Borneo and Haiti, representing a range of characteristics from business model to geography, the policies they contend with, the financing sources available to them, and the microgrids they have built. Table 22 presents a brief description of each developer.

Collectively, these developers have installed 787 microgrids with an installed capacity of 14.6 MW and serve over 58,000 customers. Figure 30 shows the total number of microgrids built by each developer and by generation type.

Table 22: Microgrid Developer Descriptions

Developer	Acronym	Short Description
Chhattisgarh Renewable Energy Development Agency	CREDA	Chhattisgarh, India – Government agency installing and operating mainly solar PV microgrids through contractors.
DESI Power	DESI	Bihar, India –Private developer installing biomass gasifier-powered microgrids in communities with anchor business tenants.
Electricité d'Haiti	EDH Haiti	Haiti – EDH is the national utility of Haiti. The microgrids it develops are municipally-owned and operated. All of them are powered by diesel generators.
Green Empowerment/ Tonibung/ Partners of Community Organizations/ PACOS	GE/T/P	Borneo, Malaysia – Green Empowerment and Tonibung are non-profits working together to finance and develop micro-hydro microgrids while integrating community empowerment goals into rural electrification. PACOS is the community empowerment NGO partner.
Husk Power Systems	HPS	Bihar, India – For-profit company installing biomass gasification systems with multiple business models.
Orissa Renewable Energy Development Agency	OREDA	Orissa, India – Government-funded photovoltaic, lighting-only microgrids for the most remote villages in the state.
West Bengal Renewable Energy Development Agency	WBREDA	West Bengal, India – Government funded photovoltaic microgrids interacting with central grid expansion.

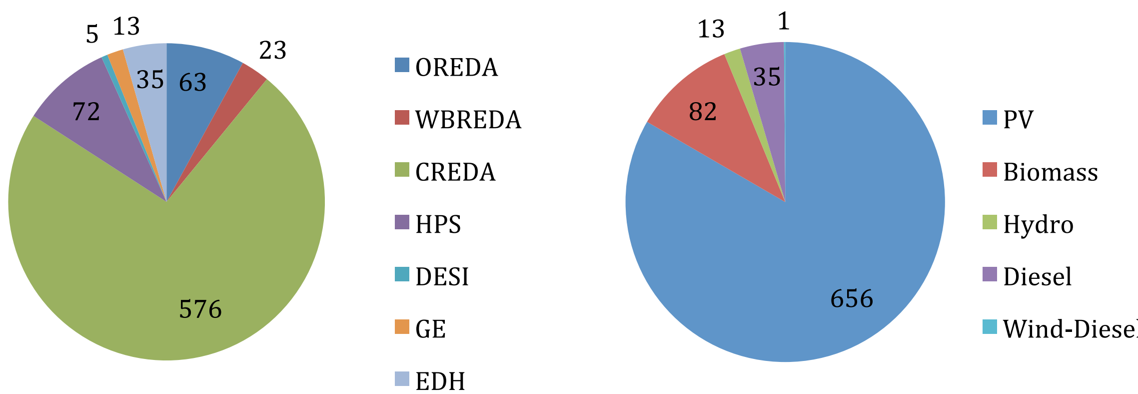

Figure 30: Total Microgrids, by Developer (L) and by Generation Type (R)

Some developers, like WBREDA, have been building microgrids since the mid-1990s, while others, like HPS, have been building microgrids only since 2008. Figure 31 shows the cumulative capacity of the seven developers' microgrids in kW built since 1996 and the cumulative investment in nominal USD for developers where such data is available. The microgrids developed by EDH are excluded from the plot as there was insufficient data on the construction year and cost. For investment, we have estimated some values for GE, CREDA, and WBREDA based on their other projects.

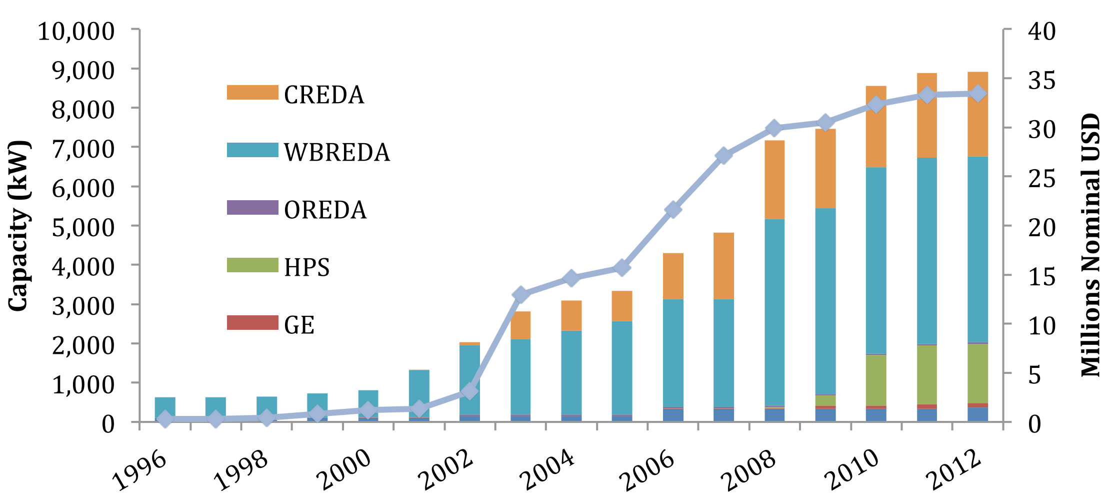

Figure 31: Cumulative microgrid capacity built per year, by developer, 1996 – 2012

5.3 Research Methods

5.3.1 Data Collection Process

The seven in-depth case studies involved interviews with six developers at their headquarters and in-person visits to and interviews with 17 separate village microgrid sites as well as with their operators in India, Malaysian Borneo, and Haiti. The locations and details of the microgrid site visits are provided in Appendix C.1. The site visits were selected to capture a wide variety of ownership structures, business models, generation sources, and financing mechanisms within the limitations of geographic feasibility and the developers' willingness to participate.

The microgrids visited were small, community-based systems with between 2 and 150 kW installed capacity and fewer than 500 customers (often less than 100 customers). The case studies include microgrids powered by PV, micro-hydro, diesel, and biomass as generation sources. While the site visits were limited by geographic feasibility and could never capture the full range of approaches or issues facing microgrids, a wide and representative range of microgrids were selected.

Detailed interviews with standardized questionnaires were conducted with microgrid developers in their main office and with microgrid operators and other employees or village energy committee members at individual village microgrid sites. The UC Berkeley Human Subjects Review Board approved all aspects of the protocol. Each interview took between 1.5 and 3 hours, consisted of open-ended questions, and often involved a guide to translate the questions and answers between English and the local dialect. We also photographed the sites, equipment and operators. Interviews were conducted between April 2012 and April 2013, and were recorded for later analysis. In-person interviews and site visits were supplemented with phone or email interviews and developer datasets (e.g. operational or financial data).

5.3.2 Literature Review

A literature review of guides and reports on rural electrification, specifically those concentrating on rural microgrids, was undertaken following the microgrid site visits. The best practices uncovered by the literature review may be roughly divided into three sections: strategic planning, operations, and social context. "Strategic Planning" groups a set of practices that reduce uncertainty and risk for the developer, including market and supply chain assessment, technological choices, and government policy. Under "Operations" we have clustered technical, commercial, and financial practices that pertain to the microgrid enterprise. Finally, "Social Context" gathers activities relating to community involvement and service. A full discussion of best practices in the microgrid sector as an output of this literature review is included in Appendix C.2.

5.3.3 Factor Analysis

A qualitative factor analysis was a significant component of our report, "Microgrids for rural electrification: A critical review of best practices based on seven case studies" (Schnitzer et al., 2014). Through the report, we sought to determine whether broadly applicable or generalized factors contribute to the success or failure of individual microgrids, or whether each case is fundamentally unique. This contrasts the factor analysis approach taken in (Sovacool, 2013), which sought to determine the factors that contribute to the success or failure of an entire national energy access program. Our factor analysis yielded a model for microgrid operations in which microgrid factors are inter-linked in "virtuous" or "vicious" cycles that lead to success or failure. We found that the factors themselves and their relative importance are determined by the business model of the microgrid developer, where business models fit into one of three prevailing categories: fully-subsidized, partially subsidized, and for-profit.

For this analysis, we take the best practices from the literature as a starting point, and provide insights from the case studies to highlight specifically how each "best practice" contributes to a microgrid's success or failure.

5.4 Results

5.4.1 Strategic Planning

Observations and interviews support the literature's recommendation to plan microgrids in a thoughtful manner, which implies much more than site analysis and selection of technological solutions (ESMAP, 2000). The thoughtful approach involves an in-depth study of the way a community functions, the economic circumstances of potential electricity consumers, and even some projection of future development in the community. As the ESMAP guide highlights, not every community needs or wants a microgrid. If suitability for a microgrid is determined, careful thought must be given to sizing, management, maintenance, feedstock availability, tariffs, expected loads, central grid expansion, and other "growing pains" the microgrid might face. A broad assessment of the "market" for a developer's microgrid is an integral aspect of strategic planning, as is technology and policy implications. We discuss these elements of planning in this section using examples from the case studies included in the United Nations Foundation Sustainable Energy For All report (Schnitzer et al., 2014). Figure 32 provides an overview of the factors under the "strategic planning" aspect of best practices covered in this section.

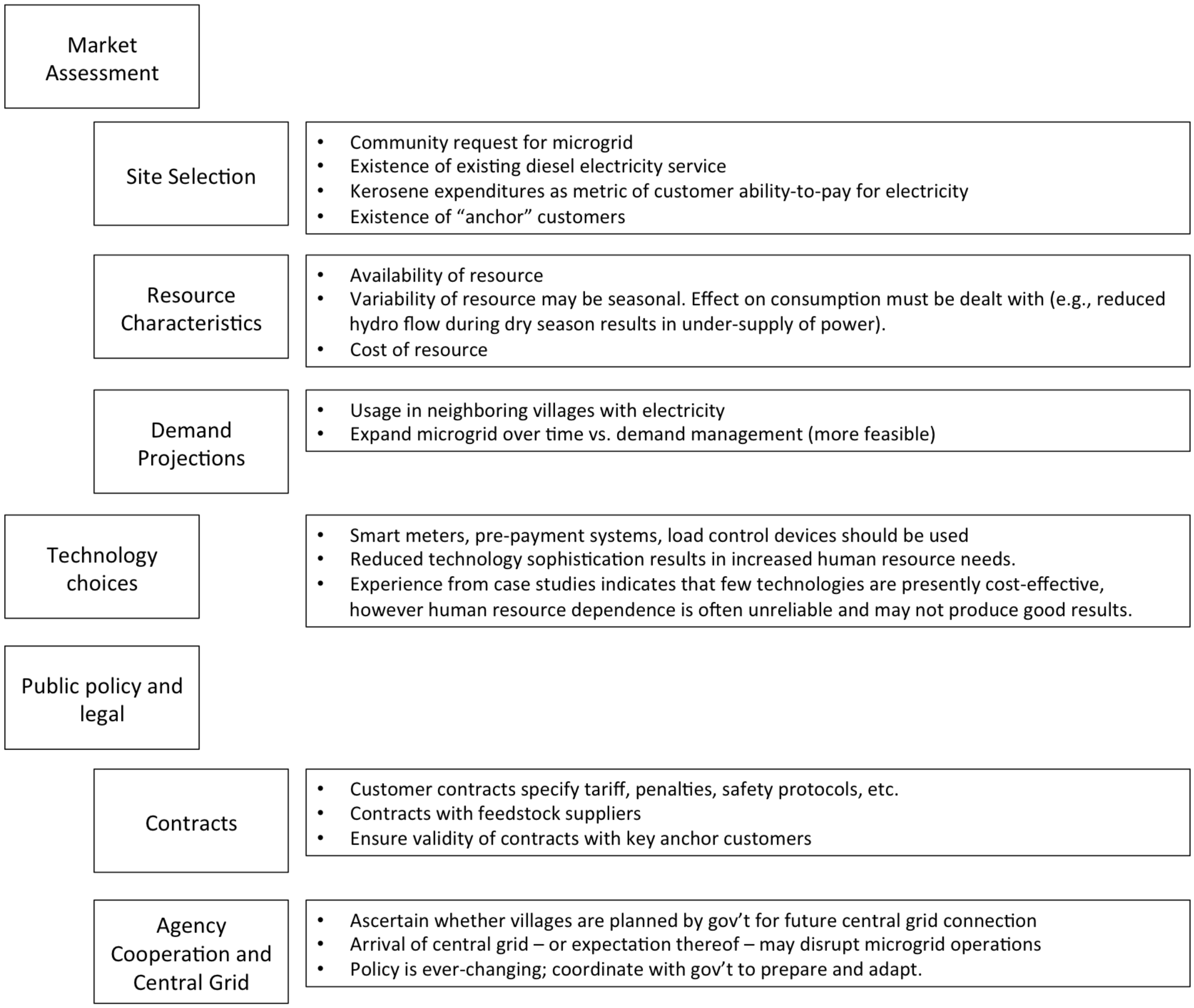

Figure 32: Overview of Best Practice Factors for Strategic Planning

5.4.1.1 Market assessment

5.4.1.1.1 Site selection

Developers approach microgrid initiation in different ways depending on their mission and business model. The Green Empowerment/Tonibung/Pacos (GE/T/P) partnership of organizations in Malaysian Borneo – a partially-subsidized (PS) business model – has had success by requiring communities to organize themselves and contact GE/T/P with a request for a microgrid and an agreement to provide 10,000 hours of labor to build the project. DESI Power took an alternative, but equally successful route of surveying 100 villages and deciding in which few to install microgrids. They also took it upon themselves to "build markets" and increase demand for electricity services within the community by investing in productive uses. A good indicator for a successful microgrid project is to select villages that have existing, poorly-run or expensive diesel microgrids, and offer electricity services for less than the price of stand-alone diesel solutions or kerosene lighting. This strategy was chosen by HPS for its Build-Own-Operate-Maintain (BOOM) plants.

