An Analysis of the Viability and Competitiveness of DC Microgrids in Northern India

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Abstract

The electrification of rural and remote villages in developing countries poses major challenges. While extension of the central power grid offers economies of scale in generation and transmission, distribution infrastructure to reach remote areas can be prohibitively costly to install and maintain. The low demand of newly electrified customers also makes many electrification projects economically unviable. Northern India provides a case study in the challenges of rural electrification. Microgrids, wherein smaller numbers of customers are connected to a local electricity infrastructure that may or may not be connected to the central grid, have long been studied as a potential way to electrify remote and rural customers.

This study proposes and analyzes a set of technical and economic models describing a solar powered DC microgrid, where a private enterprise provides lighting and mobile phone charging as a service. The models are analyzed to determine sensitivity to factors such as village size, length of distribution networks, customer load, and operations and maintenance costs. The models are tested to determine the technical and economic factors that limit the practical applicability of the proposed enterprise. The microgrid enterprise is then compared to a similar company that uses single household solar home systems (SHS) to provide the same service. The study concludes with a general discussion of the differences between the solar home system and microgrid approaches.

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Acknowledgements

The models in this work are loosely based upon the work of Mera Gao Power, a small microgrid operator providing lighting and mobile phone charging services in over 300 villages around the town of Reusa in Uttar Pradesh, India. I cannot overstate my gratitude to Nikhil Jaisinghani and Sandeep Pandey of Mera Gao, who were kind enough to host me and who took me to visit a number of the villages in January 2013. In addition to answering many questions about costs, operating assumptions, and business models, they gave me a chance to see and understand the reality of operating a business in the rural Indian context in a way that would have been impossible without their support.

I would also like to express my thanks to my advisor, Rob Stoner, and his post-doctoral associate, Reja Amatya, who both offered extremely valuable feedback and insights over the course of this study. Our weekly discussions were often wide ranging, but I always came away with a better insight into how microgrids and other electrification systems can fit into the larger picture of energy access in the developing world. I also owe a debt of gratitude to the Tata Center for Technology and Design at MIT for providing me with support and the opportunity to travel to India and study microgrid projects as they are being applied in the field. As a recovering engineer, I started this project looking at the electrification problem as a purely technical one. The travel experiences, discussion, and study that were facilitated by Rob, Reja, and the rest of the faculty and fellows of the Tata Center have opened my eyes and helped me develop a fuller understanding of the challenges that face India and the rest of the developing world.

Table of Contents

Chapter 1: Introduction

The Millennium Development Goals (MDGs) set out an ambitious program targeting the reduction of poverty, hunger, and inequality while improving access to education, healthcare and environmental sustainability, among other objectives. While none of the MDGs specifically targets energy access, it is widely understood that access to energy in the form of electricity and modern fuel is a prerequisite for achieving many of these goals [1], [2]. A large body of work has shown that access to electricity works in conjunction with other factors (education and literacy, household income, healthcare, and the development of transportation and communication infrastructure, among others) to speed the development process [3], [4], [5], [6], [7], [8]. In particular, the following linkages between energy and socio-economic development are of significance for this study:

- Access to electricity and cooking fuel allows people to spend less time collecting biomass and other traditional fuels, allowing more time for income generating activity [7], [8]
- Electric lighting provides greater flexibility in time allocation through the day and evening, providing better conditions for education and work [6], [8]
- Electricity coupled with modern telecommunication technology lowers barriers to entry for private companies, increasing the attractiveness of developing markets and helping to speed the diffusion of innovations [3], [8]

Other research has demonstrated that few, if any, of the socio-economic benefits can be attributed solely to access to electricity [9], [10], [11], [12], however. It is also argued that the relationships between development outcomes and energy are not deterministic [13], but the overwhelming majority of evidence indicates that access to electricity is frequently an enabling factor for many economic development initiatives. Nevertheless, in 2012 the International Energy Agency (IEA) estimated that 1.3 billion people worldwide still lack access to electricity at any scale [14].

The status of electrification in India

India has the largest rural population in the world, and with 293 million people unconnected to the grid, efforts to provide electricity there face major obstacles [14]. This is reflected in the 2010 IEA estimates which show that, despite a 75% rate of electrification nationwide, greater than 90% of urban customers are grid connected as compared with only 52.5% of rural customers [2]. In addition to the disparity between rural and urban rates, the figures vary wildly from state to state; the 2011 census data indicate that electricity is available to 97% of households in the states of Goa and Himachal Pradesh, as compared with only 16% of households in Bihar [15]. With such heterogeneity, not only in electricity access, but also in geography and climate, economic activity and culture, India provides many examples of successful and unsuccessful electrification efforts.

As noted in the IEA report, India faces major challenges in both generation and distribution. Although new generation capacity is being added constantly, the growth of the population and the inclusion of previously unconnected rural customers is projected to require an overall increase of at least 600% by 2030 from its present level to 960GW [16]. With supply lagging demand throughout this period, the IEA expects electricity shortages and frequent power cuts well into the future [2]. In addition to the challenges in power generation, India's power distribution system suffers from high technical losses (disproportionately at the distribution level due to overloading of transformers, resistive losses, etc.) and "non-technical" losses (due to power theft, inaccurate or non-existent metering, and a poor record of billing and collections) that are among the highest in the world (see Figure 1) [2]. Further compounding the problem, with annual mean GDP per capita in the range of $2000 in much of the north and east, many cannot afford to pay for service, resulting in very low levels of access in addition to rampant theft, as shown in Figure 1.

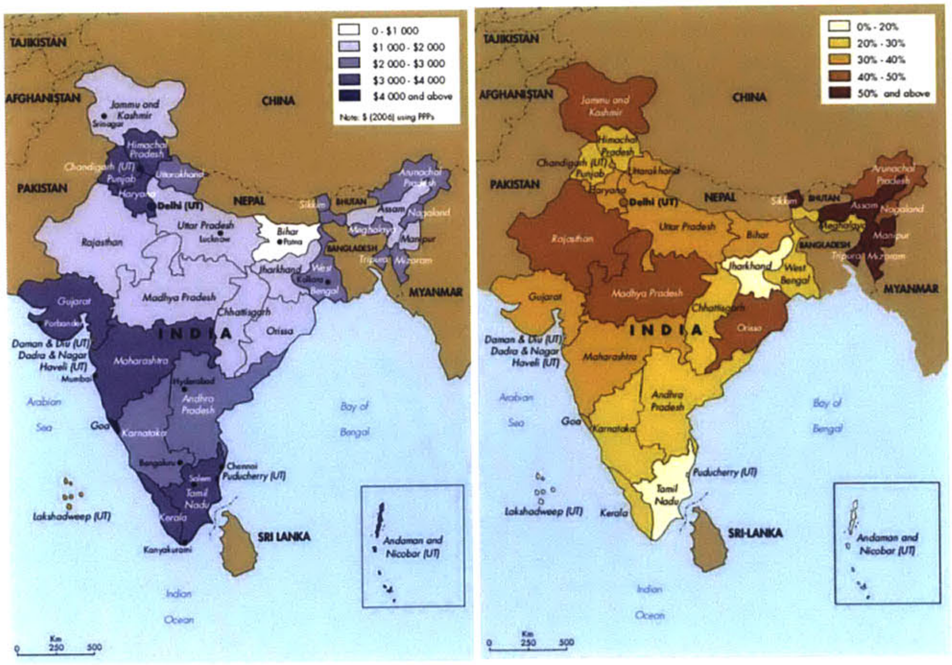

Figure 1: GDP per capita per state (left) and electricity losses by state (right)

Some Indian states, such as Punjab and Tamil Nadu, have implemented a policy of providing free, or very inexpensive electricity to farmers and Below Poverty Line (BPL) households. Such policies are paid for by substantial taxes on industrial and large commercial consumers, which discourages development of industry in these areas [2] and contributes to the perpetuation of regional poverty as industry and jobs migrate to states with less expensive power, and lower rates of poverty [17].

Recent studies have noted that, due to political interference at the state level in the setting of tariffs, the average farmer pays just 10% of the cost of supply, while the average residential consumer pays only 60%. With too few large customers to subsidize agricultural and residential consumption, many power producers and distributors are insolvent [2] and unable to access wholesale markets reliably, leading to a downward spiral in quality of service, and further discouraging investment in the industrial sector [17]. It is in this context that the government of India has launched several ambitious electrification initiatives in recent years.

Indian policies and programs for rural electrification

There has been much debate in the Indian government over the definition of "electrified" over the years, with significant implications for the official statistics and data used to craft new policy measures. Prior to 1997, a village was considered electrified if electricity was used for any purpose whatsoever anywhere within the revenue collection area of the local government. From 1997-2004 that definition was modified to specify that the electricity be used "within the inhabited locality" of the local revenue collection area. Recognizing that the previous definitions were inadequate in practical terms, in 2004 the definition was been further refined to specify that:

1) "The basic infrastructure [is made available at]... any of the public place like schools, Panchayat Office (village council), health centres, dispensaries, community centres, etc., and
2) The number of households electrified should be at least 10% of the total households in the village." [18]

These changes resulted in a massive increase in the official count of un-electrified villages, and in 2005 prompted policy makers to launch the Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY) scheme, a program designed to provide complete electrification of the country by the end 2009 [19]. Under RGGVY, the objective was to "electrify the 125,000 villages still without electricity; to connect all the estimated 23.4 million households below the poverty line with a 90% subsidy on connecting costs granted by the Ministry of Power, and finally, to augment the backbone network in all 462,000 electrified villages" [18]. This proved to be an optimistic target, and by 2008 it was apparent that the goal would not be met; a continuation of the program was announced and the deadline was pushed back to 2012 [20]. As of the time of this writing, it seems highly likely that the objectives of RGGVY will not be met, and the deadline will be extended yet again. The reasons for the difficulties implementing the RGGVY scheme are the subject of debate, but basic problems such as limited financial support from the federal government and some cases accusations of corruption and fund mismanagement have been widespread [2], [21], [22], [23]. At the state level there have been difficulties with land acquisitions for distribution substations, as well as with overcoming local objections to the clearing of forests for transmission lines, and with obtaining the authenticated lists of BPL households necessary to secure federal funding [2].

The RGGVY scheme primarily aims to provide electrification through grid extension, but there is a provision for Decentralized Distributed Generation (DDG) systems based on conventional fuel sources (typically diesel generators) where grid connections would be too expensive, or are not technically feasible. In addition to grid extension and distributed generation under the RGGVY scheme, the Remote Village Electrification (RVE) Program implemented by the Ministry of New and Renewable Resources (MNRE) has been providing basic lighting and electricity service from renewables, primarily in the form of solar PV systems [24]. While the RVE program is ostensibly promoting "the most appropriate technology through the identification of locally available energy resources", nearly 95% of the villages under program that have been electrified were provided with solar home lighting systems with a 90% capital subsidy from the MNRE [25]. To avoid a duplication of resources and effort, villages of over 300 inhabitants are typically addressed through DDG projects under the RGGVY scheme, while smaller villages are served through the RVE program. According to MNRE's strategic plan for 2011-2017, the RVE program is targeting the electrification of 10,000 villages and the distribution of 20,000,000 solar lighting systems by the end of 2017 [26].

Alternative methods of electric service

So far, we have summarized the importance of electricity in achieving broader development goals, examined the state of electrification in India and the challenges of operating the grid there, and outlined several major programs that are currently in place regarding rural electrification. The ultimate objective of this work is to explore alternative models of electrification in rural India, and examine their technical and economic viability and competitiveness with each other through quantitative modeling. The meaning of "electrification" here is slightly fuzzy, and as noted in the discussion of the status of the Indian grid, the definition is important in order to define metrics and track the progress of programs. There are many unresolved questions. If 10% if the homes in a village (as required by the most recent RGGVY definition) are connected to 120/220V AC service, is that village really "electrified"? Do the connected households have the appliances and other powered devices they would need to benefit from electric service? If, as the evidence in India indicates, the service is subject to frequent blackouts, will electrification provide the intended catalyst for development? If there is no guaranteed minimum demand, is there any incentive for distribution companies to expand and maintain infrastructure beyond government mandates? A comprehensive analysis of these questions is beyond the scope of this work, but these questions clearly must be addressed.

Policy makers and private companies typically conduct assessments of the viability of electrification efforts under the assumption that the electric grid should provide the high level of reliability and load service of developed countries [27]. This emphasis on a high level of service often results in costly over design and can make electrification programs economically unviable. Electrification systems designed to meet social objectives (i.e. those that target poverty reduction or improved quality of life for base of pyramid residential customers) suffer fewer penalties associated with under-design, because these goals may still be achieved even if the electricity service has less than the 99.9% reliability that is typical of most developed countries [27]. Simply put, in rural India, and in other developing country contexts, residential electricity users can tolerate much lower levels of service and still derive enormous benefits in terms of education, income generation, and security [8]. The question thus becomes one of how to meet a level of demand consistent with *newly electrified rural customers* cost effectively.

Recent work relating to demand assessment has attempted to create "bottoms up" models of energy use that take into account geographic, social, and economic factors facing individual households [28], [29], [30]. One author in particular [30] notes that total household energy use in India is almost completely dominated by cooking, and it is highly unlikely that electric cook stoves will be taken up in large numbers due to the high upfront costs, frequent power cuts, and wide availability of inexpensive biomass. In [29], the authors project electricity demand out to 2050 and note that the major drivers of electricity demand for India are lighting, cooling, and appliances. While much of the growth in electricity consumption in later years of the model is attributed to televisions and refrigerators, lighting and space cooling dominate projections for short-term electricity demand [29]. Rural electric consumption in India is projected to increase roughly 500% by 2050, but the projected annual consumption of 250 kWh per capita at that time is still extremely low by western standards [28]. These findings suggest that electrification systems designed to deliver sufficient power for appliances and other energy intensive devices are unlikely to see enough demand to make them economical until well into the future.

Furthermore, evidence from the National Electrification Program in South Africa suggests that the growth of electricity demand there was slower and more uneven than expected at the outset of the program. The authors of important studies analyzing the effectiveness of these programs [31], [32] note that while the plan was successful in providing nearly universal access, after several years it was found that electricity consumption among the majority of low-income households remained near 50kWh per month, despite initial projections showing an increase to approximately 350 kWh/month. Further analysis indicated that low-income South African households are very price sensitive, and consequently, the cost of appliances, availability of affordable credit, and electricity tariffs all had a significant impact on demand growth. In particular, the authors also noted that the Electricity Basic Services Support Tariff, which provided for 50 kWh/month free of charge, had the effect of severely limiting the growth in demand that might have otherwise taken place [31]. On the basis of this experience, it seems clear that demand for electricity in rural India will grow, but the experience in South Africa suggests that the combination of economic, social, and government policy factors that impact this growth are difficult to predict. In the face of such uncertainty, one has to question the logic of investing in costly infrastructure designed to support a level of demand that may not appear for many years.

Research objective

In this study, we are primarily concerned with the provision of basic services such as mobile phone charging and lighting, which have been shown to improve quality of life and are not especially energy intensive [7]. This is in stark contrast to the use of electricity for cooking, irrigation, powering machinery, refrigeration, or heating and cooling (except via small fans where applicable). In addition, our focus is on the delivery of services to small villages (defined as less than 300 people) where the extension of the grid and distributed generation using traditional means (diesel generators, etc.) is likely to be cost prohibitive. This is directly comparable to the services provisioned though the RVE program, which focuses on (subsidized) solar home systems and solar lanterns. There are at least 10,000 villages that would fall within the RVE scheme, or up to 3 million people [25].

By focusing on the provision of specific, minimal residential services (evening lighting and phone charging), rather than of power, our intent is to draw attention to schemes whose design may be much simpler, and therefore less costly, than one designed with more general use in mind. The economic value of such services may be very low, or at best unreliable in comparison with other services that would enable commercial activities, small scale industry, the provision of education and health services, street lighting and so on; however, the cost of providing such services increases very rapidly with peak demand, and may be far out of reach for consumers who would derive much personal benefit from minimal services, and attach some level of value to them. The considerable uncertainty in demand and growth that leads to over-specification of peak service capacity for microgrid and grid extension projects (an important determinant of system cost) is also a less important factor for systems designed to provide minimal service because they make use of a narrow range of fixtures and appliances with well-known power requirements, usage patterns, and costs.

The specific aim of this study is to present a technical-economic analysis of a DC solar micro-grid (wherein a single photovoltaic panel and battery bank is used in conjunction with household wiring and distributed lights and mobile phone chargers to provide service to an entire village), and compare that system to the *de facto* standard for small village electrification under RVE: the solar home lighting system. We will start with a technical model for the microgrid, then expand it to include cost modeling and basic component optimization, and finally simulate a full business model that incorporates financing, operations, maintenance, and other costs. By exploring the sensitivity of different technical and economic parameters, we can gain insights into the viability of a hypothetical business that owns and operates such microgrids and assess the strengths and weaknesses of the DC solar microgrid compared to the alternatives. The emphasis of this analysis is on the operational and maintenance constraints of operating in the rural Indian context, and the assumptions in the model have been validated through extensive interviews, field study, and data provided by private companies operating in the space. The final chapter will compare the levelized cost of service for a DC microgrid and a comparable SHS business from a full life cycle perspective. The objective is to provide a tool to guide decision making about the most efficient allocation of capital for policy makers, NGOs, and others involved in the financing of international development.

Chapter 2: Literature review

As noted in [33], the electrification efforts under the RVE program have taken the form of either SHS (typically a single 12 or 24V battery connected to one or more CFL or LED lights, along with a small PV panel and charge controller) or PV powered AC microgrids (wherein a centralized bank of panels and batteries is connected to a low voltage AC distribution system (110/220 V) and inverter, providing AC service to the customer). All systems for electrification have relative strengths and weaknesses, so no design is appropriate for all scenarios. As such, it is useful to touch upon the findings of previous studies regarding both the SHS and AC microgrid before analyzing the DC microgrid in later chapters. The primary benefit of both SHS and PV microgrids is that there is abundant sunlight in many un-electrified regions, meaning there is "free fuel" and much lower operating costs compared to diesel generators, biofuel reactors, etc. [34].

The potential advantages of solar home lighting systems as a means of providing basic service are considerable, and the technology has been of interest to many academics. Among the benefits noted in the literature are:

- Ease of distribution/installation as compared to extending grid connections or building AC microgrids [35]
- Ease of maintenance and operation as compared to diesel generators, etc. [36]
- There are stable loads and fewer problems with theft because SHS are owned by individual households as compared to whole communities [33]
- The low cost provision of basic services like lighting by SHS can encourage growth of demand that is necessary to make grid extension economical [37]

While these positive attributes are attractive, SHS in general have a number of drawbacks:

- Continuous charging/discharging of batteries strains battery lifetime and appropriate replacements may not be locally available [38]
- Execution of maintenance is more difficult as compared to microgrids due to the distributed nature of the systems [33]
- There is widely varying quality of design and construction with different components and manufacturers (i.e. CFL vs. LED lighting, etc.) [39]

- Relatively high upfront costs due largely to PV panels and batteries [34]. This is compounded by the fact that the panels and batteries in SHS are typically quite small and have higher normalized costs (i.e. $\$/W_p$ for solar panels) than for larger systems
- SHS have limited potential to meet long term trends in demand as DC devices are not universally available for all functions [37]

In contrast, the AC microgrids studied in the literature have been noted as having the following strengths in general:

- Relatively simple maintenance and lower operating costs due to the centralized nature of the system [40], [41]
- Ability to support a much greater range of functions such as irrigation pumping, powering machinery, air conditioning, refrigeration, etc. [41]

The noted weaknesses of PV AC microgrids relative to alternatives include the following points:

- High capital cost [41]. This is driven by the cost of inverters and power distribution networks, which are unnecessary with SHS.
- Because they provide an AC outlet, there is a risk of inefficient end devices being used, causing large deviance from the expected load profile [42]. This is particularly true when CFL lights are replaced with incandescent light bulbs; unfortunately a common occurrence due to the wide availability and relative cheapness of incandescent bulbs compared to LEDs or CFLs [33].
- Unmetered electricity consumption at individual households can lead to increased load and faster than anticipated battery degradation [40].
- Despite the modularity of PV panels and batteries, AC microgrids can be inflexible to demand increases as power electronics and distribution networks must be upgraded [40]

One recent study explicitly compared the PV AC microgrid and SHS from both a technical and economic perspective and showed that, over the full life cycle of both systems and for a household load of 18W operating 4 hours daily, an AC microgrid would require more than 180 closely spaced customers in order to be cost competitive with SHS [42]. Others have tracked both SHS and microgrids as installed under RVE in the state of Bihar and found that "twice as many SHS households as compared to microgrid households had at least one broken light, and the lights had been broken on average five times longer. The difference in maintenance structure between SHS and micro-grid villages thus makes a difference" [33]. The same study also noted considerable problems with capacity utilization in micro grids, and noted that as consumers change from CFL to incandescent bulbs the actual utility of the system (as measured in lumen-hours of lighting service) declined drastically over time [33]. This capacity degradation is not seen in SHS because the DC appliances are not easily replaced with cheaper and less efficient alternatives.

An important conclusion of [43] is that partnerships with local entrepreneurs and SMEs greatly increases the effectiveness of both SHS and microgrids as a means of electrification, because these partnerships provide a local party who is responsible for the execution of operational and maintenance activities. This in turn increases the willingness of rural customers to pay for service, because there is increased transparency and accountability in the operation of the system. Systems developed in partnership with a local entrepreneur are also more likely to be upgraded as demand grows over time [43]. In [44], the authors note numerous problems associated with the common practice of providing capital subsidies for end user ownership of solar lanterns; in particular noting that there is less of a sense of ownership when systems are provided at nearly zero cost to the end user. The same study analyzed a rental/fee for service model of SHS distribution and compared the costs (for both an entrepreneur and end user) to those costs in an SHS ownership scenario. This study found that while there are benefits to rental/fee for service in terms of longevity of devices (because maintenance burden is shifted to local entrepreneurs who have more incentives and ability to repair/replace equipment as needed), an entrepreneur would a require a minimum daily rental fee of Rs 3.33 to profitably support rental of 2.5W LED lanterns to 50 customers [44]. This figure exceeds the calculated daily cost of Rs .95 for owning a similar lantern, leading the authors to conclude that customers would be unwilling to pay for such a service [44].

The results of this literature review point to the general conclusion that SHS are attractive because they are easy to distribute, have low upfront costs, and have no problems associated with unanticipated demand because their DC output limits possible loads. The major downside of the SHS is maintenance; replacements are generally not available and end users lack the technical expertise to make repairs. The decentralized nature of SHS also makes maintenance much more difficult for qualified technicians. The rental/fee for service model solves many maintenance problems, but at least one study suggests that the rental fees necessary to support the entrepreneur running such an operation are too high to be commercially viable. In contrast, PV AC microgrids can provide much greater utility to end-users and suffer from fewer maintenance problems due to their centralized nature. However, these systems are much more costly and technically sophisticated, requiring significantly more technical expertise to service. The PV AC microgrids that have been installed under RVE have also suffered from unanticipated loading and degradation of service over time, as inefficient loads like incandescent bulbs are added to the network.

All of the above conclusions point towards a different model of electrification: the fee for service PV DC microgrid. By combining the attributes of these different systems and leveraging the relative strengths of each (simple DC loads, centralized equipment, and fee for service operation), it appears on the surface that such a system may provide an equivalent level of service to SHS, but at a lower cost. In the chapters that follow, we will examine such a system from both a technical and economic perspective, before presenting a direct comparison to the SHS.

Chapter 3: Technical and economic models of a solar powered DC microgrid

The system we will analyze in this work is a fee for service DC microgrid powered solely by PV panels. It is loosely based upon the model that is currently being implemented by Mera Gao Power in the villages surrounding Reusa in the northeast region of Uttar Pradesh. Mera Gao is a privately owned company that currently operates similar microgrids in 380 villages, and is rapidly expanding [45]. Many of the parameter values (in both the technical and economic models) have been provided directly from interviews or email communications with the founders of Mera Gao and other companies operating in the space.

As mentioned previously, the technical system consists of a simple bank of batteries and PV panels that are connected through a charge controller to a low voltage (12 or 24V DC) distribution network. The distribution network can consist of up to three distribution lines (depending on the size and physical layout of the village) that extend from the battery bank towards the customers, each of whom is provided with two 1W LED bulbs and a step down converter that can be used to produce a 5V output for charging a mobile phone. The distribution network has a simple light activated switch that applies power when the sun goes down, allowing the customers to use the system continuously throughout the night. In addition, the current on each distribution line is monitored and the service is interrupted if the load exceeds a set point (which depends on the number of customers on each line). This is important for safety (fault detection), but also serves as a mechanism to prevent unauthorized loads from being added to the system (i.e. theft of electricity). The charge controller provides maximum power point tracking for the PV panels, and also prevents the batteries from being over charged or discharged.

The customers are provided with the LED bulbs and phone charger and any replacements free of charge, but the company operating the grid owns all of the hardware in the system. Customers pay a one-time connection fee, and a flat monthly service fee thereafter regardless of their individual electricity consumption.

This work will use Monte Carlo simulations to assess the impact of various uncertainties on both the technical and economic performance of the system. We start with the technical model, which outputs technical performance metrics and other parameters that impact system cost such as battery and PV capacity. These technical outputs are then fed into a set of cost models for the major components (battery and PV panels). The resulting system Cost of Goods Sold (COGS) is then used, among other inputs, in the business model. The economic analysis uses the COGS to estimate replacement costs over the lifetime of each component, and incorporates other costs such as maintenance, financing, and G&A administrative costs. The economic model also uses the fee for service scheme described above to calculate revenues for each installed system based on the number of customers served. The evolution of cash flows over time is subjected to standard discounting to evaluate the net present value of the enterprise for a given set of input parameters. The overall analysis procedure is outlined in Figure 2 below.

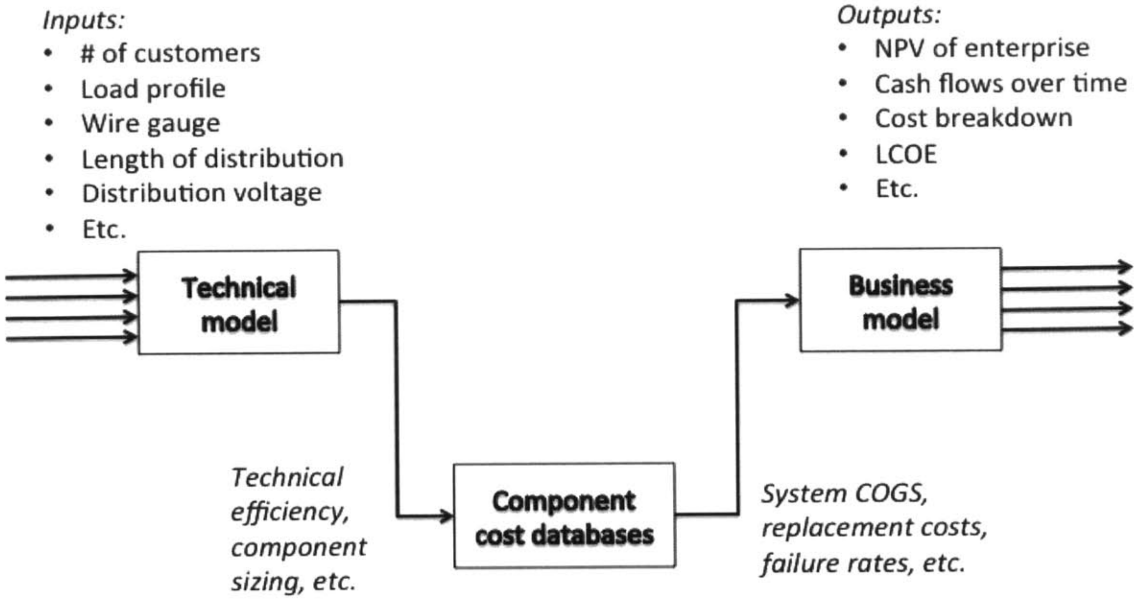

Figure 2: Analytical framework for modeling

Description of technical model of a solar powered DC microgrid

The technical analysis begins by fixing the constraints of the system and setting up the initial distribution of customers along each distribution line. Each distribution line is a given length (specified during initialization), and customers are placed at random positions along the line. In the base scenario, the load at each customer is drawn from a random binomial distribution, with a value of either 2W (representing two LED lights) or 5.33 W (representing two LED lights plus a mobile phone charger). Figure 3 below illustrates the initialization of the model.

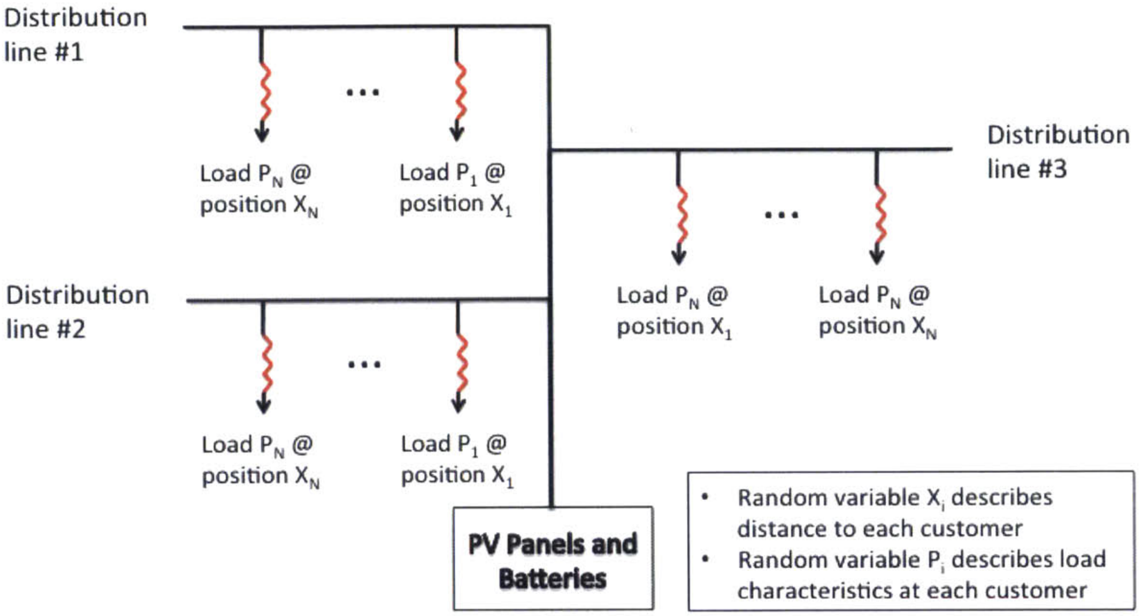

Figure 3: Initialization of the technical simulations

The user can simulate between one and three distribution lines, each of which is initialized in a similar fashion. The user also selects the wire gauge of the distribution line (assumed to be solid copper wire), from which the total resistance to each customer is calculated. The current to each customer, I_i, and total distribution losses, L, are then are then calculated as:

$$I_i = \frac{P_i}{V_D}$$

$$L = \sum_{i=1}^{N} I_i^2 * R_o * X_i$$

Where R_o is the resistance per foot of the wire gauge selected, and X_i is the position (measured in feet from the battery bank) of the i^{th} customer along the distribution line, P_i is the load at the i^{th} customer, V_D is the distribution voltage, and N is the total number of customers.

The total power delivery requirement of the system, P_T, and the distribution efficiency η_d are defined as:

$$P_T = \sum_{i=1}^{N} (P_i + L_i)$$

$$\eta_d = \frac{\sum_{i=1}^{N} P_i}{\sum_{i=1}^{N}(P_i + L_i)}$$

The total battery capacity, C (measured in amp-hours), and solar panel size, PV (measured in watts-peak) requirements are calculated as in [42] as:

$$C = \frac{P_T * h_l}{MDOD * \eta_b} * D$$

$$PV = \frac{P_T * h_l}{\eta_{cc} * \eta_b * (1 - PV_t) * (1 - PV_d) * (1 - PV_m) * EHFS}$$

Where h_l is the number of hours of load daily, $MDOD$ is the maximum depth of battery discharge allowed by the charge controller, D is the number of days of battery capacity (assuming no sunlight), η_b is the full cycle charging-discharging efficiency of the battery, η_{cc} is the efficiency of the charge controller, PV_t is the PV panel loss due to temperature, PV_d is the PV panel loss due to dust, PV_m is the PV panel loss due to mismatch, and $EHFS$ is the average hours of full sunshine daily.

A summary of the default values for each of the technical parameters is given in Table 1 below:

Distribution Parameters:	Value:	Units:	Notes:
Wire gauge:	16	*AWG*	
Resistance, R_o:	6.59	*mOhm/ft*	
Length of distribution wire:	1000	*ft*	
Number of customers, N:	30		
Number of distribution wires:	2		
Distribution voltage:	24	*Volts*	
Load Parameters:			
LED load:	2	*Watts*	
Phone charger load:	2.5	*Watts*	500mA charging at 5V
24->5V converter efficiency:	75%		
Hours of load daily, h_l:	5	*Hours*	
Battery Parameters:			
Battery charge efficiency, η_b:	85%		Reference: [42]
Maximum depth of discharge, MDOD:	70%		Reference: [42]
Days of battery capacity, D:	2	*Days*	Reference: [42]
Solar PV Parameters:			
Charge controller efficiency, η_{cc}:	85%		Reference: [42]

PV loss from temperature, PV_t:	10%		Reference: [42]
PV loss from dust, PV_d:	10%		Reference: [42]
PV loss from mismatch, PV_m:	10%		Reference: [42]
Equivalent hours of full sun, EHFS:	5		Reference: [42]

Table 1: Default values for all technical model parameters

Each simulation run consists of 1000 instantiations of the technical model, and the results are accumulated into cumulative distributions that capture the uncertainty from the random variables describing customer placement and load. The purpose is to avoid designing for the corner case where all customers are at the end of the line and every phone is charging simultaneously; this case is unrealistic and would force us to over-specify the battery and PV capacity, driving costs unnecessarily high. By examining the cumulative distributions, we can design for any level of service reliability and choose an optimum tradeoff between cost and service. A sensitivity analysis of the variables that drive the performance metrics (efficiency, capacity) and system cost (and, by extension, the viability of the enterprise) will be presented in the following chapter.

COGS models of microgrid components

Each instance of the technical model results in a specification of battery capacity, solar panel capacity, and calculations of metrics like distribution efficiency and total load as defined above. The capacity specifications are fed into simple cost models for PV panels and batteries that approximate the nonlinearity of normalized prices (i.e. \$/Watt peak for panels and \$/W-hr for batteries) as a function of component size. These models were developed by assembling databases of prices for components of various sizes from online retailers. The simplified cost models do not account for phenomena like regional pricing differences, exchange rates, transportation costs, etc. A best-fit regression is derived from each component cost database, which is then used to approximate component cost for the capacity specification as determined by the technical model. The PV panel and battery cost models are shown in Figures 4 and 5 below.

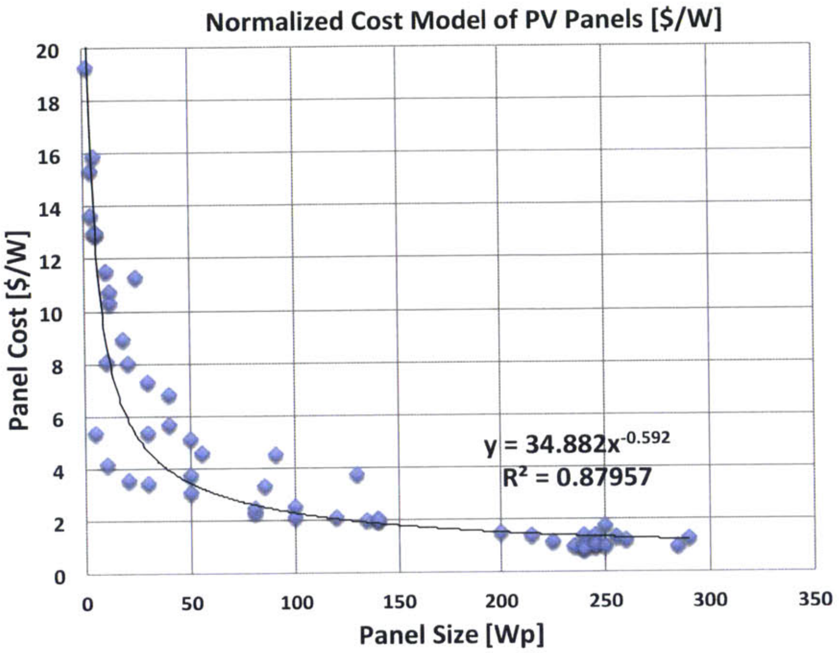

Figure 4: Cost model for solar panels

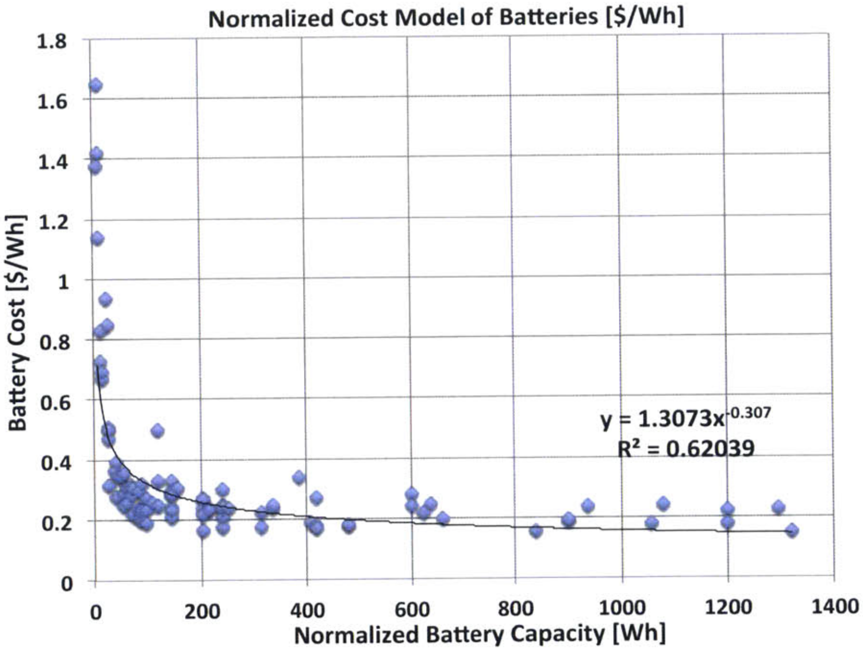

Figure 5: Cost model for batteries

The cost of PV panels and batteries are approximated as:

$$C_{pv} = 34.882 * PV^{-.592}$$

$$C_{bat} = 1.3073 * BAT^{-.307}$$

Where *PV* is the panel capacity (in watts-peak), and *BAT* is the battery capacity (in watt-hours), and the coefficients in the equations are derived from the best fit regressions of the component cost data as noted above. The final system COGS is given by:

$$COGS = C_{pv} + C_{bat} + N * (C_{LED} + C_p) + W_o * L + C_{cc} + C_{BOS} + C_{trans}$$

Where C_{LED} is the cost of each LED lighting fixture, C_p is the cost of each mobile phone charger, W_o is the cost/foot of distribution wire, L is the total length of distribution wiring, C_{cc} is the cost of the charge controller, C_{BOS} is the "balance of system" cost (covering small items such as mounting hardware for panels, enclosures, etc.), and C_{trans} is the cost of transportation to get components from supply centers to the villages where they will be installed. The cost of lighting fixtures, phone chargers, wiring, charge controllers, and transportation were set based on interviews with Mera Gao and their practical experience with sourcing similar components in India. A summary of cost parameters is presented in Table 2 below.

Cost Parameters:	Value:	Units:	Notes:
Wiring cost, W_o:	$.1	*$ (US)/foot*	
LED cost, C_{LED}:	$2	*$ (US)*	2x 1W, 12V LED modules
Phone charger cost, C_p:	$1.5	*$ (US)*	
Charge controller cost, C_{cc}:	$75	*$ (US)*	
Balance of system cost, C_{BOS}:	$50	*$ (US)*	
Transportation cost, C_{trans}:	$50	*$ (US)*	

Table 2: Other component costs for microgrid COGS model

In addition to the initial calculation of system COGS, each of the component costs is used to calculate replacement costs as the systems are deployed and require maintenance.

Description of the economic model of a microgrid enterprise

Revenues, maintenance (replacements, employee salaries, etc.) and administrative costs (fixed costs, collections agent salaries, etc.) are calculated on a monthly basis as the enterprise installs new systems, collects revenue from customers, pays employees, and incurs other expenses. The net income (revenue minus all expenses) in each month over a ten-year period is then discounted assuming a 10% discount rate to arrive at a net present value (NPV). By examining the sensitivity of the enterprise NPV to changes in various parameters we can determine the drivers of economic viability for this hypothetical business. We can also use the NPV calculation to derive a "levelized cost of service" (LCOS), or the minimum monthly fee that must be charged for the enterprise to break even (i.e. NPV=0). It is on the basis of LCOS that we can compare the competitiveness of the DC microgrid to alternatives such as SHS.

Replacement costs and component lifetimes

To estimate replacement expense each month, each system component is assigned an average lifetime, *MBTF*, (in months) and the total replacement cost is given by:

$$E_{replacement} = N_{sys} * \left(\frac{C_{pv}}{MBTF_{pv}} + \frac{C_{bat}}{MBTF_{bat}} + \frac{C_{cc}}{MBTF_{cc}} + \frac{C_{w}}{MBTF_{w}} + \frac{C_{load}}{MBTF_{load}}\right)$$

Where N_{SYS} is the total number of installed microgrid systems (cumulative), $MBTF_{pv}$ is the PV panel lifetime, $MBTF_{bat}$ is the battery lifetime, $MBTF_{cc}$ is the charge controller lifetime, $MBTF_{w}$ is the distribution wiring lifetime, and $MBTF_{load}$ is the lifetime of LED light fixtures and mobile phone charger loads. A summary of the component lifetime assumptions is shown in table 3 below.

Component Lifetime:	Value:	Units:	Notes:
Lifetime of batteries, $MBTF_{bat}$:	36	*Months*	
Lifetime of PV panels, $MBTF_{pv}$:	240	*Months*	
Lifetime of charge controller, $MBTF_{cc}$:	120	*Months*	
Lifetime of distribution, $MBTF_{w}$:	60	*Months*	
Lifetime of load devices, $MBTF_{load}$:	36	*Months*	

Table 3: Default assumptions of component lifetimes

Operations and maintenance costs: worker salaries

In addition to incurring initial hardware cost for new systems and replacements for all systems deployed to date, the DC microgrid utility must hire and pay workers to install new systems and perform maintenance on existing installations ("field crews"), workers to collect payments from customers ("collections agents"), and regional managers to coordinate the activity of lower level employees. Field crews and collections agents are assumed to work in pairs, and each team is responsible for covering a quota of microgrid systems each month. The growth of the employee base occurs as the enterprise expands and installs microgrids in new villages; staffing levels and salary expenses accrue in proportion to the growth in the installed base of systems. The enterprise will employ one senior executive who is responsible for the overall expansion and management of the organization. As new systems are installed and the organization serves a larger geographical area, regional offices will be opened and staffed by one regional manager and the field crew and collections agents necessary to support that area. The regional offices also serve as holding points for inventory (to be used in new installations and for replacements). Worker salaries are low by western standards, but as noted in [2] GDP per capita in the Indian states where the enterprise would likely operate (Uttar Pradesh, Bihar, Rajasthan, Madhya Pradesh, Chhattisgarh, etc.) is below $2000 annually, making the salary assumptions regionally appropriate. Salary assumptions and staffing levels are also validated through observation of Mera Gao's operating experience running a similar enterprise. A summary of salary assumptions and growth rates is given in Table 4. In the next chapter we will explore a range of values for these parameters to determine their sensitivity on the model outputs.