Some developers choose to install microgrids in a place with a business "anchor" customer to ensure at least a minimum level of revenue. Alternatively, a developer could look for a "plant manager" first, and expect that the microgrid will operate well if managed by a qualified person. The HPS Build-Maintain (BM) model involves advertising in the newspaper for village entrepreneurs, and siting plants in villages with the most promising entrepreneurs and who meet their minimum threshold requirements.

Developers whose goal is to target the poorest un-electrified portion of the population – via fully subsidized (FS) business models such as CREDA and OREDA will inevitably choose sites that may not have the above characteristics to begin with, but a significant amount of interest creation, training, and community building accompanies the microgrids to maximize success.

5.4.1.1.2 Resource Availability and Variability

The logical place to begin an assessment of a potential microgrid installation is the feedstock or resource attributes. For example, DESI and HPS research the availability and price of rice husk before installation. Flow rates in the nearby stream should be measured over an extended period of time for a micro-hydro plant to account for seasonal variations, as exemplified by GE/T/P. Insolation throughout the year must be accounted for in PV systems, such as OREDA's and CREDA's installations.

Once customers have electricity on a regular schedule and level, they re-adjust their lifestyles to match that schedule and level. At that point, customer satisfaction and quality of service become defined as receiving service at the advertised level and following the schedule promised. Over time, customer lifestyles change as a result of access to electricity, and associated loads change as well. Resource variations, if they drop below the minimum threshold service level at the initial setting of expectations or ones that have evolved over time, can cause a decline in the quality of service and disappoint customers. This is regularly seen during the dry (low river flow) seasons at the GE/T/P microgrids. It also occurs in WBREDA's and OREDA's PV grids when the microgrid operates for only half of the time scheduled due to variable solar output. This variation in resource and the projected change in expectations over time must be strategically accounted for in the planning process.

To account for resource variability, a developer can either build capacity (more PV panels, batteries, and/or larger micro-hydro turbines), include a backup source (an HPS BM plant had a backup diesel generator), or manage customer allotments and expectations carefully. The GE/T/P Buayan microgrid tried to get all customers to scale down their usage during the dry season, but struggled to get customers who were used to certain appliances to limit their usage to lighting-only. This situation suggests that it is best to not allocate usage allowances based on the highest generation capacity (e.g., available output during the rainy season), but design allocations based on a lower capacity instead. A more expensive alternative is to implement a technical demand-side solution that could adapt to changing supply-side capacity limitations.

5.4.1.1.3 Demand Projections

Electricity demand is extremely hard to predict, especially in a village that has never had access to electricity. The ESMAP guide and conversations with developers indicate that predicting demand is key to sizing the microgrid, as they must balance the goals of minimizing costs while building an adequately-sized microgrid. A sensible way to predict demand is to visit a nearby village that already has electricity and deduce the likely demand of the target village, as the ESMAP guide suggests (ESMAP, 2000). As seen in the cases of CREDA, OREDA and GE/T/P, demand can quickly outgrow initial installed capacity in less than three years. Benchmarking demand against a nearby village that has had electricity for some time can help avoid this predicament. That said, it is difficult for developers to size a microgrid at the time of installation in a way that could meet electricity demand growth for the life of the system. Therefore, developers are left with two alternatives: 1) build their microgrids so that they are incrementally expandable or 2) manage demand effectively. Based on our field visits, there does not seem to be an affordable, incrementally expandable microgrid that a low-income community could feasibly sustain through tariff collection, so this leaves demand-side management as the more feasible alternative. In addition to the technical challenge of incrementally expanding the microgrid, erratic investment over time is often difficult for donor agencies and governments to feed into microgrid projects. These funders often prioritize a "spread the wealth" approach by funding projects in disparate communities rather than funding additional capacity the same community over time.

5.4.1.2 Technology choices

When developing a microgrid, it is difficult to assess how sophisticated its technology should be. Most developers who were interviewed indicated that they regretted not having more sophisticated technology integrated into their installed microgrids, such as smart meters, automated payment collection technologies, or load controlling devices. Many of them did not have the option to install all the devices they would have liked, because they were either not available or too expensive at the time of installation.

Regardless of the ultimate decision on technology, the choice comes down to balancing the dependence on human resources against the additional cost of technological devices. Every village is different, but if one foregoes an automated solution, then one must invest the appropriate time and effort into identifying, training, and motivating people to carry out the necessary operational activities for the lifetime of the system, especially those pertaining to demand management.

5.4.1.3 Public policy and legal issues

5.4.1.3.1 Contracts and Business Customer Service

Well-designed contracts with customers, feedstock providers, and businesses are not absolutely necessary for success, but can contribute to the smoothness of operations in the years after installation. The majority of microgrid developers in our sample do initiate some type of contract with customers in order to specify tariffs, penalties and safety protocols, among others. Such contracts are often developed jointly with the community itself.

Developers have benefited from contracts that ensure reliability and low prices with feedstock providers. In the case of HPS, they discovered cases of collusion between HPS employees and local rice mills that significantly increased the price of rice husk.

If tariff collections are dependent on a single or a few anchor customers, then well-researched contracts should accompany the decision to site the microgrid near them. DESI Power experienced a failed contract with a Vodafone cell phone tower operator when the tower operator contracted DESI Power to purchase electricity but did not notify Vodaphone, whose diesel supplier continued to deliver fuel to the tower, which the tower operator then sold at a profit. When Vodafone discovered this, they forced the operator to end the contract with DESI Power. In this case, DESI would have benefited from conducting more due diligence on its customer to ensure that their contract was legitimate. One basic principle of a contract is to allocate risk to the party most able to bear it; once that is done the party bearing the risk is incentivized to control the risk, but must allocate sufficient effort to do so.

5.4.1.3.2 Agency Cooperation and Central Grid Expansion

Failing to include cooperation with government agencies that might affect a microgrid's operations will inevitably lead to poor performance. Such cooperation can resolve issues around central grid expansion and increase the likelihood of sustainability over time. Private or public developers must investigate what the future plans and possibilities are for other government agencies or even competing electrification organizations. As evidenced by our field visits, it is not uncommon for central grid expansion to curtail the life of a microgrid.

OREDA has made efforts to coordinate with the state electricity agency to delineate exactly which communities should be electrified using distributed generation sources as opposed to central grid expansion. This coordination enables them to install their systems without being displaced by a central grid connection that delivers less reliable power than what their microgrids are capable of.

WBREDA has seen central grid expansion into the Sundarbans severely disrupt its operations. When news that the central grid would be extended to their village arrived, WBREDA customers became unwilling to continue paying for microgrid electricity, which was slightly higher than the cost of electricity from the central grid. Customers wrongly assume that the central grid will deliver unlimited power on a 24-hour basis, reducing their willingness to pay for the microgrid, which offers limited power for fewer hours per day. From the beginning, WBREDA recognized that their microgrids are an interim solution until the central grid reaches every village in the state. WBREDA recommends building microgrids that can easily be integrated into the central grid when it does arrive. However, its interactions with the nodal agency of the Ministry of Power, which ultimately decides on central grid extension routes, have not prevented sub-optimal outcomes for customers.

CREDA views its solar PV microgrids as a stopgap solution before central grid extension due to the limited loads that the microgrids can support. Since the agency has this clarity, it makes provisions to relocate its microgrids from communities that get connected to the central grid to areas that are far from the central grid.

The Government of Haiti has sought to provide regulatory clarity for microgrid developers with respect to central grid electrification. A new provision ratified by the Board of Directors of the national utility, Electricité d'Haiti (EDH), indicates that private developers can build, own and operate microgrids in areas not presently covered by EDH, so long as they are public-private partnerships. It further indicates that the towns being served by the microgrid operators may continue to do so upon the arrival of and interconnection with the central grid.

While interactions with the government and its electrification initiatives vary by country, state, and even village, it is likely that circumstances will change during the lifetime of the system due to government decisions. As such, it is best to either coordinate with the relevant government actors to prepare for or control certain factors and adapt to the changing government context.

5.4.2 Operations: Commercial and Financial Considerations

All developers are limited by their financial resources and funding sources. Donor or investor-funded business models can both succeed, but all cases point to the need for ensuring funding for more than just upfront installation costs. Before beginning an installation, it is essential to ensure that there are sufficient funds from subsidies, grants, tariff collection, or other sources for the financial viability of the microgrid throughout its life. The contrast between OREDA and CREDA's experience highlight this need. Initial capital costs for OREDA's microgrids were funded by government subsidies, but insufficient funds and effort were put into training and auditing operations throughout the life of the systems. While they succeeded in deploying a large number of microgrids, many of them are currently not operational. In contrast, CREDA ensured adequate subsidies for ongoing maintenance, auditing and training activities to support its microgrids over time.

A key input to most of the models discussed in this report is tariff and penalty design, which vary depending on each developer's business model, as well as the local cultural context. General observations from our site visits indicate that having an independent and/or paid payment collector usually increases the likelihood of payment collection, as does clearly defining and strictly enforcing penalties. While microgrid performance appears to correlate with success in payment collection, it is unclear if higher payment collection is due to the fact that customers who are satisfied with the quality and capacity of service are more willing to pay their tariffs. It is possible that reliably collecting tariffs enables the operator to employ reliable staff who makes more of an effort to collect payments.

Our field observations support the common assertion that "people don't take care of things that they get for free" (Martinot et al., 2002) in the context of energy access. Observations also support the notion that tariff collection success often has benefits beyond financial sustainability (Alliance for Rural Electrification, 2011), including service and schedule reliability. Figure 33 provides an overview of the best practices factors under the commercial and financial aspects of operations covered in this section.

Cost recovery requirements and tariff structure	• Cost recovery requirement often drives tariff design:
	    • For-profit microgrid owners need tariffs to cover all costs including return to investors
	    • NGO & gov't-owned microgrids tend to need only to cover operational costs
	• Generation technology also drives tariff design
	• In-kind community contributions may affect tariffs
	• Consumer ability-to-pay must be considered

Tariff design	• Tariff designs include fixed fee or kWh rates • Microgrid cost structure is linked to tariff design • Use of energy (kWh) rates contingent on metering system
Frequency of tariff collection	• More flexibility in collection correlated with lower collection rates • Penalty enforcement for non-payment correlated with higher collection rates • High frequency payment collection (e.g., daily or weekly) correlated with high higher collection rates
Likelihood of customer payment	
Payment collectors	• Salaried collectors from outside the community may be more successful at collecting payments than volunteer (or even paid) collectors from within the community. • Incentivizing payment collectors (e.g., graduated pay scale or commission) to increase payment collection rates may not actually be successful due to satiation
Penalty enforcement	• Penalty enforcement appears to be correlated with higher collection rates and with more successful microgrids • If microgrid operated by community, a good indicator of penalty enforcement is whether the local leader respects microgrid rules.
Developer motivation	• Developers unmotivated to collect payments are those with access to large, guaranteed operational subsidies.
Other considerations	• Deposit collected payments in secure location with multiple levels of oversight • Microgrids with connection fees or in-kind labor contributions at time of installation are correlated with higher payment rates in future

Figure 33: Overview of Best Practice Factors for Commercial and Financial Aspects of Operations

5.4.2.1 Cost Recovery Requirements Determine Tariff Structure

Different business models, cost structures, and categories of organizations (NGOs, government agencies, or for-profit entities) determine tariff structures and can have substantial differences. It is impossible to compare tariff design without first looking at the elements of the microgrid that tariffs are expected to cover.

Comparing developers in Table 23, it is possible to see the linkages between developer type and cost recovery requirements that must be addressed in tariffs. For-profit companies need tariffs to cover all costs including their return to investors. Due to their high cost requirements, their tariffs are some of the most expensive. The NGO developer, GE/T/P, has designed its microgrid program to enable financial self-sufficiency of the village-owned microgrid once it has been installed. Tariffs are therefore intended to cover all aspects of the microgrid other than the capital costs, except in a few rare maintenance situations. Finally, government-owned grids usually expect to cover operational costs and regular maintenance. The O&M costs of the EDH grids in Haiti are much higher than those in India because they are powered by diesel generators. The government-owned microgrids can and often do serve poorer customers due to their lower tariffs.

Table 23: Comparison of costs to be recovered by tariffs

Developer (Business Model)	**Tariff Price (Local Currency)**	**Tariff Price (USD, January 2014 exchange rate)**	**Operating Expenses**	**Major Maintenance**	**Capital Costs[22]**	**Profit (for Developer)**
CREDA (FS)	5-10 Rs/mo.	0.08 – 0.16/mo.	Partial	No	No	No
DESI Power (PS)	5 – 8 Rs/kWh	0.08 – 0.13/kWh	Yes	Yes	Partial	No
Green Empowerment/ Tonibung/Pacos (PS)	3 – 20 RM/mo.	0.91 – 6.09/mo.	Yes	Partial	No	No
Haiti (PS)	~200 HTG/mo.	4.55/mo.	Yes	No	No	No
Husk Power Systems (FP)	~150 Rs/mo. (average)	2.41/mo.	Yes	Yes	Yes	Yes
OREDA (FS)	10 – 30 Rs/mo.	0.16 – 0.48/mo.	Partial	No	No	No
WBREDA (PS)	80 – 270 Rs/mo.	1.28 – 4.32/mo.	Yes	Partial	No	No

Aside from cost recovery, other factors contribute to tariff design differences. The difference in cost structure of each type of generation technology plays a role as well. For example, biomass gasifiers require a constant supply of feedstock, while photovoltaic systems require an expensive battery replacement every few years, but have low costs for routine maintenance in between. Another driver is the level of in-kind operational contributions to the microgrid. The OREDA, GE/T/P and some of the EDH systems depend on volunteers within the community to operate

[22] All these developers with the exception of DESI Power rely at least on partial capital subsidies provided by their governments or donors. In India, for example, the Ministry of New and Renewable Energy provides a 150 Rs/W subsidy for solar installations and also up to a 30-40% capital cost subsidy for all renewable sources (Deshmukh et al., 2013). Capital cost recovery, therefore, refers to recovery on the portion of capital costs paid with debt or equity by the developer.

and maintain the microgrid. In some cases, in-kind community involvement is required on the planning and commissioning side of the microgrid, such as those developedby WBREDA and GE/T/P. Lastly, the tariff design must also account for the ability of the customers to pay. One of the most complex external social dynamics to understand is the income disparity between villages. OREDA-powered communities may have incomes of just 500 – 1,000 Rs (USD 8.13 – 16.27) per household per month, which puts them amongst the poorest in the country.

In other words, there is no standard formula for tariff design, but it must balance the factors driven by both the developers' motivations and the customers' expectations. Whatever "financially sustainable" means for those specific microgrids, the tariffs must meet that requirement in order to keep that microgrid running according to its stated schedule and level of service. The Haitian microgrids provide an example of tariffs often set too low to operate reliably. Even with 100% payment collection, microgrid income fails to cover diesel costs and minor maintenance activities required to keep the microgrid operating according to schedule, which promptly forces it into the vicious cycle. These tariffs have been set by the municipality itself or by elected members of the community. The choice of tariff levels seems to be dictated more closely by the tariffs found in neighboring systems rather than by an accurate calculation of cost recovery requirements.

5.4.2.2 Tariff Design

Most developers choose to charge based on a fixed monthly fee, because it is the simplest type of tariff design and does not require metering. In some cases, this type of tariff is also somewhat aligned with the cost recovery goals. For example, GE/T/P's microgrids do not require repayment for capital and have essentially zero marginal costs. They have recurring, nearly fixed O&M costs that can be accounted for with the fixed monthly tariff payment.

DESI Power utilizes conventional energy meters to charge its commercial customers on a post-paid energy (per kWh) basis. Some HPS microgrids use prepaid meters that deduct payments from the customers' balance on an hourly basis. They charge fixed monthly fees on other microgrids.

The remaining developers included in our study charge a fixed monthly fee and allow unlimited energy use within the customer's load limit. Some operators provide a single service level option and charge the same price to all customers. However, these developers usually aim to provide lighting and mobile phone charging only. Other developers offer a wider variety of service level options. For example, WBREDA offers three options varying between 75W and 300W at between 80 Rs and 270 Rs (USD 1.30 – 4.39) per month. Differences in tariff types across developers are shown in Table 24.

Table 24: Tariff payment types used by developers

Tariff type	Tiered[23]	Untiered
Energy basis (per kWh)		DESI, WBREDA
Time basis (e.g., fixed monthly fee)	WBREDA, GE/T/P, HPS, EDH, DESI	OREDA, CREDA

5.4.2.3 Frequency of Tariff Collection

Tariff collection is often designed to accommodate the income streams in the village, and, as such, collection frequency ranges from a daily to monthly basis. Monthly collection was most common among the microgrids included in these case studies, and flexibility in payments is often granted, allowing for non-payment of up to three months. However, the more flexible payment collection options tended to align with less successful collection overall. It is worth noting that those sites with greater flexibility also prioritized electricity penetration in the community over payment collection rates, and therefore may have expected suboptimal collection rates. Table 25 lists the frequency of payment collection for each of the developers.

[23] "Tiered" signifies there are multiple capacity levels at different prices customers can choose to sign up for.

Table 25: Frequency of payment collection

Frequency of Payment Collection	Developer[24]
Flexible	GE/T/P, OREDA, EDH
Monthly	OREDA, HPS (BM), EDH, CREDA, WBREDA
Weekly	DESI, GE/T/P
Daily	DESI (residential), HPS (some BOOM visit daily for monthly collection)
Pay as you Go (pre-pay)	HPS

Developers that strictly enforce penalties and actually shut off service to non-paying customers soon after a violation occurs tend to maintain high collection rates, as is the case in HPS BM microgrids. Alternatively, some developers that are averse to enforcing penalties have maintained high collection rates by collecting payments more frequently. DESI Power and some HPS BOOM plants collect tariffs daily. As gleaned from our interviews with DESI Power staff, the daily collection period resolves two issues: The first is that customers are not self-motivated to make payments and the second is that due to individual circumstances, customers may not be able to make the payments at the exact time or place they are supposed to. In response to these constraints, DESI Power designed their payment collection system around daily household visits and daily tariff collection from residential customers.

Similarly, HPS BOOM employees, who are incentivized to maximize payments, have discovered that daily visits to non-paying customers increase the likelihood that they will pay their monthly bill. Of course, while more frequent household visits can increase payment collection, it also costs significantly more to carry out than monthly collections from a single, centralized location.

[24] This is the most common collection type for that developer. Variations may exist within each developer portfolio.

5.4.2.4 *What factors influence the likelihood that customers will pay?*

Based on our case studies, successful tariff collection is most likely when strict penalties (or required pre-payment), and salaried collectors are present. Salaried collectors who are external contractors, rather than within the community, may improve collection rates as well. Pre-payment, door-to-door collection and frequent collection also increases customer payment rates.

As has been discussed previously, some developers do not have strong incentives to collect tariff payments, as funds to support operations may be available through alternative means. In general, developers who have these resources at their disposal do not obtain high levels of payment collection. Table 26 below provides a comparison of these factors for each developer. There are other factors that influence a customer's ability or interest to pay, but these are the factors a developer or operator can decide upon or influence to the greatest extent. Within these selected tariff collection factors, making a tariff higher or lower does not seem to influence the likelihood of collection as much as the decision to pay a collector from outside the community and enforcing penalties reduce the frequency of non-payment.

Table 26: Tariff collection process details and frequency of non-payment

Developer	Tariff Price (Local Currency)	Tariff Price (USD, January 2014 exchange rate)	Collector Internal or External to the Community	Collector Paid	Penalties Enforced	Frequency of Non-payment
CREDA	5-10 Rs/mo.	0.08 – 0.16/mo.	Internal	Yes	Sometimes	Moderate
DESI	5 – 8 Rs/kWh	0.08 – 0.13/kWh	External	Yes	Sometimes	Low
GE/T/P	3 – 20 RM/mo.	0.91 – 6.09/mo.	Internal	No	Rarely	Moderate
Haiti	~200 HTG/mo.	4.55/mo.	Internal	Varies	Varies	High
HPS – BM	70 – 190 Rs/mo.	2.41/mo.	Internal	Yes	Strictly	Low
HPS – BOOM	60 – 180 Rs/mo.	0.16 – 0.48/mo.	Internal	Yes	Somewhat strictly	Moderate
OREDA	10 – 30 Rs/mo.	1.28 – 4.32/mo.	Internal	No	Almost Never	High
WBREDA	80 – 270 Rs/mo.	0.08 – 0.16/mo.	External	Yes	Sometimes	Low

5.4.2.4.1 Collectors

In many communities, payment collectors from within the community struggle with confronting their own friends and relatives about non-payment or enforcing penalties. WBREDA discovered this issue and transitioned from payment collectors from within the community to hiring an external payment collector to visit multiple communities, which increased their payment rates.

5.4.2.4.2 Strict Penalty Enforcement

Enforcing penalties does not guarantee high collection rates, but they do appear to be correlated. The correlation may be due to penalty enforcement being reflective of the generally good practices of the microgrid operator. The GE/T/P case study includes a notable example comparing two different villages – one with a leader that enforced penalties and another where the leader not only did not enforce penalties but also broke rules himself. HPS threatens to turn off electricity to an individual customer or even the entire village if non-payment is prevalent. Within HPS microgrids, HPS BM plants enforce penalties much more strictly than HPS BOOM plants and have higher collection rates.

5.4.2.4.3 Developer Motivation

It appears that microgrids that have a greater dependence on tariffs to fund their operations end up with higher collection rates. Lacking a back-up option for operational funding is likely the motivation for imposing penalties and experimenting with different methods to maximize payments.

For example, extensive government subsidies are available to CREDA to cover its ongoing expenses. Tariff rates are low and collections are not a high priority compared to providing access to electricity. OREDA grids also suffer from this lack of motivation. They have no immediate need to collect tariffs because the government is a committed funder and their daily or weekly collections did not seem to actually affect the immediate performance of the microgrid, because this did not directly fund the maintenance work. Rather, maintenance was contracted out to a third party by OREDA, creating a disconnect between tariff collection and microgrid operational reliability. Tariff collections were supposed to fund operational costs ten years after the microgrid was built – a large temporal disconnect that was perhaps too long to influence customer behavior. On the other hand, HPS has experimented with collection methods because its operations directly depend on collected payments.