Salary assumptions:	Value:	Units:	Notes:
Field crew salary, S_f	2400	*$ (US)*	Annual
Collections agent salary, S_c	2400	*$ (US)*	Annual
Regional manager salary, S_m	4800	*$ (US)*	Annual
Executive salary, S_e	70,000	*$ (US)*	Annual
Salary overhead, S_o	1.3		Assume 30% overhead on all salaries for taxes, etc.
Field crew monthly maintenance quota, Q_f	15	*Microgrid systems*	Each crew member is responsible for 15 villages
Collections agent monthly quota, Q_c	15	*Microgrid systems*	Each crew member is responsible for 15 villages
Number of employees per regional manager, Q_m	20	*Employees*	

Table 4: Default salary and employee growth assumptions

In any given month, the total operating/salary expense is given by:

$$E_{ops} = (n_f * S_f + n_c * S_c + n_m * S_m + n_e * S_e) * S_o$$

Where n_f is the total number of field crew employees, n_c is the number of collections agents, n_m is the number of regional managers, and n_e is the number of senior executives employed by the enterprise at that time. As described above, employees are added in step with the addition of new microgrid systems:

$$n_f = [N_{sys}/Q_f];\, n_c = [N_{sys}/Q_c];\, n_m = [(n_f + n_c)/Q_m];\, n_e = 1$$

For every 150 new villages that are served, a new regional office will be opened which will serve as a headquarters for that region's operations as well as a storage location for spare parts and other inventory. Each regional office is assumed to have several fixed costs associated with its operation, as summarized in Table 5:

Fixed G&A assumptions:	Value:	Units:	Notes:
Travel expense, F_t	1200	*$ (US)*	Annual
Rent expense, F_r	1200	*$ (US)*	Annual
Legal expense, F_l	1200	*$ (US)*	Annual
Miscellaneous expense, F_m	240	*$ (US)*	Annual
Scale factor for new offices, N_o	150	*Systems per office*	Number of villages administered by each regional office

Table 5: G&A cost assumptions for regional offices

The total general and administrative (G&A) expenses are given by:

$$E_{G\&A} = \frac{N_{SYS}}{N_o} * (F_t + F_r + F_l + F_m)$$

Revenues for the DC microgrid enterprise

Under the default scenario of the simulation, customers are charged a one-time connection fee of $2 and pay a monthly service fee of $2 for each connection. These are the actual fees charged by Mera Gao, and were arrived at through price experimentation and analysis of customer willingness to pay. For villagers, the lighting and mobile phone charging services provided by the DC microgrid enterprise are replacing traditional means of meeting those needs; namely by offsetting the purchases of kerosene for lighting, and by eliminating the need to travel to larger villages and pay micro-entrepreneurs with grid connectivity or solar home systems for phone charging. The monthly service fee is a critical parameter for the viability of the enterprise, and while a detailed analysis of the base value of \$2 is outside the scope of this work, it is a useful starting point that is grounded in the experience of Mera Gao. The \$2 connection fee is not critical to the viability of the enterprise, but serves as a disincentive to prevent villagers from signing up for the service and cancelling membership after a very short time. In later chapters we will use the service fee as a way to define the levelized cost of service and the levelized cost of energy for microgrid enterprises that offer a variety of service levels (i.e. higher levels of customer load). The enterprise revenues are given by:

$$R = N_{SYS} * N * P_m + N_{NSYS} * N * P_c$$

Where P_m is the monthly service price, P_c is the one time connection fee, and N_{NSYS} is the number of new systems installed in a given month.

Financing costs

Because the microgrid enterprise will incur the initial capital cost of each system, it is important to include a realistic model of financing the operation under different growth scenarios. Rapid expansion into new villages will be tend to be more capital intensive but will generate larger revenues quickly and hence will suffer less from discounting of future cash flows. Conversely, a gradual expansion into new villages will require less external capital as profits from the installed base can be directed towards the initial costs of new systems, but will push revenue growth into the future and suffer from greater discounting of those revenues. In order to estimate financing requirements, the economic model tracks monthly net income and also cumulative net income; the amount of external financing required is equal to the minimum of the cumulative cash balance over the 10-year period of the simulation. It is assumed that the enterprise will borrow money at the start of operations and accrue interest over 10 years, making a balloon payment of the principal plus all accrued interest at the end of the period.

The net income in month "*j*" is given by:

$$NI_j = R_j - \left(COGS * N_{NSYS_j} + E_{replacement_j} + E_{ops_j} + E_{G\&A_j}\right)$$

Where the monthly revenues and expenses are calculated according to the methodology detailed above. Cumulative profits in month "j" are given by:

$$P_{cumulative_j} = \sum_{i=1}^{j} NI_i$$

The financing requirement, *FIN*, is the minimum of all monthly cumulative profits over the 10-year operating period for the enterprise:

$$FIN = \min\left(P_{cumulative_j}\right)$$

Interest is compounded monthly and calculated as:

$$C_{interest} = \ FIN * ((1 + IR)^{120}) - 1)$$

Where *IR* is the effective monthly interest rate on borrowed capital. The default value of the interest rate is 5% annual for all simulations in this analysis. In the final month of the economic simulation, the microgrid enterprise incurs an additional expense of ($C_{interest}$ + *FIN*) as it repays the loan and all interest. In the next chapter we will explore the impact of higher interest rates for a variety of enterprise growth scenarios.

Enterprise growth and NPV calculations

We have now discussed in detail how system COGS, replacement costs, operations and maintenance, and G&A costs are modeled for the microgrid enterprise. Many of the costs in a given month are linked to either the number of new systems installed in that period (as one time expenses), or the cumulative base of systems that have been installed to that point (which determines how replacement costs, hiring, and G&A costs grow over time). We have also briefly discussed how the growth strategy for the enterprise can affect financing costs. The expansion to new villages is modeled using a geometric growth formula until the enterprise reaches a specified size, at which point the expansion stops. In month "i", the number of new systems installed, N_{NSYS_i}, and the total number of installed systems, N_{SYS_i}, are given by:

$$N_{NSYS_i} = N_{NSYS_{i-1}} * \ R$$

$$N_{SYS_i} = \sum_{j=1}^{i} N_{NNSYS_j}$$

Where *R* is the growth rate of the microgrid enterprise.

In the next chapter we will explore how the growth rate affects financing costs and net present value. The NPV of the enterprise is:

$$NPV = \sum_{i=1}^{120} {NI_i}\Big/{(1 + d)^i}$$

Where d is the discount rate applied to all future earnings and expenses. A summary of the default values of growth parameters and discount rates used for simulations are presented in Table 6.

Enterprise growth characteristics:	Value:	Units:	Notes:
Growth rate, *R*	10%		Monthly
Maximum number of villages, *M*	10,000		From RVE program targets
Discount rate, *d*	10%		Annual

Table 6: Default enterprise growth and NPV parameters

Chapter 4: Sensitivity analysis of DC microgrid enterprise

In the previous chapter we introduced and discussed in detail the technical and economic models describing our hypothetical microgrid company. In this chapter we will explore the tradeoffs between technical performance and costs and perform a sensitivity analysis on several parameters to determine the system performance over a range of operating conditions. As described above, the main output of the technical model is the distribution efficiency and PV panel/battery capacity required to meet a given load, and the main output of the economic model is the NPV of the enterprise over a 10-year time frame. For the purposes of discussion, we will define the "Levelized Cost of Service" (LCOS) to be the monthly service fee (P_m) required to achieve NPV = 0 for a given set of operating assumptions (having units of $/month). The associated "Levelized Cost of Energy" is then defined as the LCOS divided by the average energy consumed during a month ($/kWh).

The cumulative distributions for each output are based on a Monte Carlo simulation of 1000 instances of the model, where the positioning of customers on each distribution wire are random (leading to variability of I^2R losses) and each customer is randomly assigned a load of either 2W (representing 2 LED lights) or 5.333W (2 LED lights plus a mobile phone charger) with equal probability. The resulting variation in load gives the system designer the opportunity to design for any level of service reliability desired, but for simplicity we will generally consider the 50% point of each distribution when it is helpful to take a single value for an output (for instance, the LCOS is the monthly service fee to make the median NPV = 0). The outputs of both the technical and economic models for the default values of parameters (as described in the previous chapter) are presented below.

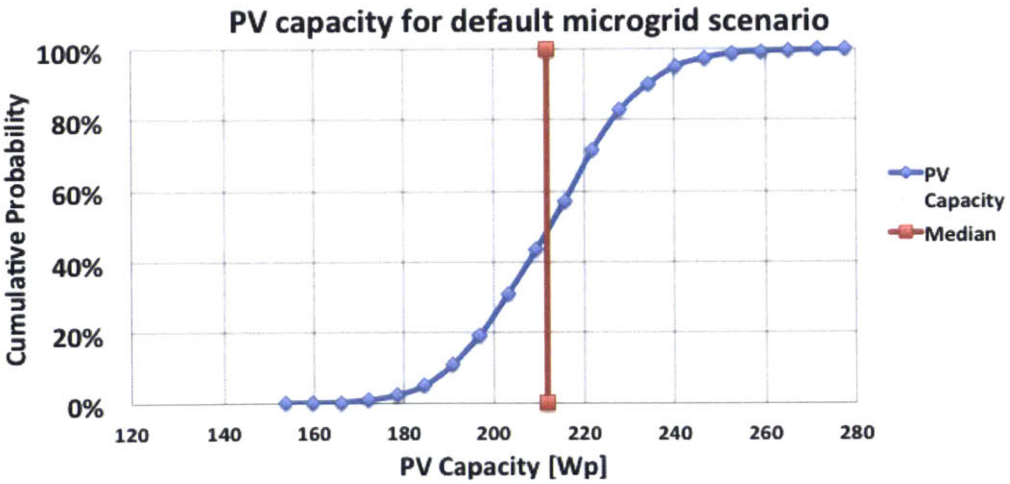

Figure 6: PV capacity distribution for default N=30 microgrid

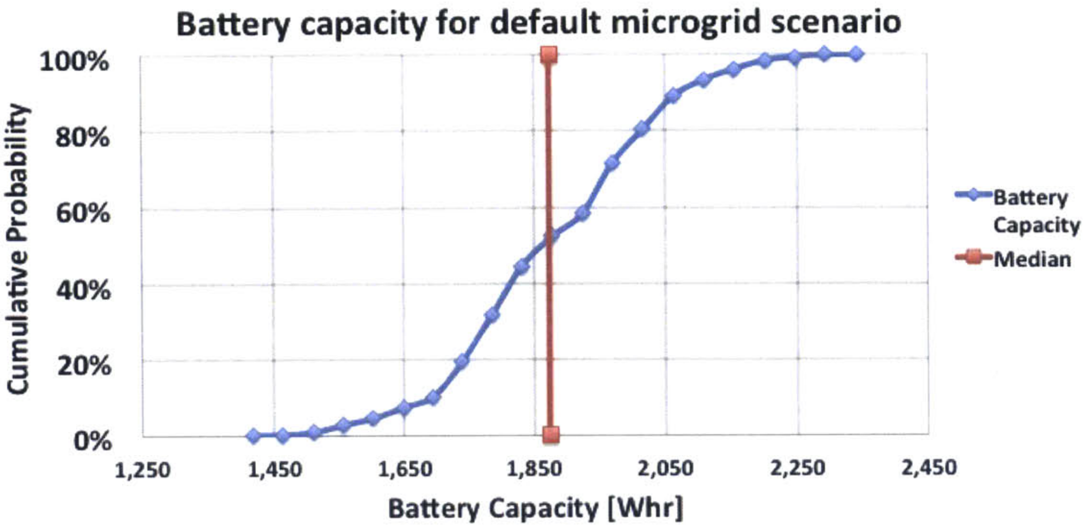

Figure 7: Battery capacity distribution for default N=30 microgrid

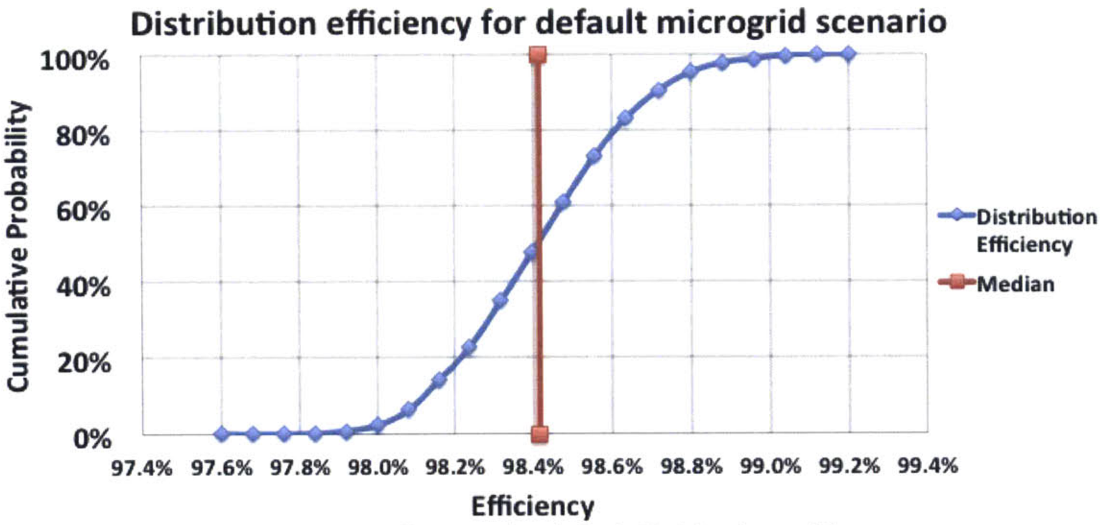

Figure 8: Simulated distribution efficiency for default N=30 microgrid

The resulting system COGS and a breakdown of COGS by individual component is presented in Figures 9 and 10.

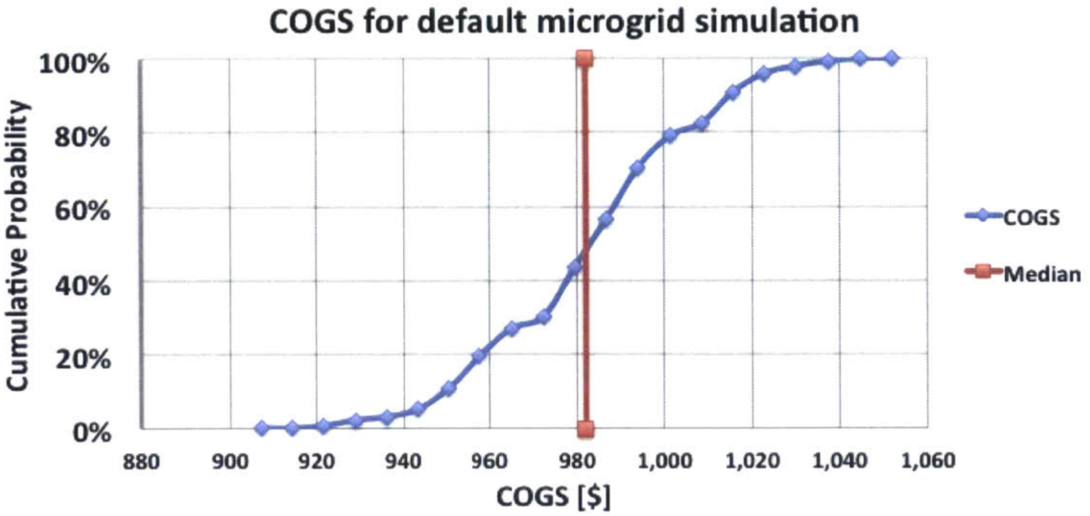

Figure 9: COGS model output for N=30 microgrid

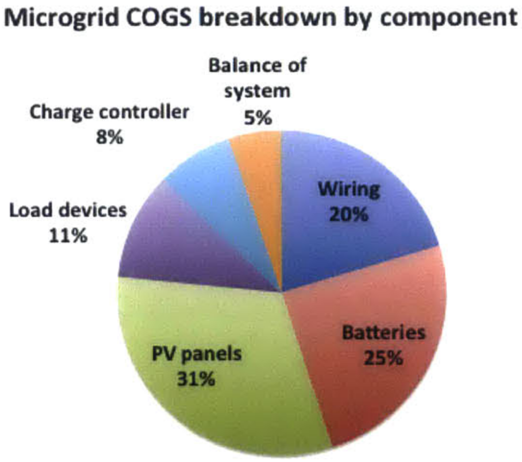

Figure 10: Breakdown of COGS by component for median N=30 microgrid simulation

For the microgrid enterprise, perhaps the most critical parameter is *N*, the number of customers served in each village (assuming one microgrid system is installed per village). This parameter is critical because it determines the sizing of components like batteries and PV panels (which directly impacts COGS), the revenue each system can generate (because each customer pays a flat monthly fee regardless of energy consumption), and the relative efficiency of the operations and maintenance field crews. The limiting factor for the productivity of field crews is the physical separation of the villages - each team can only realistically service the villages that are within a close proximity of their office, or else the majority of their time will be spent travelling from village to village rather than actually diagnosing technical problems and replacing broken components. The technical complexity of the microgrid system also does not increase as we add customers over the ranges examined in this work; it doesn't matter if there are 5 customers or 70, there is still one bank of batteries, one charge controller, one bank of PV panels, etc. We find that the percentage of total costs attributable to O&M worker salaries decreases steadily as the number of customers per village increases, because the fixed salaries of the workers get spread out over a larger number of customers at the same time that the installations get more expensive (and hence COGS and component replacement costs grow). In this context, the term "cost" means the net present value of each of the cost factors (worker salaries, interest due on financing, initial COGS of the microgrid installation, component replacements that occur over time, etc.) over the 10-year simulation. This effect is captured in Figure 11 below, where all model parameters are held constant except *N*.

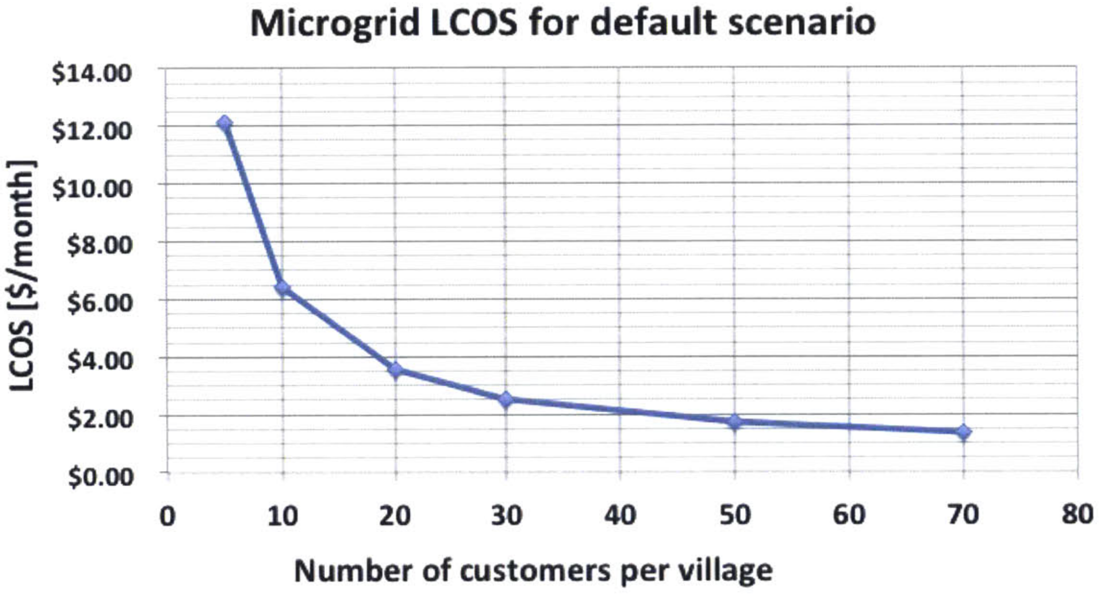

Figure 11: Levelized cost of service (LCOS) for various size microgrids, with all other parameters set to default values

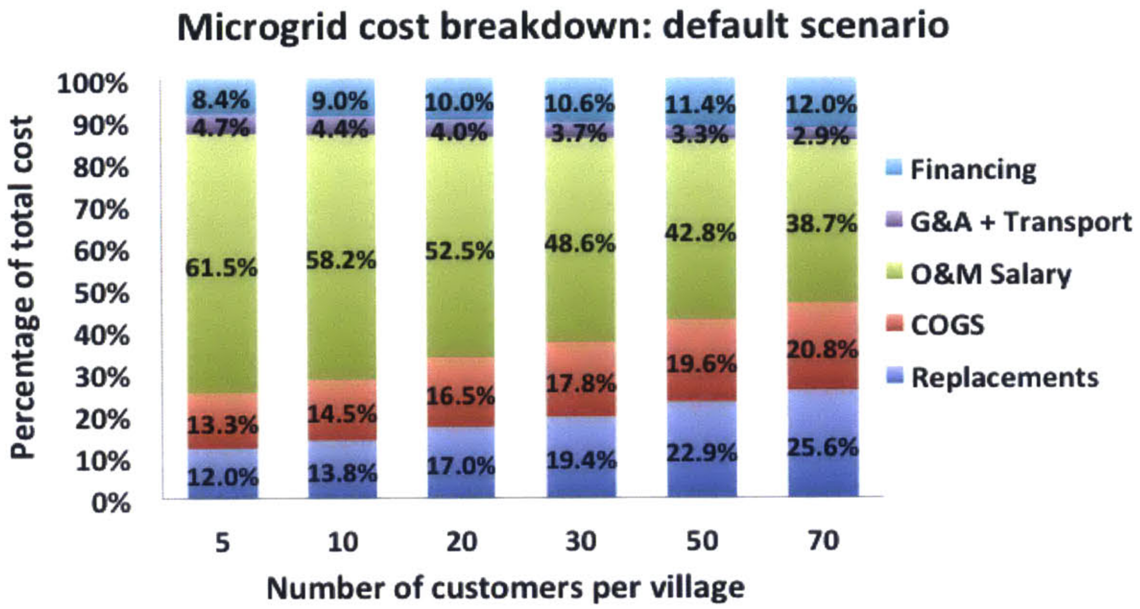

Figure 12: Breakdown of total microgrid costs by component

As the graphs above indicate, it is significantly more costly to serve a smaller number of customers with each microgrid system. There are several reasons for this. First, the aggregation of load pushes the design towards larger PV panels and batteries, which are significantly less expensive per unit of capacity than smaller components (see Figure 4). This effect is especially significant for the first 10 customers or so; once the panel size gets above ~100 Wp and the battery capacity exceeds 200 W-hr, normalized component prices level out. Second, with an increasing number of customers per village, the fixed salaries paid to employees of the microgrid enterprise get spread over a larger paying customer base. At the N=5 and N=10 data points, the worker salaries are a disproportionate fraction of the total costs. Finally, a larger customer base is able to generate significantly more revenue for the enterprise. In Figure 13 we can see the enterprise NPV when operating at the LCOS for simulations with N=10 and N=70; the spread of outcomes (i.e. the best case and worst case NPV) is not particularly sensitive to N. We can see from Figure 14, however, that a charging a 5% premium over the LCOS generates significantly more revenue (and hence a higher NPV) for the N=70 scenario.