5.4.2.4.4 Other Considerations

- After payments are collected, funds must be kept in a safe place. If an individual can withdraw funds, the community puts itself at risk for theft. At the OREDA microgrid in Palsipani, the payment collector stole all the funds a few years ago and forced the community to start collecting from scratch. Soon after, the community essentially gave up on tariff payments entirely. This issue can be resolved by ensuring that the account into which funds are deposited is jointly held by diverse community members, or in tandem with the developer.
- HPS incentivizes the payment collector financially based on collection success, which they report in their collections. Yet HPS has found that payment collectors reach a threshold of interest, and beyond that bonuses do not work well.
- Keeping records of payments is also important for tracking patterns and enforcing penalties. The GE/T/P microgrid in Buayan did not have proper records, and the managers found it difficult to determine how much they were collecting each month and which members owed what amount of payment.
- An initial connection fee or labor contribution may contribute to willingness to pay or to take care of the system. HPS and WBREDA both charge connection fees and have moderate levels of payment collection while GE/T/P requires labor contributions in lieu of a monetary contribution. OREDA has felt that they have had to convince customers to take

the electricity service in the first place, does not charge a connection fee, and has poor rates of payment collection.

5.4.3 Operations: Technical

From a technical perspective, microgrids face the challenge of reducing the complexities of an electricity grid power system to a system that is simple, reliable and robust enough to withstand operations in a rural, remote environment. The best practices literature highlights two areas of operations in the technical domain that are most pressing for microgrid operators to address: demand side management (DSM) and maintenance. We do not address the technical challenges pertaining to system design, installation or procurement. While important, these challenges fall outside the operations focus of our research. Figure 34 provides an overview of the best practices factors under the technical domain of operations covered in this section.

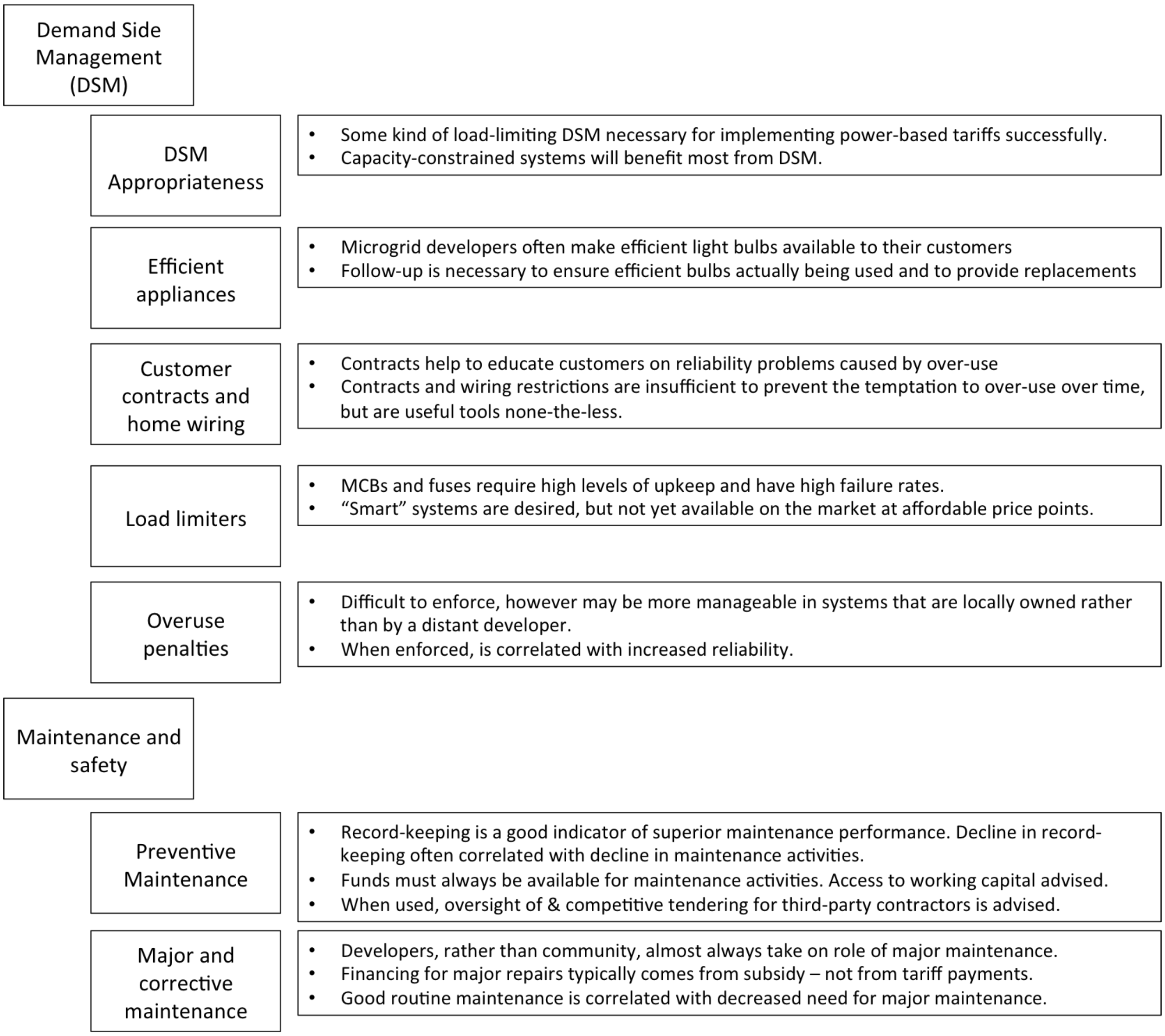

Figure 34: Overview of Best Practice Factors for Technical Aspects of Operations

5.4.3.1 Demand Side Management (DSM)

In this section, we discuss to what extent the implementation of these measures was aligned with the consensus on “best practices” for microgrid DSM, and the degree to which these measures were effective.

With the exception of the Haitian government, all of the developers included in this study used at least one type of DSM measure with the intention of increasing microgrid reliability and reducing operating costs. Table 27 lists the demand-side measures commonly found in microgrids, and indicates which ones are used by the developers.

Table 27: Demand side management measures utilized

Developer	Efficient appliances	Restricting Residential Use			
		Customer agreements	Home-Wiring Restrictions	Over-Use Penalties	Load limiters
CREDA	✓	✓	✓		✓
DESI			✓	✓	✓
GE/T/P		✓		✓	✓
Haiti					
HPS	✓	✓	✓	✓	✓
OREDA	✓	✓	✓		✓
WBREDA	✓	✓	✓	✓	✓

5.4.3.1.1 DSM Appropriateness

Most of the developers included in this study faced problems that could be solved through demand-side interventions, and some were successful in their implementation. With the exception of DESI Power (and, at times, HPS), all other tariffs were, in some way, power-based. Power-based tariffs require some mechanism for restricting customer demand, such as over-use penalties, efficient appliances, or load limiters, which are effectively demand-side management measures.

Four of the developers in particular stood out as being particularly constrained by available power – GE/T/P, OREDA, WBREDA, and CREDA. As such, demand-side measures were most critical for these developers for the sake of preserving microgrid reliability on a day-to-day basis. The microgrids in Haiti were unique in that they were not at all capacity-constrained, as their generators were sized at a level that is far greater than even the peak load – and especially greater than the average load – on the systems. The importance of using demand-side interventions for HPS was related primarily to its use of a power-based tariff, which can be loosely followed even without strict demand-side controls. Power consumption was not a threat to reliability, as it very rarely neared the 32 kW limit on their generators.

The only developer in this report to utilize an energy-based tariff for their residential customers was DESI Power. DESI Power stood apart as the sole developer that did not encounter scenarios appropriate for demand-side measures to control power consumption. We attribute this to the fact that DESI caters primarily to a relatively small number of commercial customers, and its grids tend to be very well-sized relative to its loads. Only one of its microgrids serves residential customers directly, and it is a small number – about 75 households. The main issue on this microgrid is that residential customers bypass their meters, which adds up to theft of about 2-3 kWh/day (approximately 5% of total energy). An energy-limiting controller may be more suitable for DESI's customers, as a load-limiting device is not appropriate for its case.

5.4.3.1.2 Efficient Appliances

The literature strongly advocates for energy-efficient microgrid loads, and specifically recommends that developers go to lengths to make energy efficient light bulbs accessible. HPS, GE/T/P, OREDA, CREDA, and WBREDA pursue this strategy. Such a strategy was not appropriate for the Haiti microgrids, as demand is far below available supply, and further reducing demand would actually have the detrimental effect of increasing unit energy costs. DESI Power actually has an incentive for its customers to use inefficient appliances as it sells power on an energy basis, and cannot significantly increase its customer base. GE/T/P educates consumers about efficient appliances during installation, but outcomes vary depending on self-regulation and the frequency of community inspections. While OREDA and WBREDA provided light bulbs to their customers initially, they have not done sufficient work to follow up with their customers to provide them with efficient light bulbs when one breaks or fails. CREDA also provides CFLs to consumers and provides replacement bulbs through its operators. HPS's load limits are suitable only for usage of CFL or LED lights, but it is not uncommon to find incandescent bulbs being used by customers on grids without a load-limiting device.

5.4.3.1.3 Customer Contracts and Home Wiring Restrictions

The ESMAP guide provides detailed guidance on customer contracts and advocates for their usage (ESMAP, 2000). WBREDA implemented such contracts early on, and relied on behavioral change efforts to manage loads. They hoped that if customers understood that overuse would lead to poor reliability, that they would voluntarily limit their usage. WBREDA also wired homes for just two lighting sockets, which proved to be an effective mechanism for curtailing over-use early on. The contracts indicated that penalties would be imposed for over-use, but the contracts and even the home wiring restrictions were ineffective in preventing frequent overuse as customers began to use higher consumption loads over the years.

In OREDA's grids, over-use was frequently found in microgrids located in proximity to areas with central grids, where higher power appliances were available. Customer contracts and an understanding within the community that exceeding limits would lead to brownouts were insufficient to prevent widespread use of incandescent light bulbs, fans and TVs in certain microgrids.

5.4.3.1.4 Load Limiters

Strongly recommended as a best practice in the literature, load limiters were found on GE/T/P, HPS, CREDA, and WBREDA's microgrids. GE/T/P utilized miniature circuit breakers (MCBs) to limit customers' usage. As mentioned previously, customers were able to circumvent the MCBs in some cases. However, they did prove to be effective in microgrids where penalties for bypassing MCBs were enforced.

HPS has gone through several different types of load limiting, from fuses to MCBs to pre-pay "smart" meters with current sensors and relays. Each of these measures was flawed – fuses needed replacement each time the customer exceeds the load limit; MCBs needed to be reset by the operator, and the MCB hardware apparently did not work well for low-power customers; and customers were able to bypass the HPS-designed smart meters.

HPS leadership believes that in cases where there is difficulty in establishing credible threat of penalty from over-use, more technical solutions are necessary, such as a "smarter" meter or one that takes an input of 440V and converts to 220V internally to prevent bypassing.

WBREDA had similar experiences over the years. It started with MCBs, then shifted to a custom-designed limiter with a current sensor and relay. Customers complained about the MCBs once they started to demand more power and tripped them on a regular basis. As for the custom solution, they found that the inrush current on some appliances tended to trip them off. Eventually customers simply bypassed the limiters. MCBs were reintroduced to replace the custom limiters. These have been only modestly successful WBREDA estimates that it is presently losing 15% of revenues to electricity consumed above customer load limits. The key lesson from these experiences is that an ideal solution for load limiting has still yet to be found, but that a low-cost solution like an MCB is better than no limiting device.

5.4.3.1.5 Overuse Penalties

Few of the developers have instated overuse penalties. As noted previously, while the literature is clearly supportive of penalties for non-payment as a best practice, it is conspicuously silent on whether customers should be penalized for over-use. The experience of the developers studied in this report does not suggest that such penalties are necessarily a "best practice." When established, it seems that the operators sometimes do not enforce such penalties.

For example, HPS bans the use of incandescent light bulbs on its systems. There seemed not to be a penalty for using these banned bulbs other than confiscation. Even though bulbs were confiscated – in one grid as often as every two to three days – customers clearly continue to use them. On the other hand, customer overuse tends to be less of an issue in grids that are owned by a local entrepreneur rather than HPS itself. The explanation offered is that these local entrepreneurs are imposing figures in the community who have credibility to threaten penalties and also follow through with penalties in the case of a violation.

In one GE/T/P grid, it was discovered that the village "headman" bypassed his MCB and was consuming above his level of service. As the designated enforcer of the penalty for doing this, the threat of a penalty to other community members was tacitly removed. In another village, however, the headman is firm about disconnecting users who violate their service level. It was found that in this village, Bantul, the microgrid was reliable, and community members credited the strong enforcement policy with its reliability.