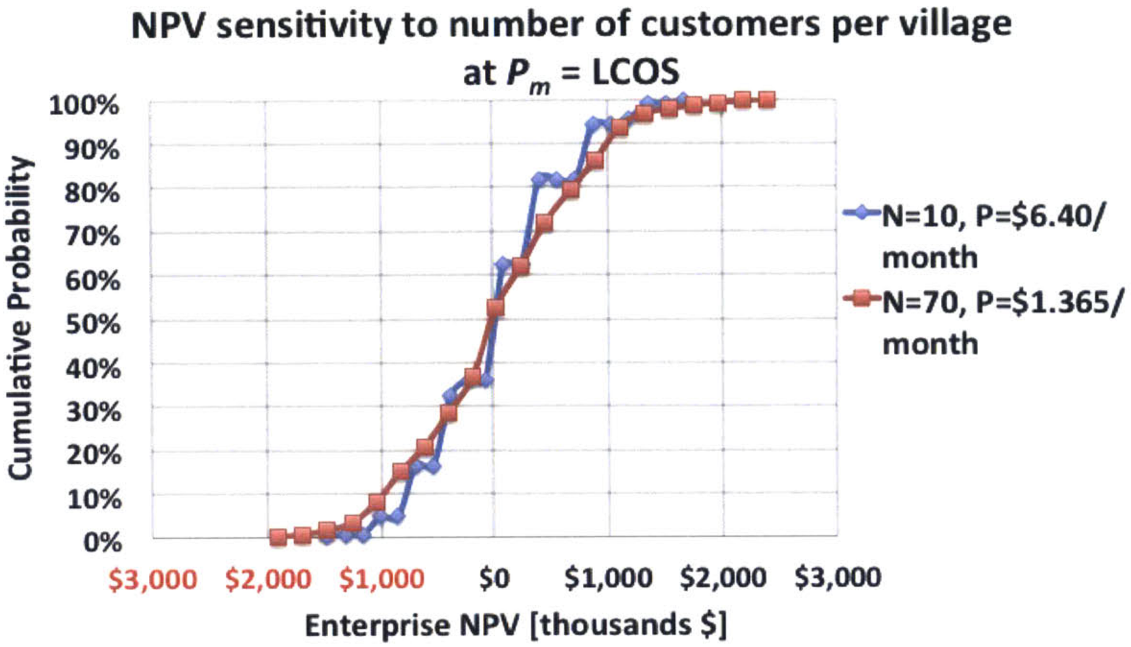

Figure 13: Sensitivity of microgrid NPV to N when operating at the LCOS

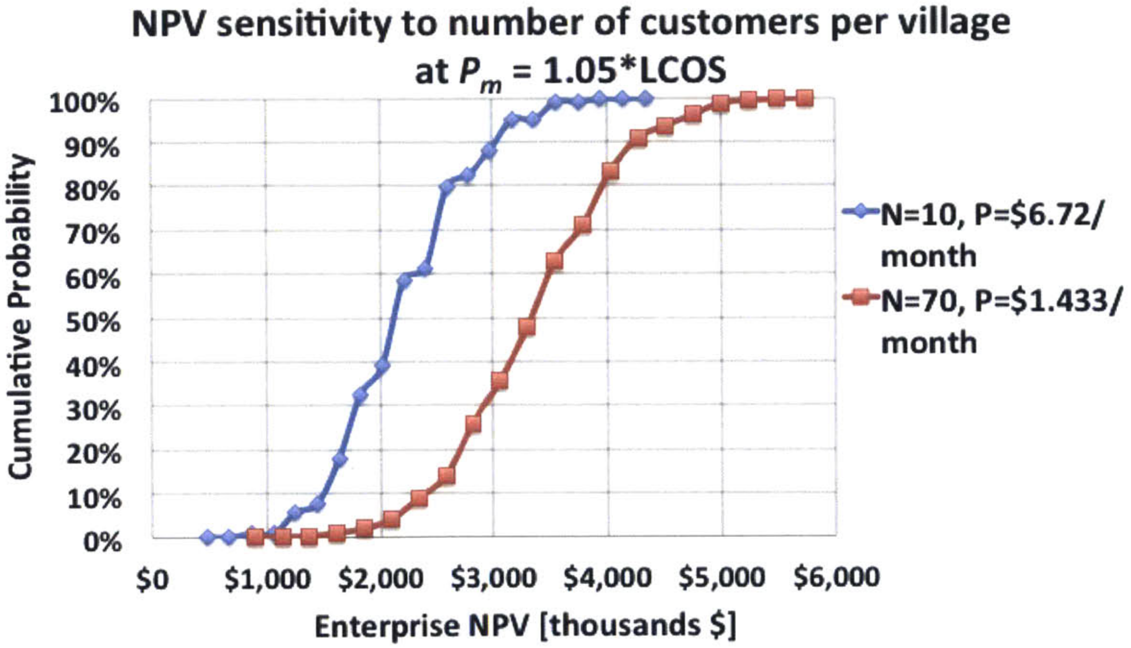

Figure 14: Sensitivity of microgrid NPV to N when operating at a 5% margin over the LCOS

Sensitivity to employee wages

As the plots in Figure 12 indicate, O&M salaries represent the largest fraction of the total costs even for systems serving a large number of customers. The default scenario calls for field crew salaries of $2400 per year ($8/day assuming an average 300 working days per year). This number is consistent with the experience of Mera Gao, but data from the Indian Ministry of Labor's 2009 report on wage rates in rural India indicates that typical wages for non-agricultural skilled workers (carpenters) were closer to $3/day (Rs. 144.60) [46]. Electrical technicians would require significantly more training and education than carpenters, hence commanding higher wages, but given that worker salaries are such an important factor in the model, it makes sense to perform a thorough sensitivity analysis on the salary assumptions from the default scenario. To test these assumptions and the potential impact of lower cost labor, simulations were run where total salary costs (i.e. the sum of all salaries, including field crews, collections agents, managers and executives) were scaled by a factor as indicated in the plots below. The results of the analysis are presented in Figure 15.

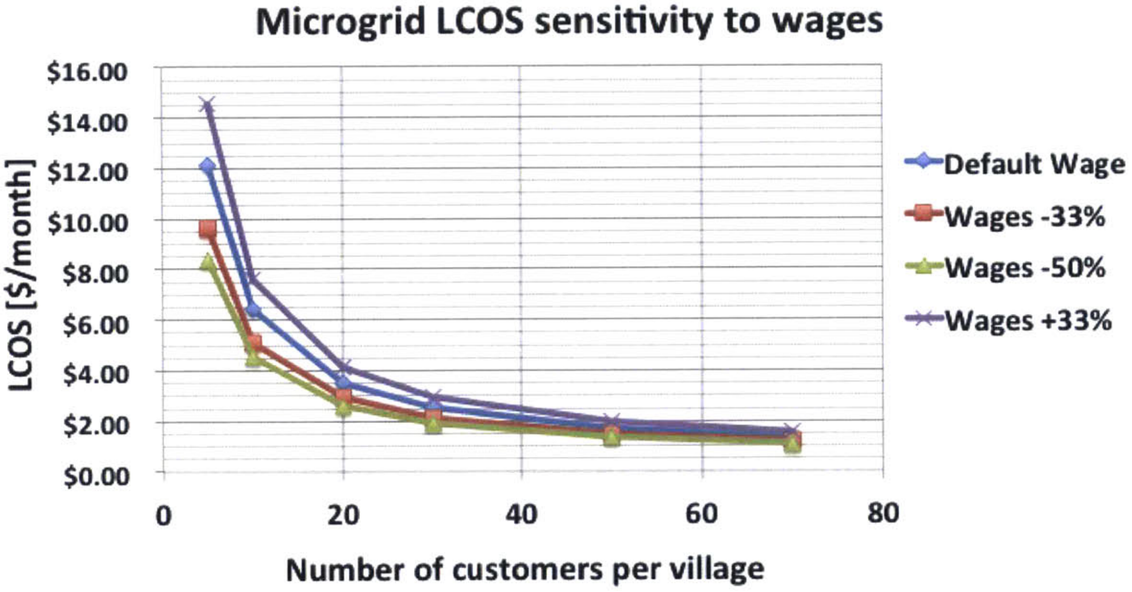

Figure 15: Sensitivity of microgrid LCOS to worker wages

The impact of wage variability is more pronounced for simulations with fewer customers for the same reasons discussed above. With N=70, a 50% reduction in total salary expenses results in only a 20% decrease in LCOS (from $1.37/month to

$1.10/month), indicating that the microgrid enterprise is relatively robust against variations in salary assumptions. The cost breakdown for the -50% wage scenario at *N*=70 shows that O&M costs in this case (23.9%) are smaller than both the COGS of initial installations (25.8% of total cost) and component replacement costs (at 31.8%). As we might expect, lower wages mean that the percentage of total costs attributable to worker salaries is lower regardless of the number of customers per village. These findings are summarized in Figures 16 and 17.

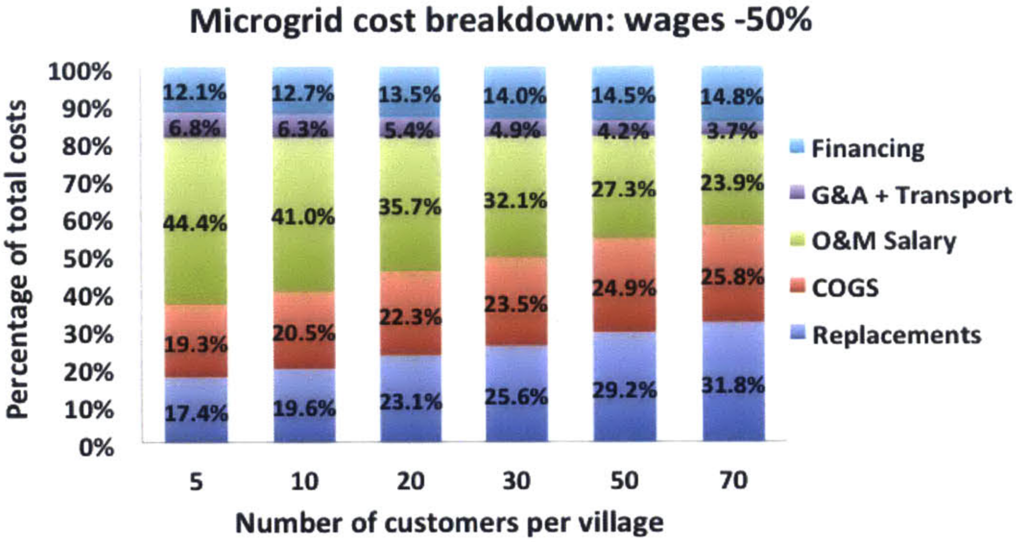

Figure 16: Total cost breakdown for the microgrid -50% wage scenario

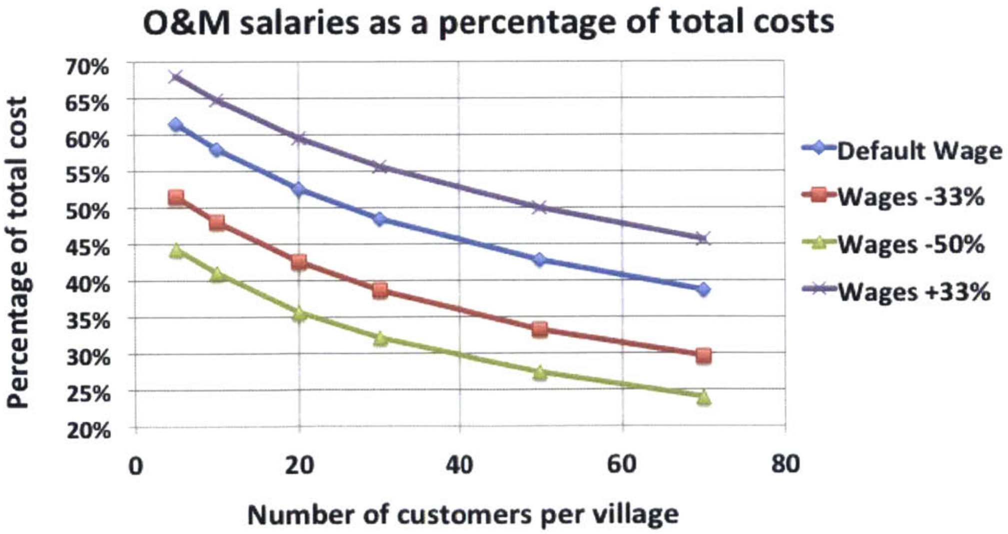

Figure 17: Percentage of total costs attributable to O&M wages under various wage scaling scenarios

Sensitivity to financing costs and growth rates

Analysis of the default scenario indicates that borrowing costs represent a smaller but not insignificant percentage of the total costs, as evidenced by Figure 7, which shows financing costs account for about 8.4% of the total costs for $N=5$, growing to 12% at $N=70$. The reason for this trend is simply that the higher COGS of the $N=70$ systems place a greater financial burden on the microgrid enterprise, as the company must borrow more money to pay for the more expensive initial installations. These larger systems can generate more revenue in the long term, but the interest on larger loans accumulates quickly. As discussed in Chapter 3, the growth strategy for the microgrid enterprise should also have an impact on the financing costs; faster growth will require more upfront capital, generating significantly more revenue early in the company's life but increasing borrowing costs. To further explore this phenomenon, LCOS and the cost breakdown were calculated for three growth scenarios: an "instantaneous deployment" scenario where all systems are installed in the first month of operation, the default scenario which grows at 10% per month (reaching full deployment of 10,000 systems in 21 months), and a "slow growth" scenario where the growth rate is reduced to 2.2% monthly (reaching full deployment in 42 months). Interestingly, the results of this analysis for the default interest rate of 5% indicate that LCOS is very insensitive to changes in growth rate, although the percentage of total costs attributed to interest charges increases with faster deployment. In other words, fast expansion results in greater interest expenses, but that expense is nearly canceled out by the additional revenue those systems can generate; so the net effect on the customer's monthly service fee is almost zero. These results are summarized in Table 7 and Figure 18 below.

N	5	10	20	30	50	70
Default growth (R=10%)	\$12.12	\$6.40	\$3.54	\$2.55	\$1.73	\$1.37
Slow growth (R=2.2%)	\$12.10	\$6.39	\$3.53	\$2.54	\$1.72	\$1.36
Instant deployment	\$11.97	\$6.30	\$3.49	\$2.51	\$1.70	\$1.34

Table 7: Microgrid LCOS for three growth scenarios at IR=5%

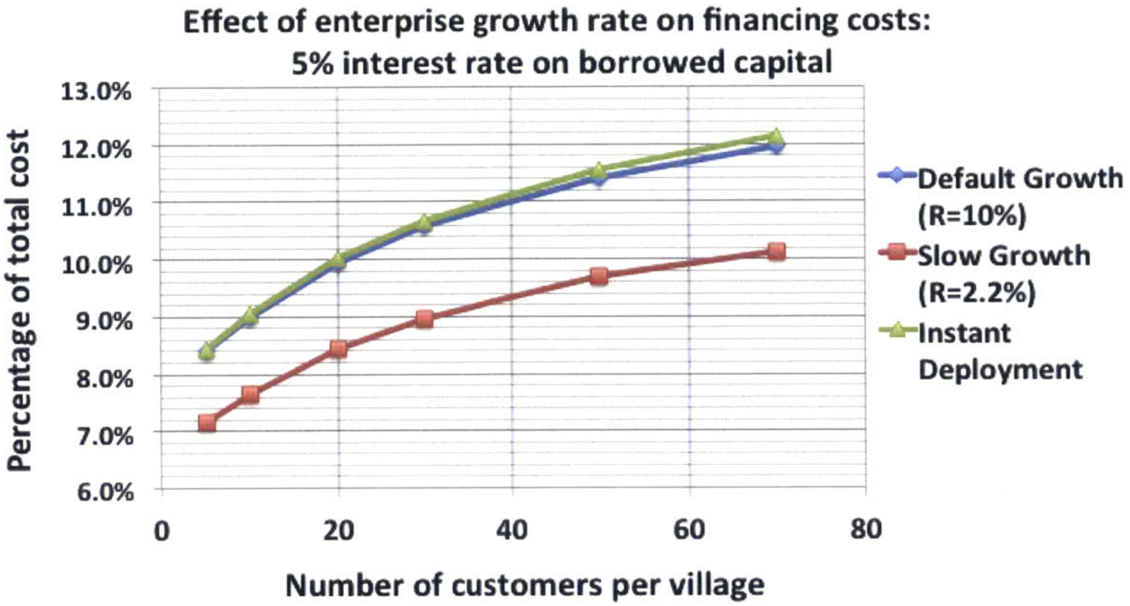

Figure 18: Financing costs as a percentage of total cost for three growth scenarios, IR=5%

To further explore the effects of financing and growth assumptions, LCOS was also calculated under each of the growth scenarios assuming a 10%, and 15% annual interest rate. As expected, higher interest rates increase the percentage of total cost attributable to financing, and also magnify the impact of the growth rate assumption. Figure 18 shows that financing costs for *N*=70 represent 12.1% of total costs for the instant deployment scenario, but only 10.1% of total cost for the slow growth scenario when we assume a 5% annual interest rate. A similar analysis at a 15% interest rate shows financing costs are 25.3% of total cost for instant deployment but only 18.4% in the slow growth. This finding supports the conclusion that enterprise growth rate should be taken into consideration primarily in the case that interest rates are high; with lower borrowing costs overall, the sensitivity to growth rate is muted. These findings are summarized in the figures below.

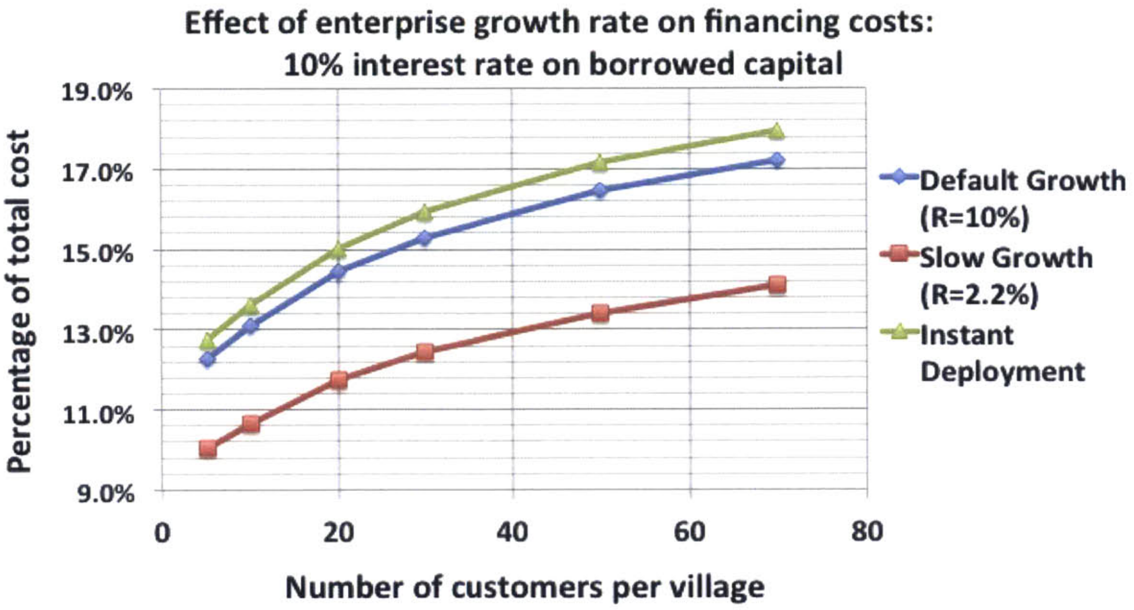

Figure 19: Financing costs as a percentage of total cost for three growth scenarios, IR=10%

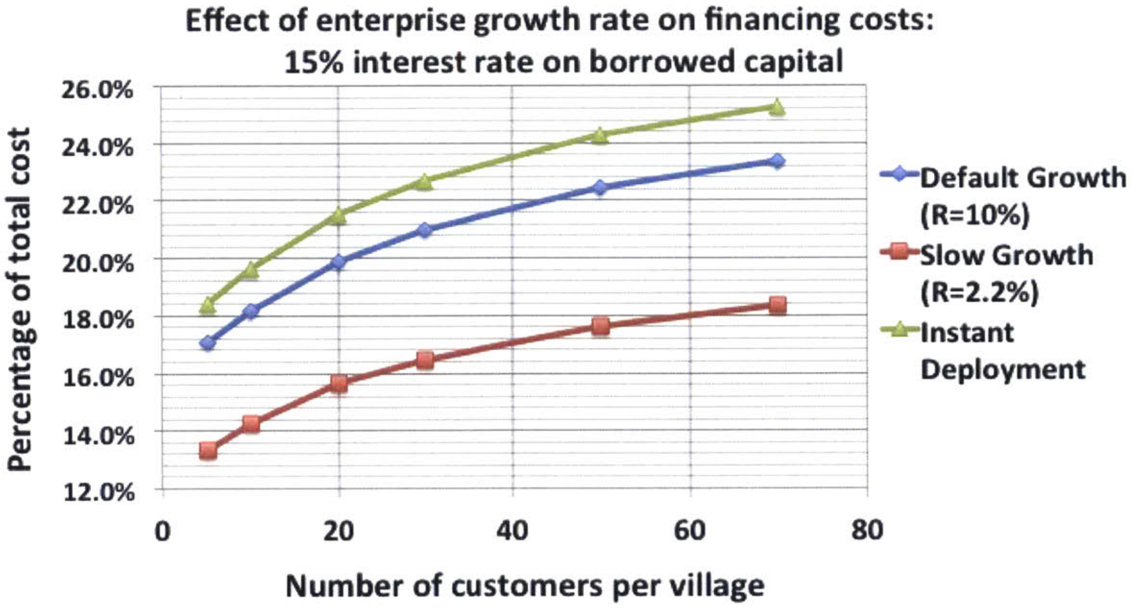

Figure 20: Financing costs as a percentage of total cost for three growth scenarios, IR=15%

The sensitivity of LCOS to the three interest rate scenarios (assuming default growth rate of *R*=10%) is presented in Table 8 below.

N	5	10	20	30	50	70
Default (IR = 5%)	$12.12	$6.40	$3.54	$2.55	$1.73	$1.37
IR = 10%	$12.65	$6.70	$3.72	$2.70	$1.83	$1.45
IR = 15%	$13.37	$7.12	$3.97	$2.88	$1.97	$1.57

Table 8: Microgrid LCOS for three interest rate scenarios

The general conclusion that can be drawn from these analyses is that borrowing costs can be a significant portion of the total LCOS in the event that the microgrid enterprise can only secure financing at high rates; in this case it makes sense to plan the growth rate of the company carefully. Higher interest rates do increase LCOS, but regardless of the financing terms, there is little sensitivity in LCOS to the enterprise growth rate because the additional revenue generated by fast expansion almost perfectly nulls out the extra interest expenses on larger borrowed sums.

Sensitivity to worker efficiency

We have already seen how employee wages have an impact on LCOS, owing largely to the fact that in the default scenario O&M wages represent the largest portion of total costs. Another parameter that will be important to overall O&M wages is the "worker efficiency", or the number of microgrid systems that can be maintained by a single field crew. As we mentioned previously, the practical limitation on this number is the physical separation of systems and the ability of field crews to travel from village to village in a reasonable amount of time in order to perform maintenance. If each team is able to serve a larger number of villages, this will obviously impact hiring and O&M costs because fewer employees will be needed. The default value of 30 villages per field crew (15 per worker) is loosely based on observations of Mera Gao's operations, coupled with the assumption that a maintenance crew will be able to visit at least one village per day in order to inspect equipment and replace components as necessary. A sensitivity analysis on this parameter is presented in Figure 21. Similar to our analysis of worker wages, we find that the effect of worker efficiency is pronounced for installations that serve a small number of customers (*N*=5 or *N*=10), with decreasing sensitivity as the number of customers increases because salary expenses can be spread across a much larger number of customers.

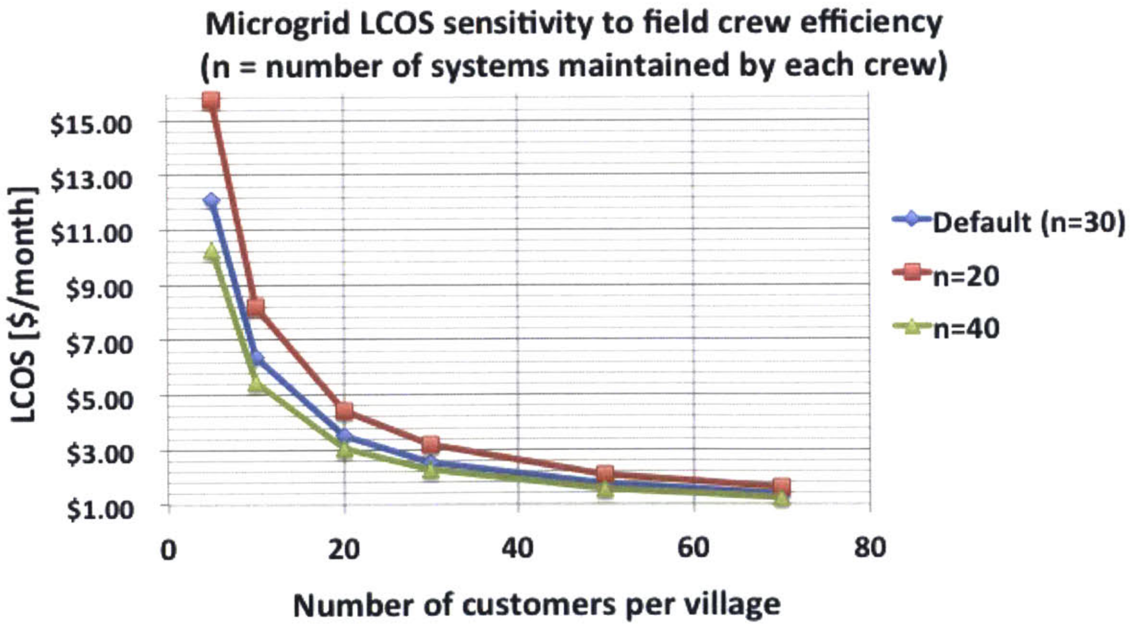

Figure 21: Microgrid LCOS sensitivity to worker efficiency assumptions

Sensitivity to customer load

All of our attention has focused to this point on the impact of operational considerations like wages, employee efficiency, financing, and enterprise growth. We have generally found that LCOS is not very sensitive to changes in our assumptions about parameter values, which suggests that the DC microgrid enterprise is a relatively robust method of delivering very basic services like lighting and cell phone charging. The question now becomes: how far can this model of electricity service be extended? If it is possible to deliver lighting and phone charging (~5W) in a cost effective manner, can we also provide higher level of services like cooling (via DC fans), small televisions, radios etc.? Unlike the previous analyses, which primarily involve economic parameters and impact how the total cost is broken down into different factors like O&M, financing, etc., increasing the customer load also requires analysis of the technical implications. The following sections will analyze these questions from both a technical and an economic perspective.

Economic impact of higher customer loads

The primary economic consequence of additional customer load is that PV panels and batteries become substantially larger, leading to higher COGS and replacement costs. To explore this phenomenon, we consider three scenarios: the default scenario with 2W of fixed load and a 2.5W variable load that is being used by each customer with 50% probability (from here on referred to as "2/2.5W load"), a medium power scenario with 20W of fixed load and a 25W variable load ("20/25W load"), and a high power scenario with 40W of fixed load and a 50W variable load ("40/50W load"). From a practical perspective, the 25W and 50W variable loads could be representative of other small appliances like fans, TV's, radios, tablet computers, etc. It is also worth noting here that we will see greater spread in the outputs on successive runs of the model because of the increased variable load, which has important repercussions for the required PV and battery capacity, distribution efficiency, and system COGS.

To approximate the COGS impact of larger loads, we can simply plug the larger capacity requirements for PV and batteries into the same component cost models used in the default case. It is necessary, however, to make some additional assumptions about the cost of higher power loads. For simplicity, it is assumed that the cost of the load devices at each customer scale linearly with the power increase (in other words, the 20W fixed load costs 10x as much as the 2W fixed load used in the default case, etc.). The two higher power scenarios also will require a substantially larger charger controller, so that cost is increased from a fixed $75 in the default scenario to $200 for the high power scenarios. Similarly, the balance of system costs are increased from $50 to $100, as extra PV capacity will require additional mounting hardware, etc. It is important to note that, while these changes increase the percentage of COGS attributable to load devices from 11% in the default scenario to 19% for the 20/25W scenario, that difference is essentially absorbed by the relative reduction in wiring costs (which fall from 20% of COGS in the default case to 6% in the 20/25W case). This is reasonable because it is assumed that the wiring is the same in both cases: 2000 ft. of AWG 14 solid copper wire. Figure 22 shows the COGS and Figure 23 shows the COGS breakdown by component for the 20/25W system. Comparison of these figures to the default case in Figures 9 and 10 reveal that there is a substantial increase in COGS associated with the increase in customer load, from a median of value $982 to $3300.

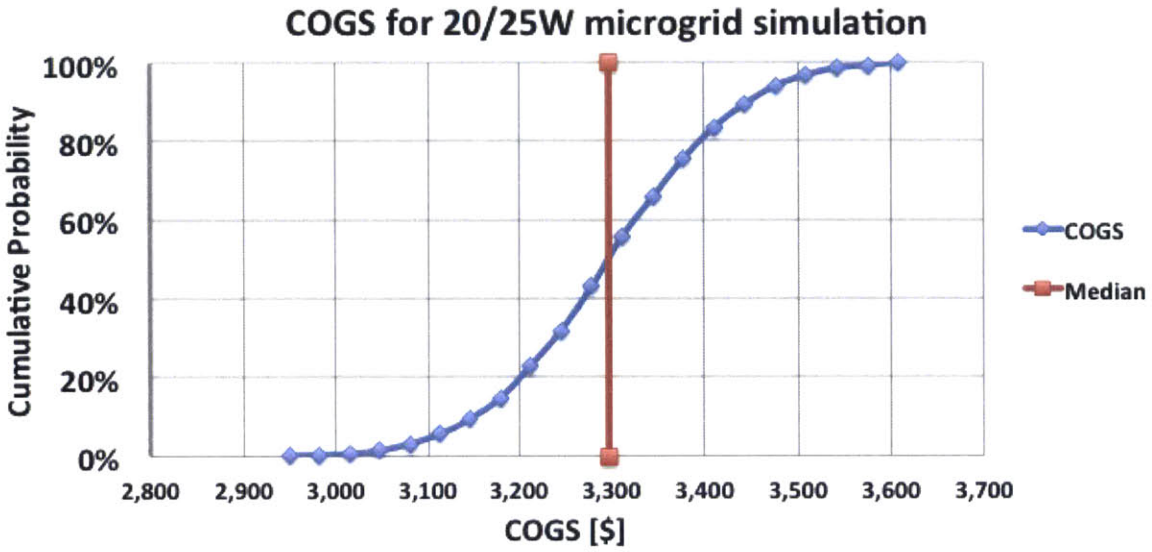

Figure 22: COGS for N=30 microgrid supplying 20/25W load

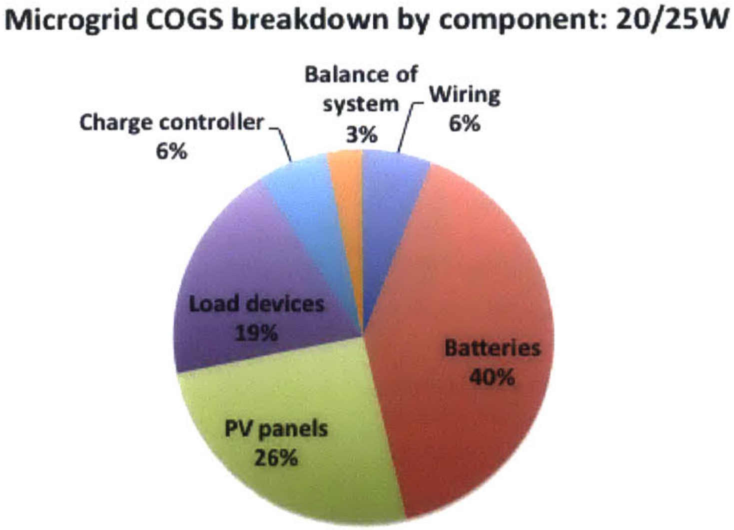

Figure 23: COGS breakdown by component for median N=30 microgrid supplying 20/25W customer load

The sensitivity of LCOS to customer load is presented in Figure 24 below. It is immediately apparent that the LCOS is quite sensitive to customer load; supplying 20/25W loads increases LCOS from \$1.37/month (in the default scenario) to \$3.91/month for the *N*=70 case.

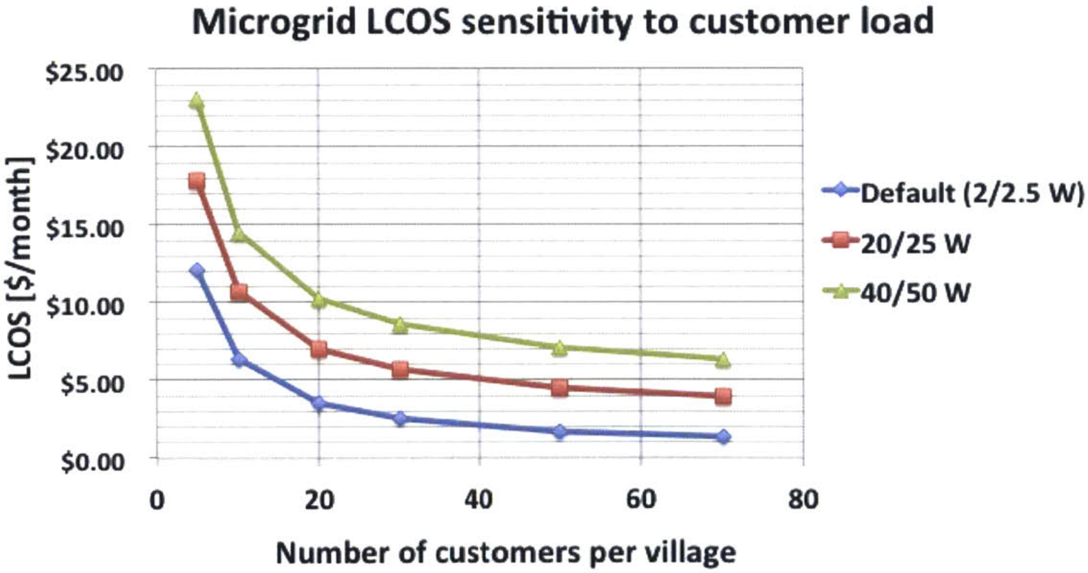

Figure 24: LCOS for microgrids supporting larger customer loads

Figure 25 shows the total cost breakdown for the 20/25W load scenario. As we might expect, in this case the COGS and replacement costs dominate the total cost because much larger and more expensive components must be installed and replaced, and accordingly, financing costs also come to represent a larger portion of total costs.

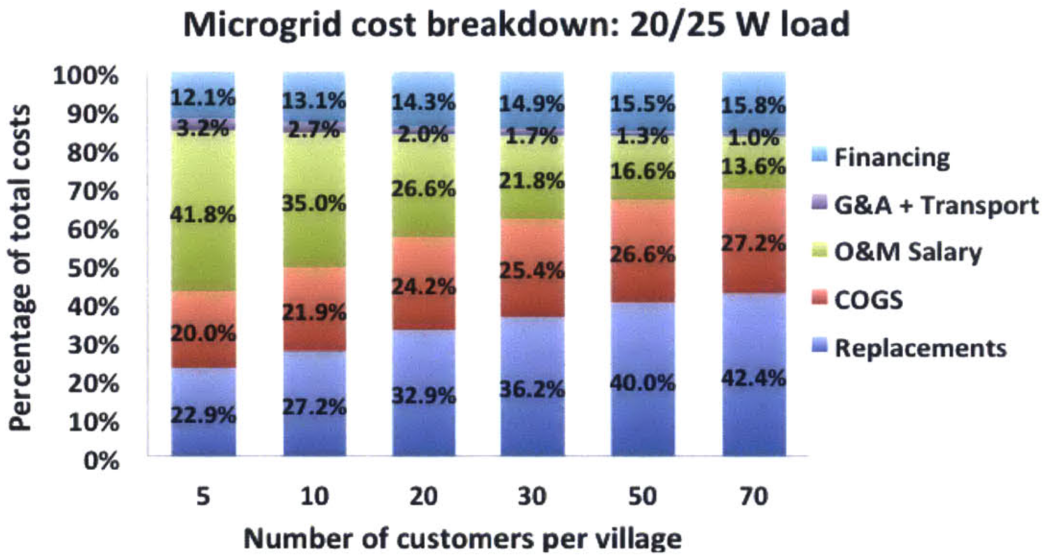

Figure 25: Total cost breakdown for 20/25W microgrids

In addition to increasing the LCOS, the additional variability caused by load uncertainty and distribution losses make the financial performance of the microgrid enterprise extremely volatile. Figure 26 shows the enterprise NPV for both the default scenario and the 20/25W load when the monthly service fee is equal to the LCOS. In both cases the median NPV=0 (by definition true because the service fee equals the LCOS), but for the default scenario best case and worst case performance are roughly +/- $2million, versus +/-$13 million for the 20/25W load scenario! This finding implies that there is substantially more financial risk when the customers are able to use such variable loads; there is a considerable probability that a given microgrid will either have far too much capacity (making the enterprise extremely unprofitable), or to little capacity (making financial returns for the microgrid enterprise great, but at the cost of much lower service reliability from the customer's perspective).

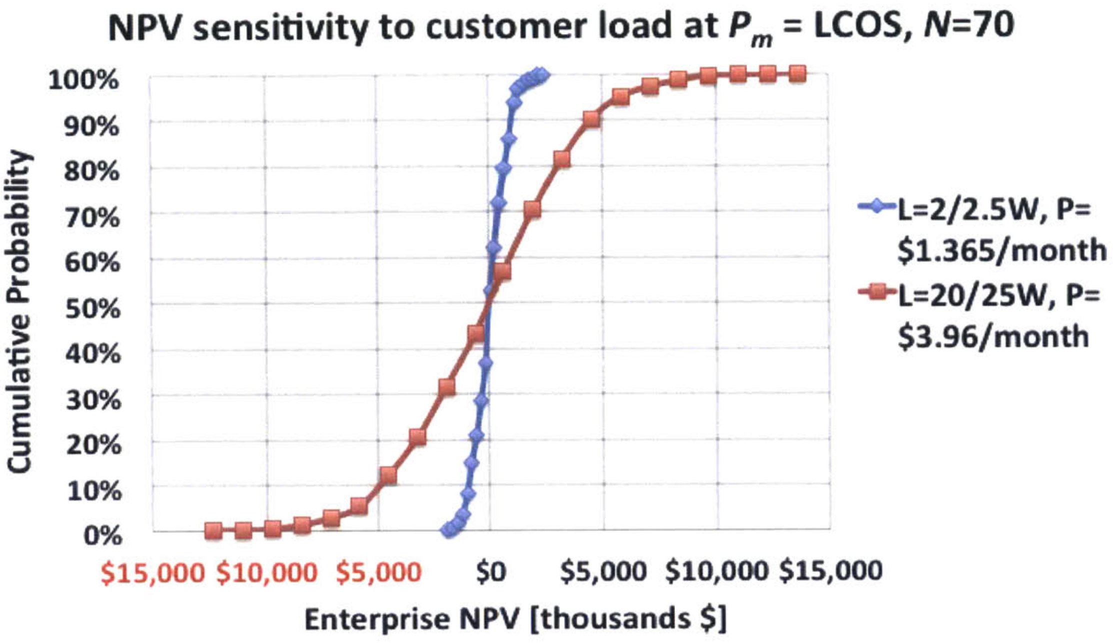

Figure 26: NPV sensitivity to customer load when operating at LCOS

While we have seen that LCOS does increase substantially in order to support higher loads, if we change our perspective from that of a company providing services (lighting, etc.), to one who provides energy like a traditional utility, the levelized cost of energy (LCOE) actually falls dramatically when we provide greater load support. The LCOE is simply defined as:

$$LCOE\ [\$/kWh] = \frac{LCOS\ [\$/month]}{Average\ monthly\ consumption\ [kWh/month]}$$

We find that, for the higher load scenarios considered here, consumption increases by a factor of ten (from 2/2.5W to 20/25W) but LCOS only increases by only a factor of 2.85 (from $1.37/month to $3.91/month). The LCOE for each of the load scenarios is presented in Figure 27.