In WBREDA microgrids, the customer contract clearly states that customers who exceed their load limit would be disconnected. During the first few years of operations, demand was low and customers did not exceed usage. However, as demand increased, customers exceeded their load limits on a regular basis. Penalties are reportedly enforced more often in cases of non-payment than in cases of over-use. Thus even the credible threat of penalty enforcement is ineffective in deterring over-use.

5.4.3.2 Maintenance and Safety

We find that maintenance performance is determined by physical and institutional drivers. The physical element pertains to the microgrid itself – the quality of components used, the quality of construction, and the ease with which components can be maintained. The institutional element pertains to the entity that is ultimately responsible for maintenance, and the institution's plan for carrying out maintenance. That institution must somehow be monitored – be it by the owner, the operator or some third-party entity. If the microgrid will be owned and operated by the developer, then the developer must set up appropriate mechanisms for management and make sure that its maintenance plan is feasible.

OREDA has grids throughout the state of Orissa in extremely remote areas. An inadequate maintenance contractor, and long-term maintenance contracts without adequate performance incentives, along with infrequent interactions with villagers partly explain why many of its microgrids had fallen into and stayed in a state of disrepair.

If ownership and maintenance activities are to be transferred to the community, time and funds must be allocated appropriately to ensure that the community is willing and prepared to manage the system on their own for upwards of 20 years. GE/T/P has developed a model for this that appears to function well. Even if systems are transferred completely to the community, catastrophic events can happen that even a diligent community may be incapable of fixing. For example, we witnessed the effects of a landslide that destroyed all the civil works in the GE/T/P micro-hydro microgrid in Terian. Planning to set aside some additional funds to assist in the event of extreme circumstances can rescue a microgrid from a situation that is otherwise irreparable by the community.

Key findings on system maintenance from our site visits and developer interviews include two points: (i) there is a great deal of variation across maintenance plans, including how maintenance is funded and who provides it, and (ii) there are distinct differences between how preventive maintenance is carried out and corrective maintenance for more significant repairs. While the literature stresses the importance of ongoing maintenance, and details specifically what should be included in preventive maintenance procedures, it does not delve into the practical realities of maintenance implementation, nor into how to deal with major repairs.

5.4.3.2.1 Preventive Maintenance

The prevailing best practice with respect to preventive maintenance is to train the local microgrid operator to take on maintenance tasks, and provide them with the necessary tools for doing so. The conventional expectation is that tariffs are designed to cover expenses associated with maintenance tasks, such as trimming branches, removing illegal connections, maintaining the generator (in the case of hydro and diesel), topping up batteries with distilled water, and cleaning solar panels. Our case studies indicate that when maintenance tasks are entrusted to the local operator, they are carried out, so long as funds are available. There is also a correlation between good maintenance performance by the local operator and diligent record-keeping of expenses for items like filters and lubricants. When there is ambiguity over who is responsible for routine maintenance, outcomes are not as good. An alternative model not mentioned in the literature is the use of third party contractors to provide routine maintenance. Such a model is in use by the three government entities in India included in the case studies – OREDA, CREDA and WBREDA – with varying success.

The local operators of the GE/T/P systems – that is, the communities themselves – are responsible for routine maintenance, and seem to be able to service the hydro generator and maintain the system with success. While every system suffers from down time, the reasons for poor performance tend to be due to customer overuse and sub-optimal power-rationing during the dry season rather than poor maintenance.

In Haiti, while major repairs are explicitly carried out by the government, even preventive maintenance issues are sometimes too expensive for local operators to cover with tariff collection.

DESI Power's microgrids are maintained by the local operators, who also keep detailed written records of their activities. They are trained intensively by DESI Power employees to remove tar build-up, change filters, and maintain the generator on a near-daily basis. While preventive maintenance appears to be adequate, DESI struggles with other issues that prevent daily operations of the microgrids, discussed in the "Major and Corrective Maintenance" section below.

The HPS site visits called attention to the fact that operationally, many things can go wrong with gasifiers. On a daily basis, tar build up or wet husk can prevent operations. HPS's local operators are well trained and care for the gasifiers and engines on a near-daily basis.

OREDA's entire maintenance plan is based on the use of contractors to carry out routine maintenance and implement major repairs. However, performance is not guaranteed, even when contractors are chosen through a competitive public tender and are well compensated. The contractor is expected to visit each system every few months and ensure it is working properly, but in reality, many systems remain in a non-functional state for years. Absence of on-site distillation tables results in the need to transport distilled water through rural, logistically challenging places. This issue has prevented the contractor from delivering water at each of the microgrid sites visited for the purpose of this case study. Distillation tables at villages would provide an easy, reliable source of distilled water for the batteries at remote sites.

Like OREDA, WBREDA contracts third party maintenance providers. Unlike the OREDA contractors, though, WBREDA's contractors keep a lineman and an operator at each of WBREDA's microgrid sites. The presence of solar distillation tables for water and on-site staff appears to ensure reliable maintenance.

CREDA either contracts third party service contractors that are different than the contractor responsible for installation, or has the same contractor provide maintenance services for five years as part of their overall contract.

5.4.3.2.2 Major and Corrective Maintenance

The ESMAP guide is somewhat resigned to the inevitable difficulties in dealing with major repairs. The guide views the issue of repair as a trade-off between designing a higher-cost system at the outset that takes advantage of on-site installation expertise and a lower-cost system that uses less durable materials, with the expectation that repairs and improvements will be made in subsequent years (ESMAP, 2000). This framing of the issue as a tradeoff is reasonable, but microgrid developers must be given some reference regarding the probability that repairs and improvements will be made over the years if a lower-cost system is chosen. Our case studies indicate that developers should be pessimistic on this point, and the case studies included in the ESMAP guide lead to the same conclusion. This sentiment is captured by an engineer implementing projects in Indonesia who was quoted in the ESMAP guide:

> "I've come to the conclusion that 'distribution' must be planned with a long term perspective - it's a nice idea to say we build and use bamboo posts temporarily and will gradually replace them with steel or concrete as they rot but how many people ever get around to doing it?" (ESMAP, 2000).

The guide acknowledges that, "without properly trained local staff and possibly a mechanism for providing technical backstopping, most repairs may not be properly made." This has the effect of increasing "life-cycle costs or [decreasing] system life over what was planned. Consumers are put at risk and the initial investment may not yield the expected benefits" (ESMAP, 2000).

Our case studies echo this anecdote and support the pessimistic view on the likelihood of major repairs being carried out. Many of the grids visited during our field visits were in need of corrective repairs. In GE/T/P's case, the Terian microgrid was rendered non-operational due to a landslide for several months prior to the field visit. While GE/T/P's preventive maintenance plan depends heavily on community work, they lack the funds and the expertise needed to implement the necessary repairs after the landslide at the Terian site – including laying new penstock and re-building the forebay. For these repairs, GE itself must find the funds to assess the site, develop a repair plan, purchase materials, and make the repairs.

In fact, all of the developers were ultimately responsible for making major repairs, and in most cases the financing for such repairs was provided by the government or an NGO. Major repairs in Haiti generally concern damaged transformers in need of replacement and generator overhauls, and such repairs are explicitly to be carried out by local offices of the national utility, Electricité d'Haiti. However, such repairs are often unfulfilled. The microgrids in Roche-à-Bateau and Pestel have both been in need of new transformers since early 2012, and the diesel generator at Coteaux has been in need of an overhaul for two years, though it is still somewhat operational. It was only through the intervention of an NGO EarthSpark International that a transformer was purchased for Roche-à-Bateaux. Three months after the transformer was delivered, EDH fulfilled the microgrid operator's request to install it. It is questionable whether EDH would have purchased the needed transformer in a reasonable timeframe.

At the time of our field visits, DESI Power's microgrids seemed to be suffering from major issues. The underground cable connecting the generator house to the distribution system on the Gaiyari microgrid had been identified as being problematic, resulting in 13 continuous days of inoperability. However, DESI had not been able to discover the precise problem. The gasifier on the Bara microgrid was said to have problems every other day. For the two days prior to our field visit, the gasifier was inoperable. For such problems that are difficult to diagnose, it is clear that local training is insufficient. DESI acknowledges this and sends its own employees to work on such severe problems. The close proximity of all of the microgrids to the DESI Power office enables DESI to quickly dispatch its technicians to its microgrid sites, but this model will not scale to additional sites that are more distant.

The third-party contractors used by OREDA, CREDA and WBREDA are responsible for making major repairs to the systems. In WBREDA's case, high levels of routine maintenance have prevented major maintenance issues from occurring. Cases where major repair issues have come up are ones where the central grid has arrived, or is expected to arrive, and customers stop making payments. Even though WBREDA does not depend on tariff collection to pay for maintenance, it ceases to award third party maintenance contracts on micro-grids that do not pay for service. As a result, the microgrids fall into disrepair and eventually cease to function. This has been the case in the Kamalpur PV microgrid, the Gangasagar wind/ diesel microgrid and the Gosaba biomass/diesel microgrid.

Failure to provide routine maintenance on OREDA's microgrids has led to the need for repairs and major problems. For example, in the case of the Anupgarh microgrid, customers have not had power for 16 months as a result of poorly executed routine maintenance. The poor maintenance led to an unspecified number of customers stealing solar panels from the roof of the powerhouse, rendering the microgrid essentially inoperable. The Palsipani microgrid did not have power for 18 months, and the Matiapadhar microgrid has not provided power to more than one or two customers for 30 months. In the case of both of these microgrids, their operators have not been able to provide power due to incomplete battery replacement. The primary maintenance contractor, Tata BP, replaced eight out of 20 batteries four days before our site visit. Such an action is "too little, too late." Partial battery replacement is poor practice, and the replacement came across as a gesture meant to give the illusion of decent performance by the contractor given that they were aware of our pending field visit.

Exacerbating OREDA's maintenance problem is the confusion over how villages "call in" maintenance requests. OREDA managers indicate that a Village Electricity Committee (VEC) can either call or visit the vendor or OREDA offices (either in their district or their headquarters), but the VECs seem to have been under the impression that it was necessary to write a letter to OREDA headquarters in order for OREDA to contact the maintenance provider. This suggests that in such arrangements, the developer should clarify the service request procedure with VECs from the beginning by providing documentation.

CREDA has a robust process of monitoring the performance of their systems, and expects regular reporting from its maintenance contractors. Consumers from CREDA's microgrids can convey their complaints through the operator, then the service provider and finally to the CREDA office. Consumers can also directly contact the CREDA office. Major repairs are funded through state government subsidies.

Table 28 and Table 29 list the type of maintenance conducted by the developers and the sources of funding for carrying out maintenance.

Table 28: Maintenance implementation

Implementer	Contractor		Developer		Operator		Community	
Maintenance Type	Preventive	Corrective	Preventive	Corrective	Preventive	Corrective	Preventive	Corrective
DESI				✓	✓			
GE/T/P				✓			✓	
Haiti				✓	✓			
HPS				✓	✓			
OREDA	✓	✓						
WBREDA	✓	✓						

Table 29: Funding sources for maintenance

Funding Source	External (Government/NGO)		Internal (Tariff-Based)	
Maintenance Type	Preventive	Corrective	Preventive	Corrective
DESI			✓	✓
GE/T/P		✓	✓	
Haiti		✓	✓	
HPS			✓	✓
OREDA	✓	✓		
WBREDA	✓	✓		

5.4.4 Social Context

Due to the local nature of microgrid systems, social context is an essential consideration for microgrid developers. Some microgrid developers state that their intentions of microgrid development concern not only access to electricity, but also social issues of empowerment, protection of indigenous resources and human development. As such, the social context of microgrid development will vary from one developer to the next, driven by their stated goals and intentions. We find that generalized best practices for social context are not useful or broadly valid in the same way that they are for strategic planning or operations. This section discusses the ways that developer intentions will drive the degree and way in which social context is factored into their operations. Figure 35 provides an overview of the best practices factors for the social context of microgrids covered in this section.