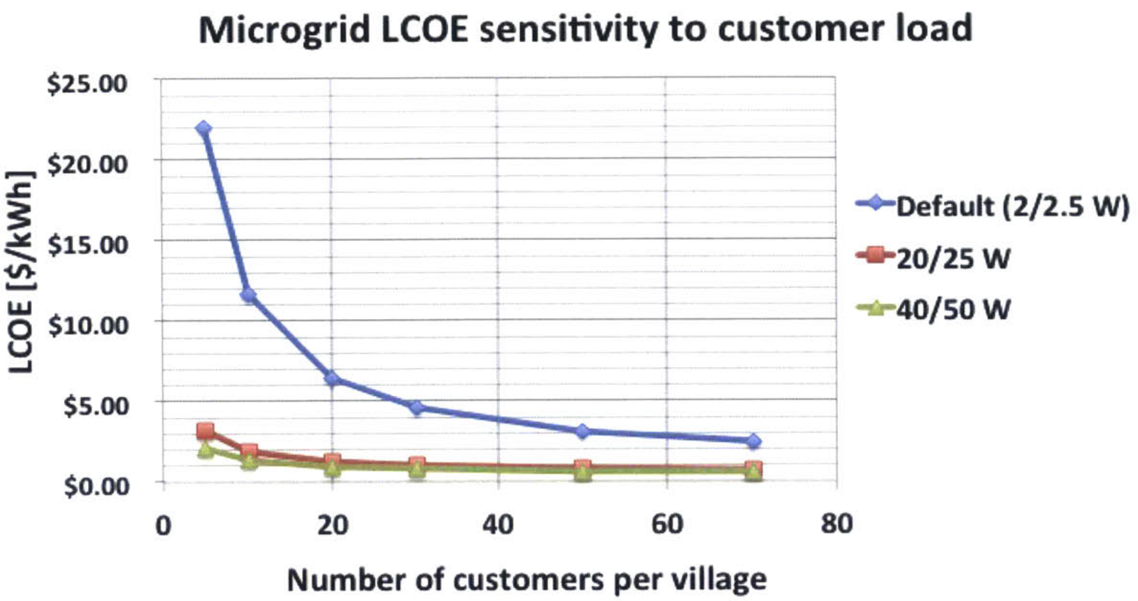

Figure 27: Microgrid LCOE for various load scenarios

Technical impact of higher customer loads

So far we have explored the economic implications of supplying higher customer loads and found that service fees must increase considerably, but on a per unit of energy basis, costs actually fall by providing more power to customers. We have also seen how greater load variability can increase the volatility of financial outcomes by increasing the risk of under or over specification of capacity. In addition to these limitations, the technical consequences of higher loads must be considered. From a technical perspective, larger loads not only increase the *average* distribution losses, but also lead to greater *variability* in performance because of the random placement of customers along distribution lines.

There are significant advantages to operating the grid with 24V DC distribution in terms of safety, cost, and system complexity (hence maintainability). With low voltage distribution, wires can be strung along rooftops with little safety risk to residents; this makes installation much easier and less costly because there are no overhead poles and buried cables necessary. In addition, the 24V distribution voltage comes directly from the battery and so there is no need for step up and step down converters or fixtures at each customer house. Customer lighting comes from two 12V LED's connected in series directly to the distribution voltage. The elimination of fixtures and voltage converters at each customer reduces the number of components and increases reliability by reducing the number of points of failure. For all of these reasons, it is extremely desirable to maintain a 24V distribution, but of course this limits the power handling capability of the distribution system. Figure 28 shows the distribution efficiency for the three load scenarios previously described.

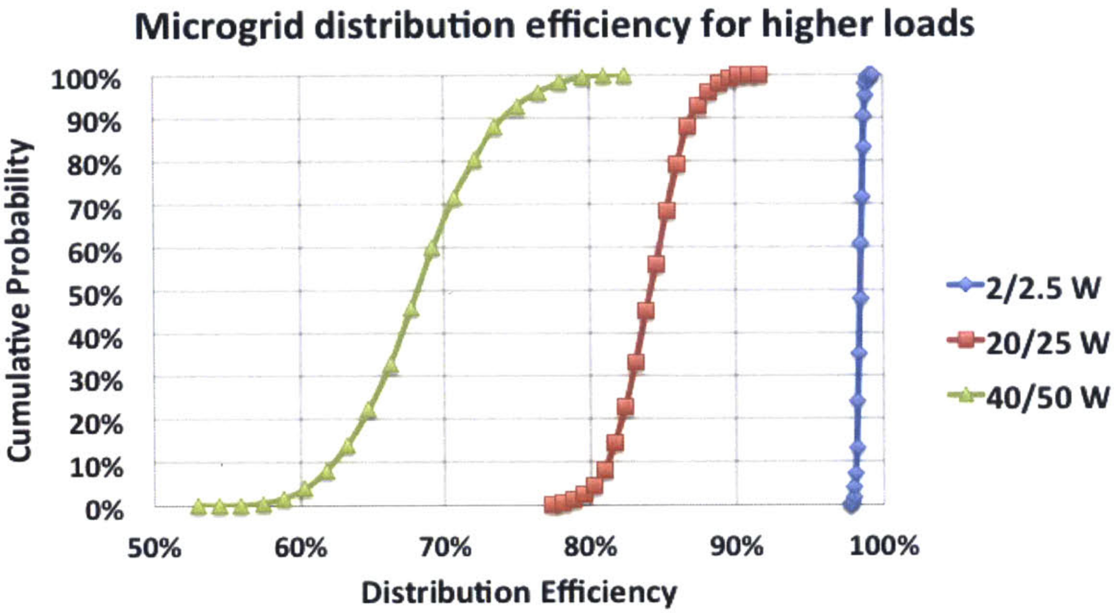

Figure 28: Distribution efficiency for microgrids supporting higher customer loads

As we can see, distribution efficiency is extremely high for the default scenario and reasonable for the 20/25W case, in the 40/50W load scenario we would expect 33% distribution losses for the median output. This is a problem because it leads to a large over-specification of battery capacity (since nearly a third of the stored energy will be lost in distribution), which further drives COGS higher.

In summary, the DC microgrid as described has a practical limitation on its' ability to supply high customer loads that is driven by both technical (distribution losses) and economic (poor capacity specification, increasing LCOS) factors. We also discussed how technical losses might be overcome by increasing distribution voltage, but this will likely degrade the economic performance by reducing reliability and driving maintenance costs higher. Finally, we might be able to change the distribution wires from AWG14 to AWG12 or higher, but this would also increase wiring costs.

Sensitivity to distribution distance

The physical separation of customers, similar to the customer load, is a parameter that affects both the technical and the economic performance of the microgrid. Increasing distribution length will add to system COGS and replacement costs by increasing the amount of wiring and likely increasing the failure rate associated with distribution wires (i.e. longer wires have more places to break). These effects were investigated by simulating three distribution length scenarios: 1000 ft. per line (the default value), 3000 ft. per line, and 5000 ft. per line. The advantage of longer distribution lines is that it might enable the aggregation of more customers onto a single microgrid system; which, as we have seen, lowers overall costs and improves business viability substantially to improving the revenue generating potential of each system. Figure 29 shows the impact of longer distribution wires on the breakdown of COGS by individual component. As distribution lines are extended from 1000 feet to 5000 feet, the percentage of total costs attributable to wiring rise from 20.3% to 54.9%!

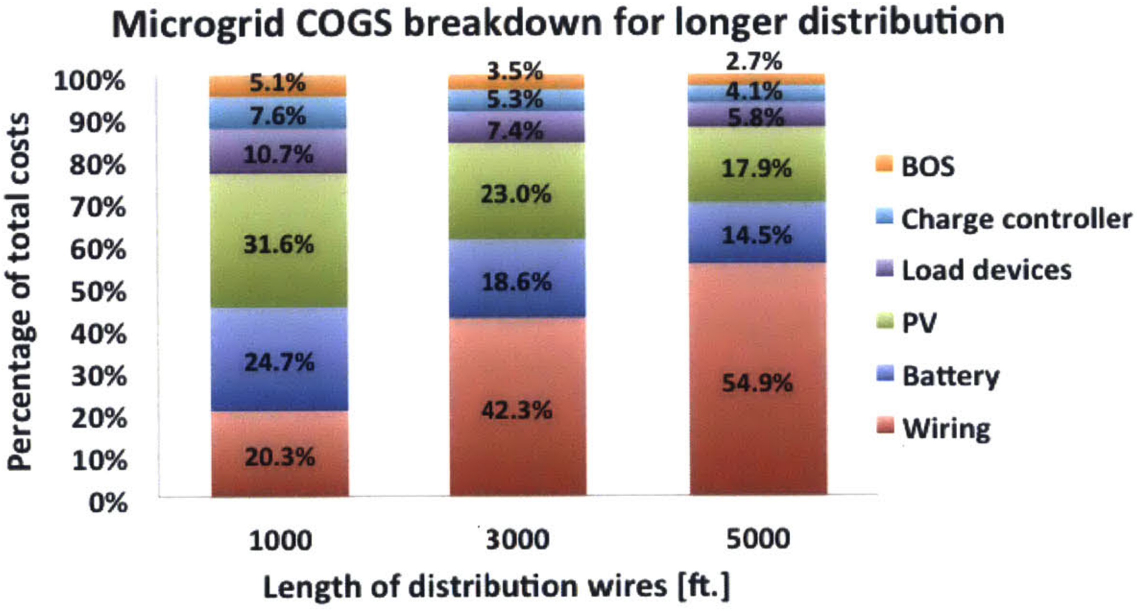

Figure 29: Microgrid COGS breakdown by component for longer distribution networks, N=30

The sensitivity of LCOS to distribution length is given in Figure 30. While can see from Figure 29 that the wiring comes to dominate the system COGS, it only increases LCOS to \$1.82/month for 5000 ft. wires when *N*=70. While this is not insignificant, it suggests that the extension of distribution wires might be cost effective if it allows the microgrid operator to add a significant number of additional customers. The LCOS of the default scenario (with 1000 foot distribution) is \$2.55/month when *N*=30, so if extension of the wires to 5000 feet can allow us to connect an additional 30 or 40 customers, it would be cost effective to do so. In a practical sense, the distribution wire length would likely be evaluated on a case-by-case basis as the microgrid enterprise expands and installs systems in new villages; if there is a large group of potential customers a few thousand feet from the main system installation it might be worthwhile to connect them rather than install a second small system.

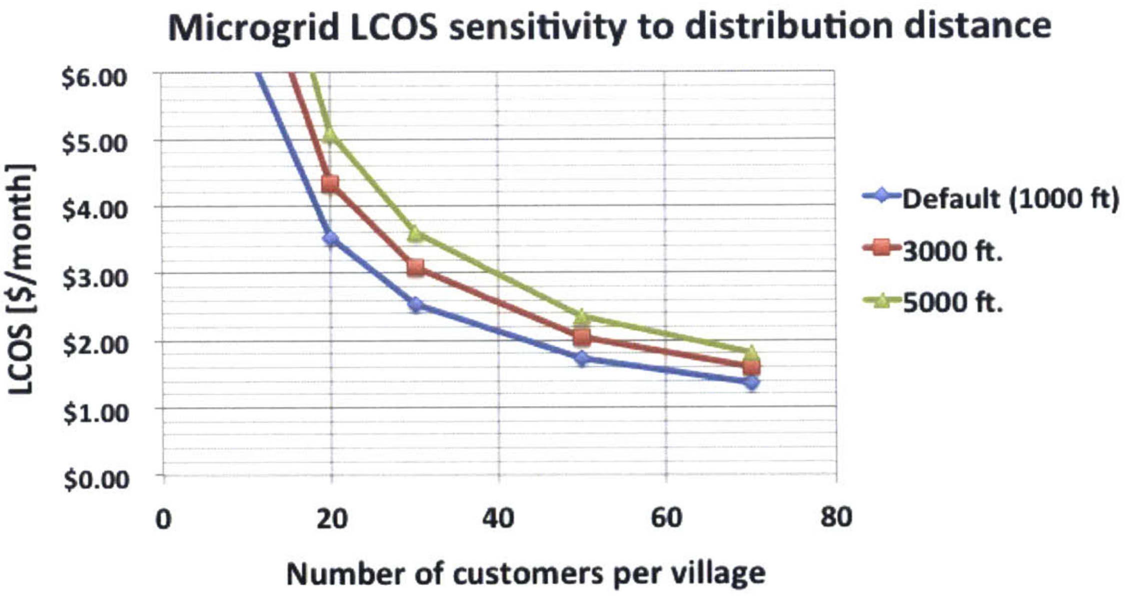

Figure 30: Microgrid LCOS for longer distribution networks

From a technical perspective, the additional wire length increases the resistive loss in the distribution network, and the random placement of customers also increases the variability of possible outputs, as described previously. Figure 31 shows the distribution efficiency for the longer distribution scenarios, and we can see that even for the longest lines the distribution loss is manageable (a median of 92% efficiency even if each lines is 5000 feet in length).

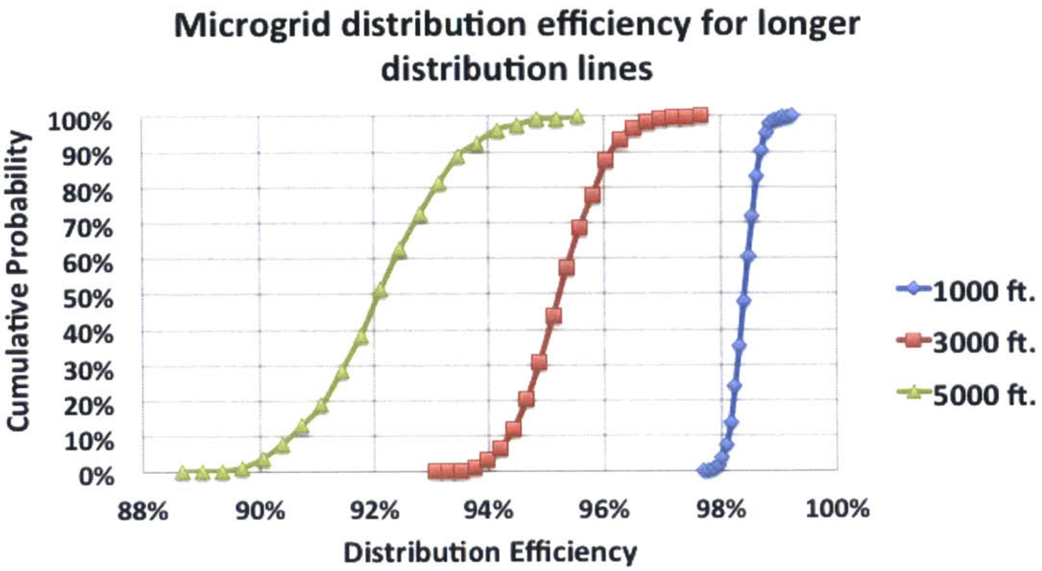

Figure 31: Microgrid distribution efficiency for longer distribution wires, 2/2.5W load

While the results in Figure 31 would suggest that the technical impact of longer distribution is minimal, it is important to note that this is only the case because each customer load is so small (2/2.5W). If we analyze the 20/25W load scenario described in the previous section *coupled with* 3000-foot distribution wires, the results are quite different. Figure 32 summarizes the technical performance when higher loads are coupled with longer distribution.

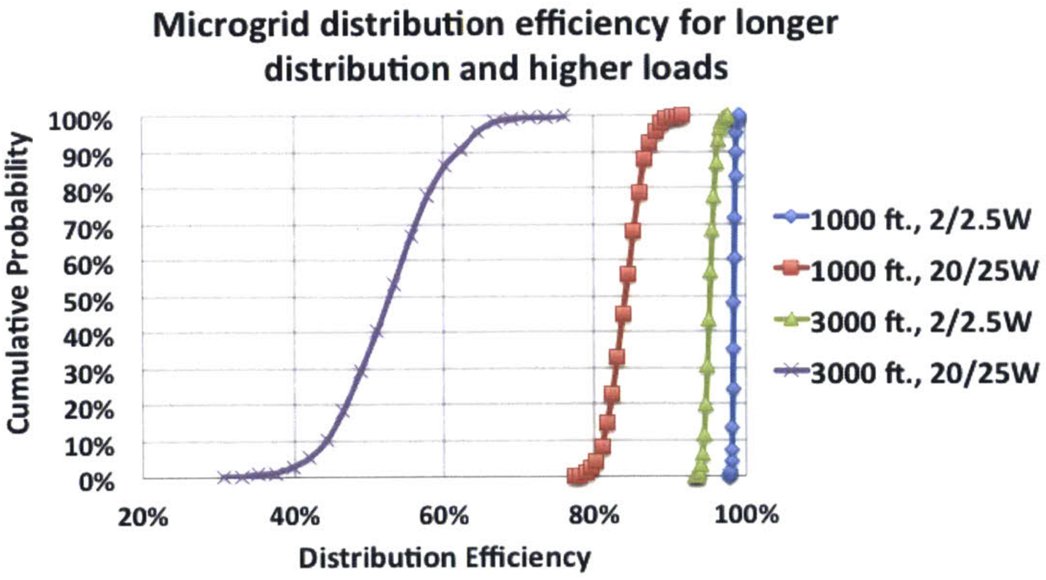

Figure 32: Distribution efficiency for higher load and longer distribution wires

It is clear from this analysis that extended distribution lengths are only really feasible for the lowest power loads, unless substantial changes are made to the architecture of the microgrid. Because resistive losses increase as the square of current and resistance increases in proportion to wire length, combining these two changes simultaneously creates a particularly difficult challenge from a technical perspective. As noted previously, we could increase the distribution voltage and we would solve the technical challenge, but this would compromise the advantages of 24V distribution in terms of system complexity, safety, and overall cost. It is also worth noting here that increased variability in the customer load combined with longer distribution will create more extreme corner cases (i.e. where a much larger load is concentrated at the end of the long wires).

Chapter 5: Comparison of DC microgrid and SHS enterprises

Our analysis to this point has focused on the solar powered DC microgrid, and we have examined the sensitivity of various technical and economic parameters in an effort to understand the critical factors underlying the viability of the business. We have also explored how the business model might be extended to the provision of services beyond simple lighting and mobile phone charging. We now turn our attention to an alternative method of delivering the same basic service, the solar home system. As discussed in previous chapters, the major practical difficulty with SHS is one of maintenance; projects funded by the Indian RVE program are required to specify a maintenance plan that can provide support for system owners in the event of component failure (particularly common with batteries). In our literature review we have seen numerous studies that document how difficult it is to enforce such contracts, the result being that many systems are deployed and simply stop working after a short period of time. In this chapter we will propose a hypothetical SHS business that operates with the same model as the microgrid enterprise analyzed in the previous chapter; the SHS enterprise owns all equipment, is responsible for all maintenance, and simply charges each customer a flat monthly fee. The advantage of this type of enterprise over one that sells SHS outright is that maintenance is guaranteed; SHS that have been deployed are still the company's assets, so there is a clear incentive to ensure they function as long as possible, because if the SHS stops working the customer will simply stop paying for the service. In this way we can expect continuous service over a 10-year period (the same time period as the microgrid simulation). While warranties on SHS can provide for maintenance over a short time, it would be very difficult to extend a 10 year warranty on a system that the customer owns outright given the expected lifetime of the batteries, light bulbs, etc. It is recognized that the hypothetical business model we are considering here is not seen in practice, but it is proposed because it gives us a direct comparison to the microgrid enterprise. For this analysis we will use the same basic models in the microgrid analysis with several key changes to capture the differences between the two companies.

Model differences for SHS and microgrid enterprises

For the purposes of modeling COGS, we can consider a SHS to be a microgrid that serves just one customer with a fixed load of 2W (LED lighting) and a 2.5W mobile phone charger. Because there is just one customer, we do not model the customer load with the same random variables used in the microgrid analysis; this analysis is a deterministic rather than a Monte Carlo one. We want every customer to have access to both the lighting and the phone charging service, so we must specify each SHS is able to power both simultaneously. Using this method, the panel size and battery capacity that are specified by the model are generally consistent with the smallest SHS systems provided by many commercial entities (10 Wp solar panel, etc.). Each individual SHS delivers much less power than the microgrid, so the charge controller cost is reduced to $10. Using these parameters, the COGS model described in Chapter 2 and used in the microgrid analysis outputs a COGS of $133 for the solar home system, a value that is used for all of the analysis to follow.

In the microgrid model, we use a shipping cost of $50 for each microgrid system (based on data from Mera Gao regarding customs, shipping, and local transportation costs). Each SHS is much smaller and easier to transport, so the shipping cost in that model is reduced to $5 per system.

In our analysis of the microgrid we use a default value of 30 systems per field crew as the model for hiring additional maintenance and collection crews when the enterprise grows. The SHS enterprise must similarly add maintenance workers as new customers are added, but in this case we assume each field crew can perform maintenance on 320 SHS. This is a significant efficiency improvement as compared to the microgrid model, because it is assumed that the 320 SHS are distributed among customers that are in only a few villages. Field crew efficiency is limited by geographical constraints for microgrids (it takes a lot of time to travel to 30 villages over dirt roads in rural areas), but for SHS the limitation is more likely the travel from house to house within a small number of villages. Intuition tells us that it would be more difficult to manage such a large number of distributed SHS, but this is certainly a critical parameter in the model. We will perform an extensive sensitivity analysis on this parameter in order to establish LCOS over a wide range of operating assumptions. Similarly, our SHS enterprise would expect to employ a larger number of maintenance crews in order to serve the same number of customers as a microgrid and so a wage sensitivity analysis will follow.