Enabling Income Generating Activities	• Income-generating activities neither necessary nor sufficient for successful microgrids. • Developing these activities is a challenging, time-consuming enterprise. • Prior to project development, establish whether community expresses desire for income-generating activities.
Community involvement	
Experience of Green Empowerment	• GE/T/P shows that community-owned and operated microgrids can be successful. • GE/T/P invested heavily in community training from the outset – twice as much spent on community activities than on capital for a typical microgrid.
Disappointments with Community Involvement	• Nodal agencies in India were unable to transition ownership to communities despite intentions. • "Community ownership means no one's ownership."
Reduced Community Involvement	• Profit-seeking developers have had positive experiences by reducing community involvement. • Dependence on community ownership or operations can be reduced if standards, technologies, and responsive customer service and regular maintenance are employed.
Community involvement revisited	• Community involvement should be determined by developer intentions. • Investment in community involvement in ownership/operations maybe justified If developer has non-financial objectives from community involvement (e.g., social justice) or if developer is uninterested in managing operations. • Community involvement should also be interpreted to qualify communities as "customers" rather than "operators." Education, behavioral change and comprehension of socio-economic constraints/priorities are necessary for any microgrid developer to undertake.

Figure 35: Best Practices Factors for Social Context of Microgrids

5.4.4.1 Enabling Income Generating Activities

There is a degree of agreement within the literature that developing income-generating activities powered by the microgrid is necessary to produce sufficient revenue for the developer. While there is no doubt that such activities result in positive social and economic outcomes within the community, our case studies do not support the notion that income-generating activities will necessarily lead to high revenues, nor that they are necessary at all for fully recovering operating costs. Furthermore, as with most aspects of microgrid operations, developing income-generating activities is no simple task. DESI Power, for example, has found that developing income-generating activities requires significantly more time and resources than they originally expected. In most areas, especially village markets, electricity is not necessarily linked in the minds of villagers to productive activities – just lighting.

DESI Power's business model rests on the notion that income-generating activities will lead to higher revenues and profitability. In Baharbari, its primarily residential microgrid, DESI assisted with the introduction of a rice huller and other income-generating loads. Their hypothesis that doing so would increase the incomes of their residential customers has been borne out, and these increased incomes have led to more customers being able to pay for electricity. DESI Power's experience is aligned with ARE's perspectives, as they have stated explicitly that no plant can run on household loads only (Alliance for Rural Electrification, 2011). As such, prior to investing, DESI seeks to combine residential loads with larger loads, such as irrigation pumps, value-add agricultural services, and refrigeration. This "consumer creation" is essential to their operational sustainability, as a small number of such loads can provide a significant and continuous revenue stream.

The literature on best practices for income-generating activities does not go far beyond merely supporting the idea. That is, the literature does not provide much guidance on how to go about developing such activities. DESI Power's experience provides a couple of examples that offer guidance:

- In Bara, DESI is giving loans to existing industries to convert their diesel engine-driven loads to motor-driven loads. The cost of the motor can be recovered within a few years by DESI through increased electricity sales.
- DESI Power complements its investment in loads with a staff position that is dedicated to assisting commercial customers to develop businesses and increase electrical load.

DESI's perspective is more aligned with the common rationale behind introducing income-generating activities than with the rationale discovered by OREDA. OREDA found that villagers do not value lighting enough to pay for lighting-only electricity service. Villagers have told OREDA administrators that they do not want to dedicate the time needed to collectively maintain the system that could never facilitate power for income-generating activities. The lesson learned from OREDA, therefore, is that a microgrid should be sized to accommodate the loads that are truly desired by the prospective customers. Thus, the rationale discovered by OREDA for income-generating activities is more fundamental than the common view that such activities will lead to higher incomes and therefore better financial performance for the operator. Rather, the rationale for income-generating activities on OREDA's microgrids is that villagers themselves, who, in OREDA's case, are some of the poorest in the country, view such activities as a means for escaping poverty. Developers should take heed when aspiring to make a difference in the lives of villagers by providing only high quality lighting services. For some communities, this may simply be insufficient and not worth paying for or looking after.

HPS' systems do not fully support the view that income-generating activities must be present to deliver cost recovery revenues, or that all communities demand such activities. However, they do not refute that view either. One HPS BM grid serves 100 business customers and 750 residential customers. While that grid's owner did not set out to develop income-generating activities and is not actively doing so, it is clear that he earns more from an average business customer than from a residential customer. As shown in Figure 36, business customers make up just 12% of his customer base, yet they account for 24% of his monthly revenues.

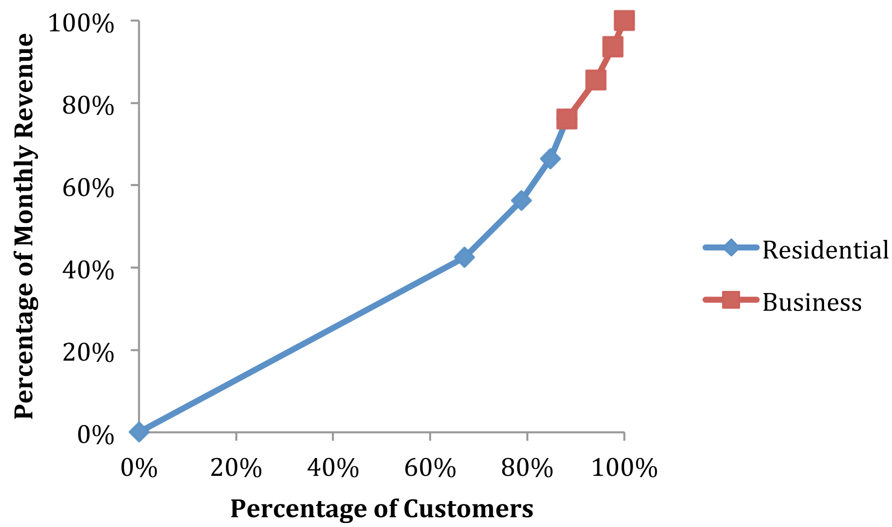

Figure 36: Percentage of Monthly Revenues Attributed to Customer Classes on one HPS microgrid. Residential customers are arranged, from left to right, into 15W, 30W, 45W and 100W classes. Business customers are arranged, from left to right, into 30W, 45W and 100W classes.

5.4.4.2 Community Involvement

Microgrid best practices recognize that levels of community participation vary depending on the developer's business model. The literature also generally supports the idea that microgrids need community or stakeholder participation at different stages to be successful and that there are challenges to maintaining community interest and involvement.

Based on our observations and research, we support this conclusion but also believe that many private and some public sector models are actually moving towards reducing their dependency on the community, and in some cases completely bypassing the community leadership and collaboration after the initial planning and commissioning stages as part of their strategy. Additionally, almost all developers found that community cohesiveness varied drastically, sometimes depending on culturally inherited social structures, and were often disappointed by a community's inability to work together to keep the system running due to conflicts, lack of motivation, or other reasons. Finally, our experience in India and Malaysia suggests that community involvement is a highly local issue, with particular social, cultural, and political conditions that should prevent cross comparison among microgrids. Table 30 shows the types of community participation used by each developer.

Table 30: Community involvement in microgrid management.
(Levels of community involvement vary drastically. Black checks signify voluntary activities, and green checks signify paid activities.)

Categories (of Voluntary/ Paid Village Participation)	DESI Power	GE/T/P	EDH	HPS (BM Model)	OREDA	CREDA	WBREDA
Daily Operations	✓ (paid)	✓ (voluntary)	✓ (paid)	✓ (paid)	✓ (paid) ✓ (voluntary)	✓ (paid)	✓ (paid)
Major Maintenance							
Collect Tariffs	✓ (paid)	✓ (voluntary)	✓ (paid) ✓ (voluntary)	✓ (paid)	✓ (voluntary)	✓ (paid)	
Enforce Penalties			✓ (paid) ✓ (voluntary)				✓ (voluntary)
Initiation/ Planning Strategy Help		✓ (voluntary)		✓ (voluntary)		✓ (voluntary)	✓ (voluntary)
Construction Labor		✓ (voluntary)				✓ (voluntary)	
Village Energy Committee Existence	✓ (voluntary)	✓ (voluntary)	✓ (paid) ✓ (voluntary)		✓ (voluntary)	✓ (voluntary)	✓ (voluntary)
VEC Bank Account Existence		✓ (voluntary)	✓ (voluntary)		✓ (voluntary)	✓ (voluntary)	
Contribute Land	✓ (voluntary)	✓ (voluntary)		✓ (voluntary)	✓ (voluntary)	✓ (voluntary)	✓ (voluntary)
Initial Community Ownership		✓ (voluntary)					
Community Eventually Owns					✓ (voluntary)		

5.4.4.2.1 Green Empowerment Maximizing Community Involvement

Green Empowerment/Tonibung/PACOS (GE/T/P) provide a strong example of community involvement and the only example of a community-owned system of all microgrids studied. They invested most of their resources into building community leadership around the microgrid, gave the community primary responsibility over the system, and succeeded in their goal of creating a community-owned and operated microgrid. GE/T/P up-front costs are USD 8,000/kW installed on average, of which only USD 2,600 goes to capital equipment. A significant portion of the up-front investment went into community leadership formation, technical training, or other community development initiatives. They found that the strength and cohesion of the community was the greatest determinant of success of the system.

GE/T/P employed multiple strategies to strengthen the community involvement in the project. Firstly, GE/T/P built projects in villages that formed energy committees and reached out to them of their own volition. Secondly, GE/T/P requires at least 10,000 hours of community labor, which results in a vested community interest from the beginning, as well as familiarizing community members with the system, its operations, and its limitations. Green Empowerment and Tonibung were also unique in partnering with PACOS, an NGO that specializes in community organization and how to involve a community in such a project. The three organizations collaborated to provide in-depth training to a few members of the micro-hydro committee, as well as a more basic training on rules, safety, cooperation, and load management to the entire village.

The training of and investment in the community prior to operations has succeeded in keeping the system operating under full community ownership. Operations are done voluntarily and the community is almost always able to either perform maintenance themselves or pay for it out of their community funds. Yet even with this investment in community-based capacity, certain GE/T/P microgrids suffered from the shortfalls of community-ownership. Sharing responsibilities among too many volunteers sometimes led to inefficiencies (e.g., in payment collection) and the community did not always cooperate (e.g., by failing to reduce loads to only lighting during the dry season). Certain leaders were better than others at regulating usage and encouraging cooperation. The best community leaders usually were from more remote and tribal villages. Other leaders or community members have even tried to sabotage the microgrid.

The GE/T/P model shows that community-owned microgrids can be sustainable, and the likelihood of success is increased by prioritizing and planning training and community-building from the outset. In addition, PACOS and many of the villages also recognized the benefits of community organization beyond just maintaining electricity in their village. The investment in leadership and social organization also enabled the village to combat the encroachment of palm oil and timber companies, raise their voices against corrupt politicians, and defend their very existence. In the GE/T/P case, the investment in community was justified by more than just the ability to keep the lights on.

5.4.4.2.2 Disappointments with Community Involvement and Alternative Strategies

Besides GE/T/P, none of the other developers regularly transfer ownership to the entire community even though many have intended to. With the exception of WBREDA in its early years, developers have not invested nearly as much into building up community-based institutions around the microgrid.

India's renewable energy nodal agencies – WBREDA, OREDA, and CREDA – maintained ownership of their microgrids but tried to involve the village to a great extent. However, after experiencing disappointment with community involvement early on, these developers began to internalize more of the operational responsibilities of the microgrids. WBREDA's initial model was centered on a partnership with a local cooperative in order to ensure local capacity to fulfill many operational functions and gain the trust of the rest of the community. The local cooperative was supposed to collect tariffs, help in planning, administer penalties and operate the system on a voluntary basis. This model worked for as long as a few years in various locations, but fell apart due to political disagreements, changes in leadership, or lack of financial motivation. In light of these failures, WBREDA changed its model and hired employees to carry out the tariff collections, operations, and other ongoing operational roles. While the cooperatives were important to get community commitment initially, cooperatives now mostly exist nominally.

Like WBREDA, OREDA originally expected communities to manage daily operations, community education, and tariff collections. OREDA helped form Village Energy Committees in each village. OREDA's initial 17 microgrid installations were scheduled to entirely transfer ownership to the village after ten years of payment collection and operations. For the microgrids that were built in 2002 and 2003, the transition has yet to occur due to their poor or non-functional state of operations. While this is partially due to under-performing maintenance contractors and unforeseen political issues, much of the performance problem can also be attributed to poor community cooperation. As the OREDA officials stated, "community ownership means no one's ownership." OREDA has not changed their village training strategy or customized it to each village, as it has changed its deployment strategy to invest in far more individual solar home systems than microgrids in order to ensure a sense of ownership of those systems. As for future microgrids, OREDA plans to maintain ownership of the system for the entire life of the project.