In our microgrid analysis we had the enterprise install systems at a fixed growth rate and we saw how the number of customers per village impacted operational efficiency and total costs. Under the default growth scenario, 10,000 microgrids are deployed over the course of 21 months; meaning that if each system serves 70 customers (N=70) then 700,000 customers were served in that time, but if N=20 only 200,000 customers were reached. Each SHS serves a single customer, so for this analysis as the number of customers increases, the enterprise growth rate is re-calculated so that the specified number of customers is obtained in 21 months. This allows us to make direct comparisons to the microgrid enterprise on the basis of number of customers per village.

The final difference between the two enterprise models relates to G&A costs and the opening of new regional offices. In the default microgrid model, each regional office covers 150 villages, regardless of the number of customers per village. It is assumed that the SHS enterprise would grow in a similar way (geographically rather than by the number of customers), so the scale factor for number of SHS systems per new office, N_o, is scaled by the number of customers per village.

Sensitivity to field crew efficiency

Figure 33 gives a comparison of the LCOS for the microgrid and SHS enterprises as a function of the number of customers per village for different crew efficiency assumptions. We can see from this result that the hypothetical SHS business does not enjoy the same reduction in costs as the number of customers in a village grows that we found with the microgrid. This is simply because it takes many more employees to serve 700,000 customers (N=70 for the microgrid) with individual home systems. Instead of 667 microgrid maintenance workers (10,000 microgrid systems divided by 30 systems per crew of 2 workers), we have 4375 SHS maintenance workers (700,000 systems divided by 320 systems per crew of 2)! Simply put, in a microgrid, adding more customers in a given system does not increase the maintenance burden in the same way that each additional SHS requires more maintenance workers. Another consequence of this fact is that there is an increased sensitivity to the worker efficiency assumptions in the SHS model.

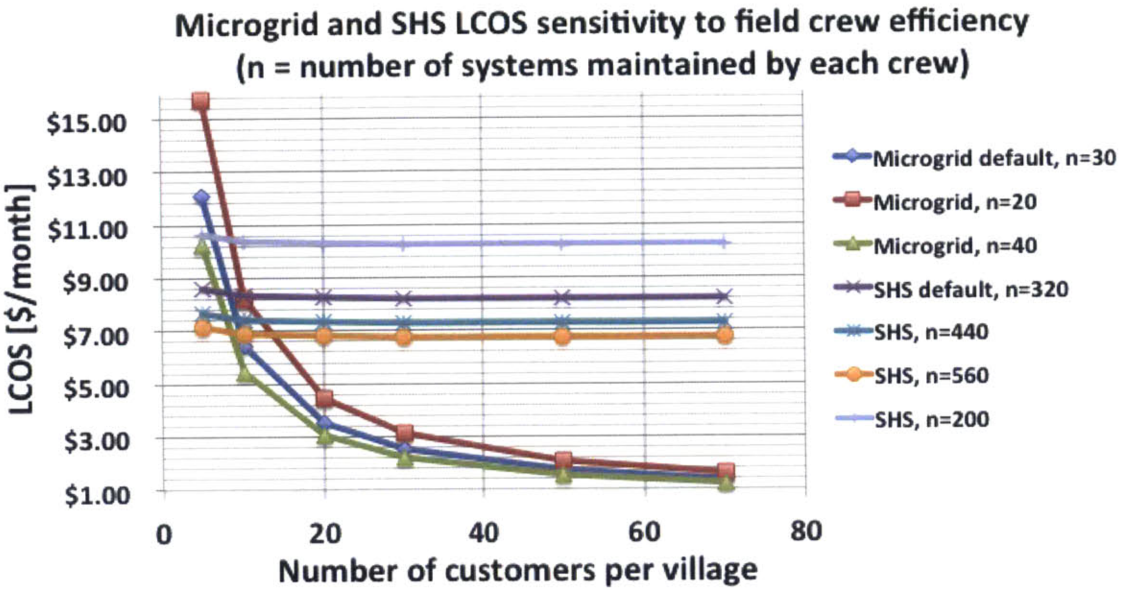

Figure 33: Comparison of LCOS for SHS and microgrid enterprises under different worker efficiency assumptions

We can further understand the difference between the two business models by looking at the cost breakdown for the SHS enterprise given in Figure 34. As we might expect, each of the cost components is essentially flat as we increase the number of customers per village. The economics of adding each additional SHS customer are largely the same regardless of how many customers are already being served in a village.

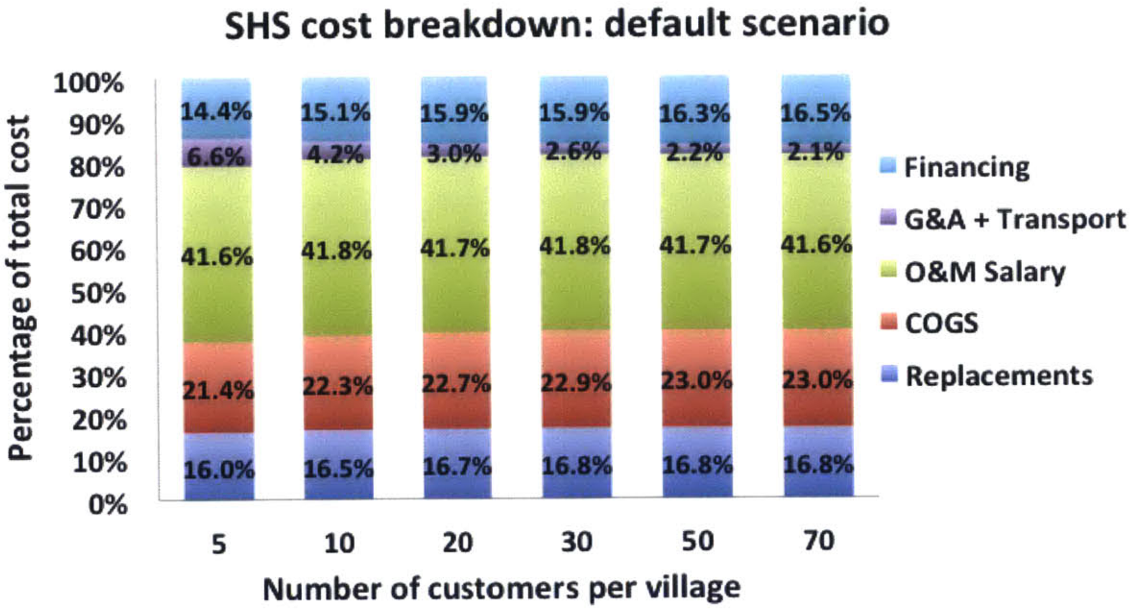

Figure 34: Total cost breakdown by category for SHS enterprise

Sensitivity to worker wages

We have already seen how the SHS enterprise has larger sensitivity to worker efficiency relative to a microgrid enterprise, and so we would expect to see a similar sensitivity to employee wages. Figure 35 shows the result of this analysis. It is clear from these plots that the SHS enterprise can realize much better performance by controlling employee wages and hiring rates, but it still remains difficult to achieve the level of operational efficiency of a small microgrid serving a large number of customers. The SHS enterprise also exhibits increased sensitivity to wages, which is good in the sense that making relatively minor reductions in overall wages can significantly reduce costs. At the same time, higher sensitivity to wage assumptions makes accurate forecasting of future financial performance much more difficult. In this sense, it might be preferable to operate the microgrid enterprise; the ability to reduce costs through wage controls might be lower, but the costs are more robust to robust to changes in worker operating efficiency and worker wages.

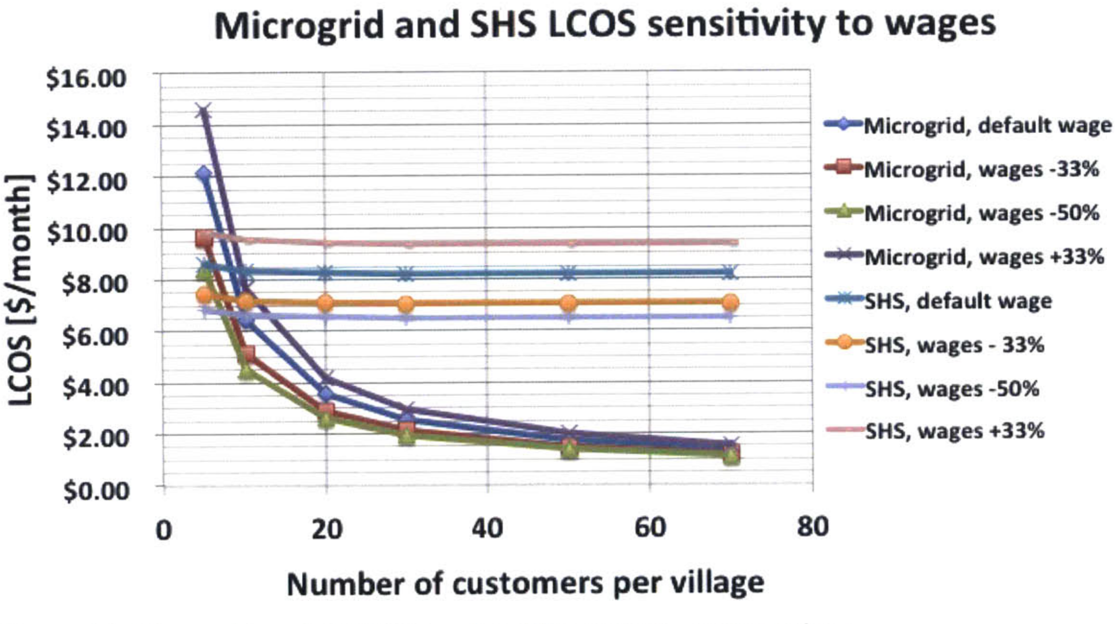

Figure 35: Microgrid and SHS LCOS under different wage assumptions

Figure 36 shows the sensitivity of LCOS for the SHS enterprise in response to changes in both the field crew efficiency and the employee wages. As we might have expected, making these changes in conjunction have much more impact than either on its' own. The general conclusion from this analysis is that, while the wage and employee efficiency assumptions in the default SHS models are critical in determining the monthly service fee required to break even, the general trend of cost as a function of village size (hence number of customers) remain constant. It is also clear that the operational efficiency in a microgrid is a key advantage that can help that enterprise control costs, especially for villages above a certain size.

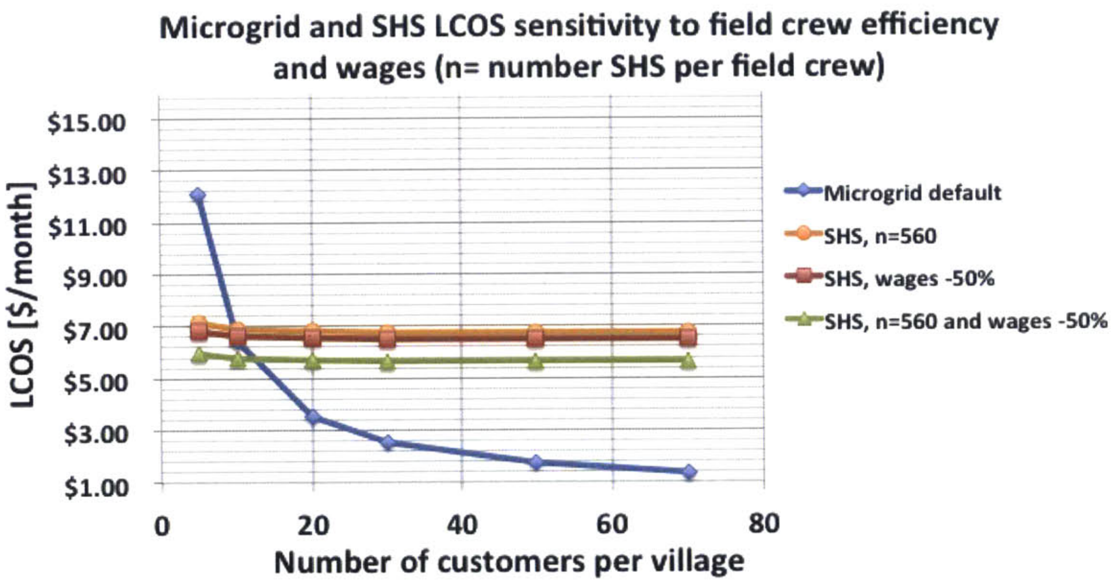

Figure 36: Effect of simultaneously increasing worker efficiency and decreasing wages for SHS enterprise

Chapter 6: Discussion

The objective of this work was to build a conceptual model of a DC microgrid enterprise that provides basic electrification in a rural Indian context, and to explore that model under a variety of operating assumptions in order to understand the factors that decide the competitiveness and viability of such a company. Furthermore we sought to understand how a microgrid company might compare to a similar service provider that uses individual solar home systems in lieu of a centralized microgrid. Finally, we looked at the practical limitations of the proposed DC microgrid from both a technical and an economic perspective to get a general sense of its' applicability to higher levels of electricity service. The purpose of comparing the microgrid to the SHS is not to make a generalizable conclusion that one system is superior to the other, but simply to put the microgrid into context with a technology that is both familiar and widely in use. This is important to note because neither the microgrid or SHS businesses proposed here actually exist; many private and public companies, NGOs, and government programs have been producing and distributing solar home systems for decades and none have chosen to implement the exact business and maintenance model we have considered. There is a reason for that- maintenance on distributed systems is very costly, difficult to manage and, as we have seen, it only gets worse as the number of customers (hence the number of systems) increases. Based on our analysis and results, we can highlight at least three factors that explain much of the differences in total costs between the proposed SHS and microgrid models.

The first factor is the effective COGS per customer of a microgrid as compared to an individual home system. Component costs are difficult to model with accuracy because they can change rapidly, as we have seen with falling PV prices in recent years. Components can also be subject to import and export tariffs, variations in supply and distribution networks, and other factors that lead to regional differences in pricing. In addition, other factors like brand reputation, customer loyalty, after sales support, etc., can cause two suppliers of a functionally equivalent component to charge very different prices. In this work we developed cost models of solar panels and batteries based on a sampling of components that are available online and to US consumers. Although we must accept these limitations of the model, there is a clear decrease in normalized prices (i.e. dollars per watt) for larger components as compared to smaller ones. Economies of scale in production and manufacturing of nearly any good (not just PV panels and batteries) lead to a reduction in costs at higher capacity, and this general behavior is the important factor; the specific pricing numbers come out of our COGS models are not the important take-away from this exercise. By aggregating demand across a number of customers, a microgrid is able to use components that are larger and therefore cheaper when compared to the equivalent capacity from several SHS. This is particularly true because we are comparing systems at the lowest end of the capacity curve, so there is an incredible benefit to aggregating even a few customers' demand. If we considered the individual load at each customer to be tens or hundreds of watts rather than a few watts, the SHS to meet that demand would already be further down the capacity-price curve and the benefits of demand aggregation would be lessened. Lower component costs lessen the financial burden of the initial installation (also reducing the amount of financing that is required), and make component replacements over time cheaper as well.

The second general conclusion that can be reached from this analysis is that operations and maintenance can be streamlined for a centralized microgrid. Because there are fewer components overall, and the most expensive pieces are all located in one place, we can expect it to be easier to find and fix problems. Intuitively we can say that a microgrid with 50 customers is only marginally more difficult to maintain than one with 20 customers; we still need to send a field crew to diagnose and repair the system, and that is where much of the cost lies. The quantitative models we developed in this work confirm this observation. Furthermore, the major components in a microgrid that are likely to fail (battery, charge controller, distribution wire, etc.) will affect many customers, so fixing the one problem will restore the service for everybody. In contrast, 50 solar home systems have 50 times as many points of failure, and fixing one problem restores service to only one customer. The analysis that was undertaken in this study shows how maintenance worker salaries can be distributed across a larger number of paying customers as the number of customers per microgrid increases. While adding customers to the microgrid does increase the number of load devices distributed among the customers, those devices (LEDs) are the simplest components in the system to replace. We also saw with our sensitivity analysis that increasing the number of customers in a microgrid decreases the overall sensitivity of LCOS to worker efficiency and wage assumptions.

A final observation is that the microgrid offers the designer an opportunity to design for any level of service reliability (i.e. battery capacity) desired. As we aggregate semi-random load profiles across a number of customers in a grid, it becomes increasingly unlikely that every single customer will be using the maximum load at a given point in time.

If each individual SHS is specified to provide lighting and mobile phone charging, then the PV panel and battery must be sized to meet that total load simultaneously. In effect, this means that 50 SHS will have a total capacity that is higher than a comparable microgrid that is designed to serve 50 customers. Because the SHS is designed for a worst-case load, the capacity utilization will be worse on average than with a microgrid. In this analysis we used the median of the outcome distributions as a point of reference, but in practice the system can be designed for any level of reliability. This "over-specification" problem with SHS is especially costly because, in conjunction with our first observation about component costs, it means that not only do a group of distributed SHS have larger total capacity but each unit of extra capacity is more expensive than it would be if we had larger panels and batteries.

We have already discussed some of the limitations of the modeling approach used in this work regarding the accuracy of component pricing, but there are several other important limitations that should be noted. To simplify the procedure, we calculated the total load and then specify battery and panel capacity to *exactly* meet that load. Of course, in the real world it will not be possible to purchase an arbitrary size of panel or battery, and the prices certainly won't be based on the capacity alone. Again, the idea was to capture the general dynamics of prices as a function of capacity and understand how those dynamics impact the overall system. Another consequence of this approach is that the capacity utilization in each instance of the model is perfect. In practice, we might expect a microgrid enterprise to choose several standard sizes of components and construct the systems using combinations of those standard sizes. This "discretization" would effectively reduce the capacity utilization that is achievable in practice. Finally, we calculate the LCOS by analytically solving the equations governing the model in order to find the price at which our enterprise breaks even. This is useful, but it does not take into consideration the customer willingness to pay. The availability of substitutes that might provide the same service (kerosene lanterns, free SHS donated by NGOs, etc.), customer perceptions about the microgrid enterprise, word of mouth referrals from other customers, and other factors will all have significant influence. In addition, customers may prefer to own their own system rather than pay for an ongoing service even if that service is more cost effective in the long run. A detailed analysis of all of these issues is beyond the scope of this work.

We have performed a detailed, quantitative analysis of a DC microgrid enterprise and highlighted how, in some circumstances, several factors can work in conjunction to reduce the cost of service when compared to a similar company that uses individual solar home systems to provide the same service. That is not to say that the microgrid is the preferred implementation in all cases. We have seen how distribution losses and rapidly escalating component sizes severely limit the applicability of this specific implementation at power levels above a few tens of watts for each customer. We have also seen how the proximity of houses to each other can have a significant impact on the technical and economic performance of the system, especially when considered in conjunction with higher loads. In villages with a critical mass of potential customers who live within a few thousand feet of each other, and where the expected load is several to several tens of watts, the microgrid may be a more cost effective and easier way to provide basic electrification than providing individual solar home systems to those customers.