CREDA also helps create Village Energy Committees, but does not truly depend on them to manage operations. With heavy ongoing subsidies, CREDA ensures the microgrids are properly maintained by an outside contractor, and has the capacity to expand the system if demand exceeds supply.

EDH microgrids in Haiti are owned by the municipality, rather than by the developer (the national utility) or the community itself. In some EDH microgrids, community involvement is present through a volunteer committee appointed by the mayor's office responsible for O&M. However, in most cases, the committee is made up of the mayor's staff or by a local NGO. In some cases, a technician paid by EDH who lives near these microgrid systems performs basic operations and maintenance.

5.4.4.3 Reduced Community Involvement

HPS and DESI Power are the least dependent developers on community involvement. All of their systems are privately owned, and most are profit-driven enterprises. The involvement of the community for each of these developers is, at most, the initial expression of interest, provision of land and paid local labor to perform operational activities. It is also important to note that these developers, while reducing dependence on the community for operations, still emphasize positive customer relations. The developers have instated a clear method of communication with their customers and respond quickly to customer complaints.

DESI Power focuses on commercial customers entirely, or as anchor customers for a village. It has determined that selling to only residential customers will not enable financial sustainability, and therefore focuses its microgrids on income-generating activities rather than household customers. This greatly reduces the importance of and dependence on a community for collaboration.

HPS believes that village cohesion is the exception rather than the rule, and avoids depending on community cooperation for its success. HPS now makes it a standard policy to adopt strict standards, do regular in-person check-ups, invent technological solutions, and circumvent local leaders in the village. A local entrepreneur franchises a HPS gasifier through the BM model, and hires his own local employees and maximizes his own profit through careful management of the system. In the other models, HPS hires local villagers and all functioning roles are incentivized with wages and bonuses.

5.4.4.4 *Community Involvement Revisited*

Microgrid developers have been told that community involvement is essential for success (ESMAP, 2000). Based on our sampling of microgrids, if the developer wants to disengage from daily operations, a sincere effort in training a community will increase the upfront costs but will also increase the likelihood of the success and longevity of the system. Alternatively, a false trust in the natural or self-motivated interest and enthusiasm of a community to maintain a microgrid over the long run without considerable training and investment by the developer will often lead to failure and disappointment, as seen in some of the government-owned microgrids.

For many private operators looking to make systems profitable instead of aiming to provide the lowest cost electricity to the poorest villages, the community is involved in a calculated, financially incentivized manner. Some developers are unwilling to deal with the variability in cohesiveness and volunteerism. Private developers instead rely on hired employees, no-nonsense payment collection policies, and a more transactional, business-like approach that prioritizes individuals' willingness to pay over communities' willingness to cooperate.

As an alternative view on community involvement, our cases support the relevance of customer creation and education. Successful developers expend effort in their initial deployment to explain to their customers how to better use their systems and how to avoid penalties, disconnections, or technical issues. Community involvement as customers rather than operators has been relatively overlooked in the literature, but our cases support the relevance of the behavioral change efforts behind introducing these communities to electricity as a service.

Along the spectrum of village involvement, there is no better or worse approach in terms of "success" defined as reliability and self-sufficiency. Low, medium, or high community involvement systems all have the ability to be successful microgrids. But when we look at alternative definitions of success such as serving the poorest, or positive externalities of village cohesion, such as

GE/T/P's example of community building to defend their existence, one can re-evaluate the goals of the microgrid, and what level of community involvement best fits those goals.

C Appendix

C.1 Description of Microgrid Site Visits

Table C-1: Description of Microgrid Site Visits

Developer	Town	State	Country	Generation Source	Capacity (kW)	Year Installed	Capital Cost (Nominal Currency)	Description of Capital Contributions	Hours	Status	Date Visited
DESI	Bara	Bihar	India	Biomass	32	2012	3,200,000 Rs	80% Minda; 20% DESI	6pm-midnight	Functional	1/9/2013
DESI	Baharbari	Bihar	India	Biomass, diesel	35	2002	3,500,000 Rs	100% DESI	6pm-midnight	Functional	1/9/2013
DESI	Bhebra	Bihar	India	Biomass	43	2006	4,300,000 Rs	100% DESI	6pm-midnight	Functional	1/9/2013
DESI	Gaiyari	Bihar	India	Biomass	150	2006	15,000,000 Rs	100% DESI	6pm-midnight	Functional	1/9/2013
GE/T/P	Buayan	Sabah	Malaysia	Hydro	14	2009	NA	GEF SGP; DANIDA	24 Hours (except for dry season, then nighttime only)	Functional	1/20/2013
GE/T/P	Terian	Sabah	Malaysia	Hydro	5	2005	100,000 RM	Green Empowerment; Seacology; Borneo Project	24 Hours (except for dry season, then nighttime only)	Non-functional (landslide)	1/21/2013
EDH	Coteaux	Sud	Haiti	Diesel	125	1994	N/A	100% EDH	7-10pm, Su, M, W, F, Sa	Not functioning properly	Multiple visits, 2012
EDH	Pestel	Grande Anse	Haiti	Diesel	85	1986	N/A	100% EDH	N/A	Not functioning properly	Multiple visits, 2012
EDH	Port-a-Piment	Sud	Haiti	Diesel	200	2009	N/A	100% EDH	6-10pm Su; 7-10pm Tu, Th, Sa	Not functioning properly	Multiple visits, 2012
EDH	Roche-a-Bateaux	Sud	Haiti	Diesel	100	2008	N/A	100% EDH	7-10pm, 5 days/wk	Not functioning properly	Multiple visits, 2012

HPS	Bhadhi	Bihar	India	Biomass	50	2010	2,000,000 Rs	61% Husk; 39% MNRE	5pm - 11pm winter / 6pm - 12am summer	Functional	1/10/2013
HPS	Samstipur	Bihar	India	Biomass	32	2012	2,000,000 Rs	61% Owner; 39% MNRE	5pm - 11pm winter / 6pm - 12am summer	Functional	1/10/2013
OREDA	Anupgarh	Orissa	India	PV	2	2002	1,500,000 Rs	50% OREDA via UNDP; 50% MNRE	6pm - 10pm; streetlights all night	Not functioning properly	1/14/2013
OREDA	Matiapadhar	Orissa	India	PV	2	2002	1,500,000 Rs	50% OREDA via UNDP; 50% MNRE	6pm - 9pm or 10pm; streetlights operate all night	Not functioning properly	1/14/2013
OREDA	Palsipani	Orissa	India	PV	2	2002	1,500,000 Rs	50% OREDA via UNDP; 50% MNRE	6:30pm or 7pm - 9pm; auto shut-off after 2 hrs	Not functioning properly	1/14/2013
OREDA	Tuluka	Orissa	India	PV	4.5	2010	1,800,000 Rs	50% OREDA; 50% MNRE	6:00 PM - 12:00 AM	Not functioning properly	1/14/2013
WBREDA	Koyalapada	West Bengal	India	PV	120	2005	24,000,000 Rs	50% WBREDA; 50% MNRE	6pm-midnight	Functional	1/7/2013

C.2 Best Practices from the Literature

C.2.1 Strategic Planning

Microgrid literature emphasizes the importance of considering a diverse set of factors that affect the technical design of the microgrid system as well as the repercussions of a chosen design on its operational structure. Specifically, the consensus "best practice" with respect to design is that developers should not design the system based on "pure technological considerations, but instead adapt to the specific social and economic characteristics of the rural community" (Alliance for Rural Electrification, 2011). With respect to operations, the consensus "best practice" is to be thoughtful about the effect of a chosen design on the price of electricity to the end user, the lifetime of the system, and the quality of energy services delivered (Alliance for Rural Electrification, 2011).

In 2000, the Joint UNDP/World Bank Energy Sector Management Assistance Program (ESMAP) published its "Mini-Grid Design Manual" to promulgate best practices particularly in technical design such as conductor sizing and pole options. In addition to these technical aspects, the report extensively addresses the inputs to system design and operational modes – namely demand projections and site assessment – with attention to local cultural and political contexts. In doing so, the manual is pragmatic and a reminder of the importance of the human element of microgrid planning, which planners can only discover through on-the-ground site visits and stakeholder consultation. Specifically, the manual advises an initial assessment of interest, population density, willingness to pay, and how these factors influence the selection of a responsible management entity and appropriate generation source before even committing to install a microgrid at the site.

These real-world planning considerations are crucial reminders that,

> "in the enthusiasm to get access to electricity in areas far from the grid, there is often an eagerness to immediately get down to the job-gathering and setting poles; stringing conductor; buying fuses, house-wiring, and lighting fixtures, etc. However, before purchasing the necessary materials and setting up a system, the proper design must be established. But even before this, it is critical that the necessary elements for a successful project are in place. While ensuring this may not guarantee success, omitting to consider them is a sure recipe for failure" (ESMAP, 2000).

The ESMAP guide advises that further planning efforts should also include matching the expected uses (e.g. lighting, entertainment, business uses) with the sizing of the grid (ESMAP, 2000). If not done properly, "Unnecessarily oversizing a mini-grid increases the cost that the community must cover. Under-sizing it will lead to consumer frustration and dissatisfaction with service quality, a dissatisfaction that can easily lead to the loss of consumers and the inability of the remaining consumers to cover costs" (ESMAP, 2000). In a similar vein, the Alliance for Rural Electrification (ARE) recommends that "Over-sizing some components... can be a good idea to anticipate a future demand growth and facilitate the mini-grid's expansion" (Alliance for Rural Electrification, 2011).

There are a variety of methods available to determine projected demand, such as surveys of existing energy services, site visits, surveys of electricity use in the nearest neighboring village with electricity access, assessing population growth trends, analyzing load growth in electrified areas. Regardless of the method, both guides emphasize that demand prediction is an important part of planning.

C.2.2 Operations: Commercial and Financial

The success of a microgrid is often dependent on cooperation among consumers with respect to their individual levels of consumption and timely payment of their electricity bills. Penalties are frequently incorporated into microgrid rules to discourage customers from consuming more power than they are permitted and from making late (or no) payments. Tariff levels – and the collection of tariff payments – are especially important factors for determining microgrid success in models that depend on revenue from users to cover operational costs. Unfortunately, the literature on best practices for tariffs often neglects to recognize the varied business models in the space, and how these models influence tariff design based on their objectives and cost recovery requirements. Subsidies are inextricably linked to tariff levels and payment and play an important role in determining microgrid success. Intuitively, it is expected that subsidies – both for capital or ongoing expenses – can drive tariff levels down and reduces the portion of the operator's revenue requirement to be collected from consumers.

Regardless of whether a microgrid operator seeks cost recovery, tariff levels imply a trade-off between the financial needs of the system and the customers' ability and willingness to pay. As ARE notes, "The concept of affordability plays of course a crucial role," (Alliance for Rural Electrification, 2011) and in the Design Principles set forth by Sovacool, it is noted that successful programs "should first consider affordability" (Sovacool, 2012). The ESMAP guide makes the point concisely: "In addition to generating the desired revenues to cover project cost, the tariff schedule should also contribute to making electricity more affordable" (ESMAP, 2000).

In cases where microgrid operations depend heavily on tariff collection, ARE finds that "setting appropriate tariffs and subsidies (i.e., obtaining the right energy price) is probably the most important factor to ensure project sustainability." The justification is that the tariff-subsidy calculation must balance customer affordability with operator self-sufficiency. The ARE report suggests that the fixed monthly fee is usually more suitable to the cost structure of microgrids, which consist of mostly fixed costs.

In contrast, the ESMAP guide does not make a definite judgment on what type of tariff design should be used, but offers extensive advice on what to consider in setting both energy and power-based tariffs. It does note that the energy-based tariff "may be regarded as a more equitable approach, because a consumer is charged according to the energy actually consumed. Those who use less electricity pay less." While this is true, the guide notes the increased cost and technical difficulty in implementing an energy tariff as a result of using electricity meters. In contrast, a power-based tariff need not necessarily require any hardware – simply an agreement between the customer and operator that the customer will use only a certain amount of power. The challenges to such a tariff are discussed further in the demand-side management section below.

Towards affordability, the ESMAP guide also recommends that operators practice the following:

- Provide a "lifeline" tariff sufficient for simple lighting so that even the poorest members of a community can have access to electricity.
- Increase the number of customers on a microgrid to spread fixed costs over as large a customer base as possible.
- Be flexible with customer payment rules. Customers being served by microgrids typically have irregular incomes which are not spread out evenly over the year. Rather, income is often earned in lump-sums coinciding with seasonal harvests. Operators could accept bulk payments for several months at a time under the monthly payment model or could accept pre-payment to accommodate these income streams.

The best practice with respect to subsidies from different sources converges on the choice between capital and ongoing subsidies. The ARE report criticizes projects that depend on up-front investment in installation to ensure longevity and states that "one of the important lessons... was that donations or large capital cost subsidies without a sustainable business plan can destroy local renewable energy markets...[and] people don't take care of things that they get for free" (Alliance for Rural Electrification, 2011). Similarly, Sovacool finds that "effectual programs encourage community ownership and...they reject the 'donor gift' model" (Sovacool, 2012). The Ashden India Sustainable Energy Collective is actively advocating for improved subsidies and tariff reform to address such concerns. Specifically, while the Collective acknowledges that capital support is necessary, they see alternatives such as performance-linked grants, avoided cost tariffs or value-added tariffs being superior to flat capital subsidies (Ashden India Sustainable Energy Collective, 2012). Such tariffs are effectively ongoing operational expense subsidies, and can be disbursed directly to consumers if they are given "energy coupons" from the government. Alternatively, the government pays a "feed-in tariff" to the project developer based on the metered number of kilowatt-hours produced (Ashden India Sustainable Energy Collective, 2012).

Tariff design is insufficient on its own to deal with non-payment and theft. These issues are a result of difficulties in payment collection rather than in the design of the tariff itself. It is not uncommon for practitioners to incorporate customer disconnection for non-payment and zero-tolerance for theft in their business models. The ARE report states that "failing to respect the payment methodology can jeopardize the sustainable operation of a system, regardless of the model used" (Alliance for Rural Electrification, 2011). The ESMAP guide recommends that "it must be clear that if the consumer no longer has the wherewithal to pay, that household will be disconnected." It also recommends that each customer enter into a written agreement wherein disconnection for non-payment is well defined. Regarding theft, the guide advises a zero-tolerance policy (ESMAP, 2000).

C.2.3 Operations: Technical

C.2.3.1 Demand-Side Management

As has been discussed, microgrid systems are typically constrained by the total amount of power available. Systems with battery storage are also constrained by energy, and high operating costs in diesel microgrids also constrain the total amount of energy available. Contending with these limitations, system operators often rely on demand side management to ensure system reliability.

A recent review of Demand-Side Management (DSM) practices in microgrids identifies several strategies and technologies (Harper, 2013).

DSM strategies include:

- Efficient appliances and lights
- Limiting business hours
- Restricting residential use
- Price incentives
- Community involvement, consumer education and village committees.

DSM technologies include:

- Load limiters (including miniature circuit breakers, fuses and intelligent load limiters that discourage users from using energy-intensive appliances during brownouts)
- Distributed intelligent load control (automatically optimizing load reduction with a "smart" controller)
- Conventional meters
- Pre-paid meters
- Advanced metering systems with centralized communication.

As the review notes, some of the above-listed strategies and technologies are designed primarily for the sake of load management. Others, such as pre-paid meters, provide opportunities for demand-side management as a secondary function.

Best practices from the literature are summarized below:

- Efficient appliances: Perhaps the greatest amount of energy and, at times, highest share of load on many microgrids comes from lighting. Due to their low cost, inefficient incandescent light bulbs are commonly used by customers. Switching to efficient light bulbs enables more customers to be served and makes power available for other energy services without augmenting installed capacity. Efficient light bulbs (fluorescent or LED) should be provided to customers who cannot afford them towards achieving these benefits (ESMAP, 2000). Energy-efficient and low-power models of appliances such as water heaters, rice cookers and refrigerators are typically more expensive than inefficient models. They are more expensive due to the use of higher quality components, but could be less expensive with a higher market demand as a result of economies of scale. While it would be ideal for customers to use such appliances, they tend to be too expensive for low-income residential microgrid customers, but commercial enterprises might be able to afford them (Harper, 2013).

- Limiting business hours: This strategy can improve load factors by setting rules that make high residential consumption and high commercial consumption non-coincident (Harper, 2013). The ESMAP guide suggests "encouraging other uses of electricity at times outside peak lighting hours in the early evening" (ESMAP, 2000).
- Restricting residential appliance use: Many microgrids place restrictions on how much power customers can consume individually. In practice, this can be done through a variety of means:
    - Customer agreements: Such agreements may be verbal or written. ESMAP recommends using written agreements, but does not explicitly recommend including a statement on appliance/usage compliance. The guide acknowledges that while such agreements are "the cheapest approach, it will probably only work for some small systems where there is a good understanding between all members of a community" (ESMAP, 2000). Harper cites several microgrids where certain appliances were banned through verbal agreements, but customers used those appliances anyway (Harper, 2013).
    - Home-wiring restrictions: Limit customer use to lighting by only installing light sockets and no plug outlets. Such an intervention provides a barrier to customers

using other loads, but there are cases where households have worked around this barrier by installing outlets for using appliances (Harper, 2013).

- Over-use penalties: A penalty for over-consumption adds "teeth" to customer agreements that set power limits or forbid certain devices. The reports reviewed mentioned penalties but carried very little information regarding actual application of overuse penalties.
- Load limiters: Load limiting devices have been associated with microgrids nearly since their inception and come in the form of several types of devices. They can be fuses, miniature circuit breakers (MCBs), positive temperature coefficient thermistors (PTCs) or electronic circuit breakers. As mentioned in the "tariffs" section, load limiters can be used to effectively replace electricity meters for power-based tariffs. The ESMAP guide advises two considerations in choosing a load limiter: 1. Likelihood of fraud and theft, and 2. Cost vs. accuracy. The best practice for installation is to restrict access to the device so as to prevent tampering, and install the device outside of the home (ESMAP, 2000).

C.2.3.2 Maintenance & Safety

Maintenance is vital not just for operations on a daily basis, but also to prevent potentially expensive or difficult problems in the future. The literature stresses the importance of developing and implementing a maintenance plan. As the ARE guide makes clear, "operation and maintenance have to be planned carefully in any business development project and integrated into the project structure itself, as well as in the financing scheme, to be sure that the system will continue to run smoothly on a long-term basis. There is no project sustainability without a carefully established business plan integrating the question of the operation, maintenance and management (O&M&M) financing" (Alliance for Rural Electrification, 2011).

Unfortunately, the type and schedule of a maintenance plan cannot be standardized across microgrids because maintenance needs vary by generation technology, community dynamics, financial resources, the local environment and the types of energy services provided by the grid. There is also variability in how maintenance tasks can be carried out; these depend on external factors such as the availability of spare parts, availability of trained maintenance providers, and ability to train local microgrid customers to perform maintenance tasks.

Sovacool emphasizes the role of customer support in successful rural electrification programs as a general lesson learned (Sovacool, 2012). However, while best practices with respect to maintenance are not completely unified, they are also not mutually exclusive. One main point is the importance of a widespread or national maintenance infrastructure, including vendors and manufacturers of spare parts, along with well-established "service centers" with trained maintenance providers. The Nepalese national microgrid program incorporates such an infrastructure and recent program evaluations partially credit this maintenance infrastructure with the program's success (Sovacool & Drupady, 2012).

Another main point on maintenance best practices places a greater emphasis on maintenance within the community itself rather than on an external national infrastructure. The ESMAP guide details the maintenance and operations activities that a microgrid operator should undertake, including starting and shutting down the plant according to the established schedule, determining when periodic maintenance should be undertaken, trouble-shooting problems, and keeping log books and records to complement those activities. The local operator will be able to undertake these tasks only with sufficient investment in operator training. The guide details what types of observations should be recorded in a logbook, including hours of operation, kWh readings at the beginning and end of each day, and voltage and current readings at regular intervals. The guide also recommends regular inspections and consistent maintenance through activities such as trimming branches and removing illegal connections (ESMAP, 2000).

Such local maintenance work will ensure that the system operates according to the schedule expected by the community, that equipment functions for its expected lifetime, and that the community is safe from electrical hazards.

On safety, the ESMAP guide recommends implementing comprehensive safety measures because "electricity can be dangerous, particularly for villagers to whom it is largely unfamiliar. Every effort should be made to minimize the risk to those using electricity" (ESMAP, 2000). The guide offers several specific ideas for communicating safety concerns to customers, such as enlisting teachers from schools and providing illustrated brochures and posters.

C.2.4 Social Context

C.2.4.1 Community Management and Involvement

Many different recommendations exist on how communities should be involved, but most reports point to the involvement of the community as essential for success of a project regardless of what business model is chosen. The ESMAP guide suggests that any project promoted from outside the community is destined to be short-lived and states that, "it must be clear that some mechanism for organizational continuity exists and that the elements are there for a long term commitment to the project. In the absence of a reliable and capable individual and community organization, it may be best to forego a project; otherwise, this effort will likely be costly, time consuming, and frustrating and in the end stagnate and collapse after the outside promoter has departed the scene" (ESMAP, 2000). It goes on to state that there absolutely must be a long-term committed organization to manage the project over the twenty to twenty-five year lifetime, or the high upfront investment will end up being useless.

Both reports identify different models as requiring more or less community involvement. For example, the ARE report suggests that private microgrid operators do not need much community involvement in operations, but still need to involve stakeholders in every step of the planning process by holding local consultations and working within existing organizational structures. This will ensure that the community is interested, familiar with the benefits of electricity and contributes their local knowledge to the design of the grid in order to set up the system for long-term customer satisfaction (Alliance for Rural Electrification, 2011).

In the case of community ownership and community-based management of the microgrid, there is recognition of the vested interest of the community (as the managers are also the consumers), but also a recognition of the challenges to the community ownership socio-business structure. Challenges include lack of technical and business skills, "tragedy of the commons" usage patterns, and difficulty in limiting individual consumption, corruption, and conflicts (Alliance for Rural Electrification, 2011). In recognition of both the advantages and challenges of community-owned microgrids, ARE explains that "community-run minigrids have myriad positive impacts on the community in terms of self-governance and local buy-in into the electrification system. However, a long preparation period including technical training and capacity building is imperative to compensate for the lack of skills and potential social conflicts" (Alliance for Rural Electrification, 2011). Beyond the training time, nurturing, and capacity building, the community could benefit from structured contracts and technical solutions, such as meters, to address some of the challenges of a community-based model.

C.2.4.2 Enable Income Generating Activities

There appears to be agreement in the literature that electrification should be coupled with development of commercial activities. This can be traced to two perspectives: Reports on microgrids state that enabling income-generating activities increases the ability for customers to pay tariffs.

Other reports, including economic development-focused literature often imply that the enabling of microenterprises is a major objective of electrification projects. The ARE report justifies such development as an integral component of microgrid operations because "the economic viability of mini-grids often depends on the presence of an industry because households do not usually provide an adequate revenue base to pay for mini-grid investments" (Alliance for Rural Electrification, 2011). It continues to discuss how stable, low priced electricity has the potential to unlock a variety of economic activities in a village and these income-generating activities both make consumers attach a monetary value to the microgrid and provide a reliable source of revenue for the microgrid operator.

Furthermore, the ability for microgrids to support carpentry, irrigation, telecom, or other industries expands the local economy, which can in turn foster stable household revenues for the microgrid. The ARE report also presents a case where the conclusion is for the program to be "as commercially oriented as possible" (Alliance for Rural Electrification, 2011).

The ESMAP report views income-generating activities as an explicit objective of microgrids, justified on the basis that such activities "generate additional income and thereby...reduce the costs that residential consumers would have to cover" (ESMAP, 2000). Sovacool finds that successful rural electrification programs "match energy services with generating income," citing the micro-hydro microgrid scheme in Nepal that "coupled its promotion of micro hydro dams with the agricultural processing needs of communities" (Sovacool, 2012).

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