Appendix A: Battery Pricing Database

Price [$]	Normalized Capacity [Wh]	Normalized Cost [$/Wh]	Vendor
$9.90	7.2	$1.38	http://www.batteryspace.com/SLA-Battery-Sealed-Lead-Acid-Battery-6V-1.2AH-S.aspx
$10.95	9.6	$1.14	http://www.batteryspace.com/sealedleadacidbattery12v08ahs.aspx
$15.81	9.6	$1.65	http://www.zbattery.com/Universal-12V-0-8Ah-Sealed-Lead-Acid-Battery?sc=2&category=62965
$13.66	9.6	$1.42	http://www.zbattery.com/Power-Patrol-12v-800mAh-Sealed-SLA1000?sc=2&category=62965
$11.95	14.4	$0.83	http://www.batteryspace.com/sealedleadacidbattery12v12ahs.aspx
$10.49	14.4	$0.73	http://www.zbattery.com/B-B-12V-1-2Ah-Sealed-Lead-Acid-Battery?sc=2&category=62965
$10.45	15.6	$0.67	http://www.zbattery.com/CSB-12v-1-3Ah-Sealed-Lead-Acid-Battery?sc=2&category=62965
$10.85	15.6	$0.70	http://www.zbattery.com/12-Volt-1-3aH-Sealed-Lead-Acid-Battery?sc=2&category=62965
$22.45	24	$0.94	http://www.zbattery.com/12-Volt-2aH-Sealed-Lead-Acid-Battery?sc=2&category=62965
$13.50	26.4	$0.51	http://www.zbattery.com/CSB-GP1222-Sealed-Lead-Acid-Battery?sc=2&category=62965
$8.50	27	$0.31	http://www.batteryspace.com/sealedleadacidbattery6v45ahs.aspx
$12.95	27.6	$0.47	http://www.batteryspace.com/sealedleadacidbattery12v23ahs1.aspx
$23.45	27.6	$0.85	http://www.zbattery.com/12V-2-3Ah-SLA-Camcorder-Battery-NP1223?sc=2&category=62965
$13.85	27.6	$0.50	http://www.zbattery.com/B-B-12V-2-3Ah-Sealed-Lead-Acid-Battery?sc=2&category=62965
$14.00	38.4	$0.36	http://www.batteryspace.com/sealedleadacidbattery12v33ahs.aspx
$15.99	40.8	$0.39	http://www.zbattery.com/Prism-12V-3-4Ah-Sealed-Lead-Acid-Battery
$11.65	42	$0.28	http://www.batteryspace.com/sealedleadacidbattery6v7ahs.aspx
$14.99	43.2	$0.35	http://www.zbattery.com/B-B-12V-3-6Ah-Sealed-Lead-Acid-Battery?sc=2&category=62965
$16.95	49.2	$0.34	http://www.batteryspace.com/sealedleadacidbattery6v82ah.aspx
$13.50	54	$0.25	http://www.batteryspace.com/sealedleadacidbattery12v45ahupgradeto5ahforupsandemergencylightss.aspx
$15.45	54	$0.29	http://www.zbattery.com/CSB-12V-4-5Ah-Sealed-Lead-Acid-Battery?sc=2&category=62965
$19.18	54	$0.36	http://www.zbattery.com/CSB-12V-17W-Sealed-Lead-Acid-Battery?sc=2&category=62965
$18.49	60	$0.31	http://www.zbattery.com/B-B-12V-5Ah-Sealed-Lead-Acid-Battery?sc=2&category=62965

$18.54	60	$0.31	http://www.zbattery.com/Power-Patrol-12v-5Ah-Sealed-Lead-SLA1056?sc=2&category=62965
$15.49	60	$0.26	http://www.zbattery.com/Power-Patrol-12v-5Ah-Sealed-Lead-Acid-Battery-187-tabs?sc=2&category=62965
$20.32	66	$0.31	http://www.zbattery.com/CSB-12V-21W-Sealed-Lead-Acid-Battery?sc=2&category=62965
$21.99	69.6	$0.32	http://www.zbattery.com/B-B-Brand-12V-5-8Ah-High-Rate-SLA-Battery_2?sc=2&category=62965
$19.62	69.6	$0.28	http://www.zbattery.com/CSB-Brand-12V-5-8Ah-High-Rate-SLA-Battery?sc=2&category=62965
$21.95	72	$0.30	http://www.batteryspace.com/sealedleadacidbattery6v12ahs_1.aspx
$15.95	72	$0.22	http://www.batteryspace.com/Sealed-Lead-Acid-Battery-6V-12AH.aspx
$21.99	72	$0.31	http://www.zbattery.com/B-B-12V-6Ah-10-hr-rate-Sealed-Lead-Acid-Battery?sc=2&category=62965
$18.90	84	$0.23	http://www.batteryspace.com/sealedleadacidbattery12v75ah20hrsforupsseascooterande-bikes.aspx
$19.99	84	$0.24	http://www.zbattery.com/b-b-12v-7ah-sealed-lead-acid-battery?sc=2&category=62965
$24.99	84	$0.30	http://www.zbattery.com/B-B-12V-7Ah-High-Cycle-Use-Sealed-Lead-Acid-Battery?sc=2&category=62965
$17.40	86.4	$0.20	http://www.zbattery.com/Power-Patrol-12v-7-2Ah-Sealed-SLA1079?sc=2&category=62965
$18.27	86.4	$0.21	http://www.zbattery.com/CSB-12V-7-2Ah-Sealed-Lead-Acid-Battery?sc=2&category=62965
$20.31	86.4	$0.24	http://www.zbattery.com/CSB-12V-7-2Ah-SLA-Battery-Fire-Resistant?sc=2&category=62965
$19.99	86.4	$0.23	http://www.zbattery.com/CSB-EVX1272-SLA-Battery?sc=2&category=62965
$28.67	88.8	$0.32	http://www.zbattery.com/CSB-12V-28W-Sealed-Lead-Acid-Battery-replaces-HC1225W?sc=2&category=62965
$20.99	90	$0.23	http://www.zbattery.com/B-B-12V-7-5Ah-Sealed-Lead-Acid-Battery_3?sc=2&category=62965
$18.39	96	$0.19	http://www.zbattery.com/Power-Patrol-12v-8Ah-Sealed-Lead-SLA1075?sc=2&category=62965
$22.37	96	$0.23	http://www.zbattery.com/CSB-12V-8Ah-10-high-rate-Sealed-Lead-Acid-Battery?sc=2&category=62965
$25.99	96	$0.27	http://www.zbattery.com/B-B-12V-8Ah-Sealed-Lead-Acid-Battery-B1-Connector?sc=2&category=62965
$27.99	108	$0.26	http://www.zbattery.com/Universal-UB9-12-Sealed-Lead-Battery?sc=2&category=62965
$29.90	120	$0.25	http://www.batteryspace.com/sealedleadacidbattery12v10ah120whs.aspx
$59.95	120	$0.50	http://www.batteryspace.com/sealedleadacidbattery6v20ah.aspx
$39.99	120	$0.33	http://www.zbattery.com/B-B-12V-10Ah-Sealed-Lead-Acid-AGM-BP10-12-Battery?sc=2&category=62965
$35.00	144	$0.24	http://www.batteryspace.com/sealedleadacidbattery12v12ah144whforupsseascootere-bikes.aspx
$29.99	144	$0.21	http://www.zbattery.com/Power-Patrol-12v-12Ah-Sealed-Lead-Acid-Battery-250-

			tabs?sc=2&category=62965
$41.99	144	$0.29	http://www.zbattery.com/B-B-12V-12Ah-Sealed-Lead-Acid-Battery-T1-Connector?sc=2&category=62965
$42.99	144	$0.30	http://www.zbattery.com/B-B-12V-12Ah-High-Cycle-Use-Sealed-Lead-Acid-Battery?sc=2&category=62965
$40.99	144	$0.28	http://www.zbattery.com/B-V-12V-12Ah-Mobile-Electric-SLA-Battery?sc=2&category=62965
$47.99	144	$0.33	http://www.zbattery.com/B-B-12V-12Ah-Sealed-Lead-Acid-Battery_2?sc=2&category=62965
$33.99	144	$0.24	http://www.zbattery.com/CSB-EVX1220F2-SLA-Battery?sc=2&category=62965
$47.99	156	$0.31	http://www.zbattery.com/B-B-12V-13Ah-10-hr-rate-Sealed-Lead-Acid-Battery?sc=2&category=62965
$34.00	204	$0.17	http://www.batteryspace.com/sealedleadacidbattery12v17ah204whs.aspx
$48.69	204	$0.24	http://www.zbattery.com/B-B-12-Volt-17aH-Sealed-Lead-Acid-Battery?sc=2&category=62965
$56.00	204	$0.27	http://www.zbattery.com/B-b-12v-17ah-Sealed-Lead-Acid-Battery-T2-Connector-?sc=2&category=62965
$44.99	204	$0.22	http://www.zbattery.com/CSB-GP12170-Sealed-Lead-Acid-Battery?sc=2&category=62965
$54.99	204	$0.27	http://www.zbattery.com/B-B-12V-17Ah-Sealed-Lead-Acid-Battery-25-Bolthole?sc=2&category=62965
$51.40	216	$0.24	http://www.zbattery.com/Power-Patrol-12v-18Ah-Sealed-SLA1116?sc=2&category=62965
$50.99	216	$0.24	http://www.zbattery.com/B-B-Battery-BP18-12-12v-18ah-lead-acid-battery?sc=2&category=62965
$42.60	240	$0.18	http://www.batteryspace.com/sealedleadacidbattery12v20ah240whs.aspx
$72.99	240	$0.30	http://www.zbattery.com/B-B-12V-20Ah-SLA-High-Cycle-Use-Battery?sc=2&category=62965
$49.99	240	$0.21	http://www.zbattery.com/CSB-EVX12200-SLA-Battery?sc=2&category=62965
$59.99	240	$0.25	http://www.zbattery.com/B-B-12v-20ah-Sla-High-Cycle-Use-Sla-Battery?sc=2&category=62965
$55.94	240	$0.23	http://www.zbattery.com/CSB-12V-20Ah-High-Rate-Sealed-Lead-Acid-Battery?sc=2&category=62965
$57.99	240	$0.24	http://www.zbattery.com/B-B-12V-20Ah-10-hr-rate-Sealed-Lead-Acid-Battery?sc=2&category=62965
$59.95	252	$0.24	http://www.batteryspace.com/sealedleadacidbattery6v42ah.aspx
$55.00	312	$0.18	http://www.batteryspace.com/sealedleadacidbattery12v26ahforwheelchairla-12v26ahs.aspx
$69.99	312	$0.22	http://www.zbattery.com/CSB-EXX12260B1-SLA-Battery?sc=2&category=62965
$79.99	336	$0.24	http://www.zbattery.com/B-B-12v-28ah-Sla-Battery-bolt-On-Contacts?sc=2&category=62965
$83.99	336	$0.25	http://www.zbattery.com/B-B-12V-28Ah-High-Cycle-Use-Sealed-Lead-Acid-Battery?sc=2&category=62965
$129.95	384	$0.34	http://www.batteryspace.com/sealedleadacidbattery12v32ahu1gelbattery.aspx
$77.57	408	$0.19	http://www.zbattery.com/CSB-EVX12340-SLA-Battery?sc=2&category=62965

$75.00	420	$0.18	http://www.batteryspace.com/sealedleadacidbattery12v35ahla-12v35ah.aspx
$71.67	420	$0.17	http://www.zbattery.com/Power-Patrol-12v-35Ah-Sealed-Lead-Acid-Battery-Threaded-Insert-w-Bolt?sc=2&category=62965
$113.99	420	$0.27	http://www.zbattery.com/B-B-12V-35Ah-Sealed-Lead-Acid-Battery?sc=2&category=62965
$85.95	480	$0.18	http://www.batteryspace.com/sealedleadacidbattery12v40ahreplacementbatterybsl1161la-12v40ah.aspx
$85.95	480	$0.18	http://www.batteryspace.com/sealedleadacidbattery12v40ahreplacementbatterybsl1161la-12v40ah.aspx
$169.99	600	$0.28	http://www.zbattery.com/B-B-High-Rate-12V-50Ah-SLA-Battery?sc=2&category=62965
$146.50	600	$0.24	http://www.zbattery.com/B-B-12V-50Ah-Mobile-Electric-SLA-Battery?sc=2&category=62965
$137.61	624	$0.22	http://www.zbattery.com/GPL12520-CSB-12V-52Ah-10-hr-rate-Sealed-Lead-Acid-Battery
$156.99	636	$0.25	http://www.zbattery.com/12V-53Ah-10-hr-rate-Sealed-Lead-Acid-Battery?sc=2&category=62965
$130.95	660	$0.20	http://www.batteryspace.com/sealedleadacidbattery12v55ahla-12v55ah.aspx
$129.95	840	$0.15	http://www.batteryspace.com/sealedleadacidbattery12v70ahla-12v70ah.aspx
$169.95	900	$0.19	http://www.batteryspace.com/sealedleadacidbattery12v75ahla-12v75ah.aspx
$176.37	900	$0.20	http://www.zbattery.com/CSB-12v-75ah-Group-24-Sealed-Lead-Battery?sc=2&category=62965
$225.00	936	$0.24	http://www.zbattery.com/12V-78Ah-10-hr-rate-Sealed-Lead-Acid-Battery?sc=2&category=62965
$191.99	1056	$0.18	http://www.zbattery.com/CSB-Group-27-12V-88Ah-Sealed-Lead-Acid-Battery?sc=2&category=62965
$261.99	1080	$0.24	http://www.zbattery.com/12V-90Ah-10-hr-rate-Sealed-Lead-Acid-Battery?sc=2&category=62965
$269.00	1200	$0.22	http://www.batteryspace.com/sealedleadacidbattery6v200ahub-gc2golfcart.aspx
$216.18	1200	$0.18	http://www.zbattery.com/CSB-Group-31-12V-100Ah-Sealed-Lead-Acid-Battery?sc=2&category=62965
$299.99	1296	$0.23	http://www.zbattery.com/12V-108Ah-10-hr-rate-Sealed-Lead-Acid-Battery?sc=2&category=62965
$199.00	1320	$0.15	http://www.batteryspace.com/sealedleadacidbattery12v110ahla-12v110ah.aspx

Appendix B: Solar Panel Pricing Database

Peak Power [W]	Price [$]	Normalized Cost [$/W]	Vendor
1.4	$27.00	$19.29	http://www.altestore.com/store/Solar-Panels/Kyocera-14-Watt-12-Volt-Mini-Solar-Panel/p718/
3	$46.00	$15.33	http://www.altestore.com/store/Solar-Panels/Sunwize-SolCharger-SC3-12V-3W-12V-Solar-Panel/p4124/
3	$41.00	$13.67	http://www.altestore.com/store/Solar-Panels/Sunwize-SolCharger-SC3-6V-3W-6V-Solar-Panel/p4123/
4.5	$71.50	$15.89	http://www.altestore.com/store/Solar-Panels/Ameresco-BPSX305M-45W-12V-Solar-Panel-with-J-Box/p10174/
5	$26.85	$5.37	http://www.altestore.com/store/Solar-Panels/altE-ALT5-12P-Poly-5W-12V-Solar-Panel/p10347/
5	$64.95	$12.99	http://www.altestore.com/store/Solar-Panels/Kyocera-KS5-5W-12V-Solar-Panel/p3297/
6	$78.00	$13.00	http://www.altestore.com/store/Solar-Panels/Sunwize-SolCharger-SC6-12V-6W-12V-Solar-Panel/p4218/
6	$78.00	$13.00	http://www.altestore.com/store/Solar-Panels/Sunwize-SolCharger-SC6-6V-6W-6V-Solar-Panel/p4460/
10	$42.00	$4.20	http://www.altestore.com/store/Solar-Panels/altE-ALT10-12P-Poly-10W-12V-Solar-Panel/p10348/
10	$115.70	$11.57	http://www.altestore.com/store/Solar-Panels/Ameresco-Solar-BPSX310J-10W-12V-Solar-Panel-with-J-Box/p10290/
10	$81.00	$8.10	http://www.altestore.com/store/Solar-Panels/Kyocera-KS10-10W-12V-Solar-Panel/p6649/
12	$124.00	$10.33	http://www.altestore.com/store/Solar-Panels/Sunwize-SolCharger-SC12-12V-12W-12V-Solar-Panel/p4462/
12	$129.00	$10.75	http://www.altestore.com/store/Solar-Panels/Sunwize-SolCharger-SC12-6V-12W-6V-Solar-Panel/p4253/
18	$161.00	$8.94	http://www.altestore.com/store/Solar-Panels/Sunwize-SolCharger-SC18-12V-18W-12V-Solar-Panel/p4463/
20	$71.00	$3.55	http://www.altestore.com/store/Solar-Panels/altE-ALT20-12P-Poly-20W-12V-Solar-Panel/p10349/
20	$161.20	$8.06	http://www.altestore.com/store/Solar-Panels/Ameresco-BPSX420J-20W-12V-Solar-Panel-with-J-Box/p10287/
24	$271.00	$11.29	http://www.altestore.com/store/Solar-Panels/Sunwize-SolCharger-SC24-12V-24W-12V-Solar-Panel/p4464/
30	$104.00	$3.47	http://www.altestore.com/store/Solar-Panels/altE-ALT30-12P-Poly-30W-12V-Solar-Panel/p10350/
30	$220.00	$7.33	http://www.altestore.com/store/Solar-Panels/Ameresco-BP330J-30W-12V-Solar-Panel-with-J-Box/p10211/
30	$162.40	$5.41	http://www.altestore.com/store/Solar-Panels/Sunwize-SW-S30P-30W-12V-Solar-Panel-with-J-Box/p8984/
40	$273.00	$6.83	http://www.altestore.com/store/Solar-Panels/Ameresco-Solar-BP440J-40W-12V-Solar-Panel-with-J-Box/p10292/
40	$227.00	$5.68	http://www.altestore.com/store/Solar-Panels/Sunwize-SW-S40P-40W-12V-Solar-Panel-with-J-Box/p9045/
50	$155.00	$3.10	http://www.altestore.com/store/Solar-Panels/altE-ALT50-12P-Poly-50W-12V-Solar-Panel/p10351/

50	$256.75	$5.14	http://www.altestore.com/store/Solar-Panels/Ameresco-BP450J-50W-12V-Solar-Panel-with-J-Box/p10188/
50	$189.00	$3.78	http://www.altestore.com/store/Solar-Panels/SolarWorld-50-Watt-12V-Poly-Solar-Panel-SW50/p9865/
55	$251.72	$4.58	http://www.altestore.com/store/Solar-Panels/Sunwize-SW-S55P-55W-12V-Solar-Panel-with-J-Box/p9386/
80	$185.00	$2.31	http://www.altestore.com/store/Solar-Panels/altE-ALT80-12P-Poly-80W-12V-Solar-Panel/p10352/
80	$199.00	$2.49	http://www.altestore.com/store/Solar-Panels/SolarWorld-SW80-Poly-80W-12V-Solar-Panel-with-J-Box/p9903/
85	$283.00	$3.33	http://www.altestore.com/store/Solar-Panels/Sunwize-SW-S85P-85W-12V-Solar-Panel-with-J-Box/p9387/
90	$409.00	$4.54	http://www.altestore.com/store/Solar-Panels/Ameresco-BP490J-90W-12V-Solar-Panel-with-J-Box/p10175/
100	$215.00	$2.15	http://www.altestore.com/store/Solar-Panels/altE-ALT100-12P-Poly-100W-12V-Solar-Panel/p10353/
100	$255.00	$2.55	http://www.altestore.com/store/Solar-Panels/altE-ALT100-24P-Poly-100W-24V-Solar-Panel/p10355/
120	$255.00	$2.13	http://www.altestore.com/store/Solar-Panels/altE-ALT120-12P-Poly-120W-12V-Solar-Panel/p10354/
130	$487.50	$3.75	http://www.altestore.com/store/Solar-Panels/Sharp-ND-130UJF-130W-12V-Solar-Panel/p6721/
135	$270.00	$2.00	http://www.altestore.com/store/Solar-Panels/SolarWorld-SW135-Poly-135W-12V-Solar-Panel-with-J-Box/p9904/
140	$284.99	$2.04	http://www.altestore.com/store/Solar-Panels/Kyocera-KD140GX-LFBS-140W-12V-Solar-Panel/p10189/
140	$288.00	$2.06	http://www.altestore.com/store/Solar-Panels/Kyocera-KD140SX-UFBS-140W-12V-Solar-Panel-with-J-Box/p10190/
140	$279.95	$2.00	http://www.altestore.com/store/Solar-Panels/SolarWorld-SW140-Poly-140W-12V-Solar-Panel-with-J-Box/p10196/
200	$299.00	$1.50	http://www.altestore.com/store/Solar-Panels/altE-ALT200-24P-Poly-200W-24V-Solar-Panel/p10356/
215	$305.70	$1.42	http://www.altestore.com/store/Solar-Panels/Kyocera-KD215GX-LFBS-215W-18V-Solar-Panel-Dark-Blue-Cells/p10454/
225	$259.00	$1.15	http://www.altestore.com/store/Solar-Panels/SolarWorld-Sunmodule-SW225-Mono-225W-20V-Solar-Panel/p10024/
235	$235.00	$1.00	http://www.altestore.com/store/Solar-Panels/SolarWorld-235W-Solar-Panel-SunModule-SW235-Poly-V25-Frame/p9854/
240	$330.00	$1.38	http://www.altestore.com/store/Solar-Panels/Kyocera-KD240GX-LPB-240W-Solar-Panel/p8979/
240	$220.00	$0.92	http://www.altestore.com/store/Solar-Panels/SolarWorld-240W-Solar-Panel-SunModule-SW240-Poly-V25-Frame/p10121/
240	$249.00	$1.04	http://www.altestore.com/store/Solar-Panels/SolarWorld-Sunmodule-SW240-Poly-240W-20V-Solar-Panel-Type-B/p10153/
240	$229.00	$0.95	http://www.altestore.com/store/Solar-Panels/Suntech-PLUTO240-Wde-240W-20V-Solar-Panel/p9663/
240	$213.00	$0.89	http://www.altestore.com/store/Solar-Panels/Suntech-STP240-20Wde-240W-20V-Solar-Panel/p10446/
245	$241.45	$0.99	http://www.altestore.com/store/Solar-Panels/Canadian-Solar-CS6P-24M-AB-245W-20V-Solar-Panel/p10560/

245	$339.00	$1.38	http://www.altestore.com/store/Solar-Panels/Kyocera-KD245GX-LFB-245W-Solar-Panel/p10222/
245	$265.00	$1.08	http://www.altestore.com/store/Solar-Panels/SolarWorld-245-Watt-Solar-Panel-SunModule-SW245-Poly-V25-Frame/p10142/
245	$275.00	$1.12	http://www.altestore.com/store/Solar-Panels/SolarWorld-245W-Black-Solar-Panel-Sunmodule-SW245-Type-B-Monocrystalline/p10155/
245	$260.00	$1.06	http://www.altestore.com/store/Solar-Panels/SolarWorld-245W-Solar-Panel-Sunmodule-SW245-Poly-v20-Frame/p10154/
250	$439.00	$1.76	http://www.altestore.com/store/Solar-Panels/SolarWorld-250W-Solar-Panel-Sunmodule-SW250-Mono-V20-Frame/p9879/
250	$247.00	$0.99	http://www.altestore.com/store/Solar-Panels/Suntech-STP250-20Wd-250W-20V-Solar-Panel/p10447/
255	$343.46	$1.35	http://www.altestore.com/store/Solar-Panels/SolarWorld-Sunmodule-SW255-Black-255W-20V-Solar-Panel-Monocrystalline/p10499/
260	$324.00	$1.25	http://www.altestore.com/store/Solar-Panels/SolarWorld-260-Watt-Solar-Panel-Sunmodule-260W-SW260-Mono-V25-Frame/p10500/
285	$279.00	$0.98	http://www.altestore.com/store/Solar-Panels/Suntech-STP285-24Vd-285W-24V-Solar-Panel/p10171/
290	$367.00	$1.27	http://www.altestore.com/store/Solar-Panels/Suntech-STP290-24Vd-290W-24V-Solar-Panel/p10333/

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