An Analysis of the Feasibility and Impacts of Implementing a Microgrid in South Africa

Using HOMER to Model and Predict Outcomes of Microgrid Implementation

Bass Connections Energy & the Environment Design and Innovation Final Report

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Ashley Meuser - Pratt ‘19
Savini Prematilleke - Pratt ‘19
Tyler Wakefield - Trinity ‘18
Cassidee Kido - Pratt ‘17
Kerim Algul - Pratt ‘17
Ryan Hussey - Trinity ‘17
Nitish Garg - Duke MEMP ‘17

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Executive Summary

1.1 billion people around the world have little to no access to reliable electricity.[i] Electricity access is essential to economic growth and development, but cost and physical barriers make it such that connection to the central grid is years away for many rural communities. Microgrids can bring power to these communities at a smaller scale, giving them the economic benefits of electricity access without the costs of connecting to the larger grid. Powering the microgrid with energy sources already found in these communities, including wind, solar, and biogas from cattle waste, makes this system self-sustaining with a low environmental impact. This project evaluates the potential for improving electricity access in the KwaZulu-Natal and Eastern Cape regions of South Africa through the implementation of a microgrid. HOMER, a program developed by the National Renewable Energy Lab (NREL), that models microgrids' physical behaviors and costs, was the main tool used in evaluating different microgrid configurations. This analysis proposes three different microgrid configurations, assesses their technical and economic feasibilities, and examines their environmental and social impacts on the surrounding community.

Introduction

Problem Background

Access to sustainable energy that is clean, reliable, and affordable is key to achieving economic growth and development. Energy access provides numerous benefits, including job creation, increased business revenue, female empowerment, improvement in education, increased food security, increased life expectancy, and reduced time spent on household chores. Key services include refrigeration, which is important both for vaccinations and food storage, cleaner fuel for cookstoves, lighting for longer business and study hours, market expansion, energy for crop irrigation, and mobile phone charging. Considering all of these opportunities that energy affords, it's clear that energy access is critical for social equity, meeting communities' basic needs, and enabling competition in the global marketplace.[ii]

Increasing energy access is challenging because houses and communities in many developing regions are spread out, often in mountainous terrain. Consequently, it is too costly to connect to the grid and may be difficult to transport materials and fuel. Start-up costs are also prohibitive for many impoverished communities. Further, for the system to be sustainable, someone with technical knowledge must be available to operate and maintain it. Ideally, a successful system should operate at an affordable levelized cost of energy while providing reliable, sustainable electricity.

Project Background

We chose to address this issue because energy serves as an enabler, and without it, over a billion individuals do not have their basic needs met or have the chance to achieve a higher economic status. Further, the current pace of development is inadequate for achieving global energy access in the foreseeable future. Not only is the rate of electrification and investment too low, but discussions about energy and poverty also assume that the population without electricity access will only demand it in small amounts over the next several decades. This assumption leads to projections of future energy consumption that are far too low, construction of energy systems that do not provide meaningful energy access, and imply those communities will remain impoverished.[iii] For the energy system to enable sustainable development, the energy generated must support more services than lighting, and the system must support load demand growth as the community's economic status improves.

We focused on energy access in South Africa for several reasons. First, providing energy for all is a priority of the South African government. 83% of households have energy access, but still 8 million citizens are without electricity, 3 million of which are located in Kwazulu-Natal.[ivv] The South African National Development Plan (NDP) declares that by 2030 South Africa will invest in its energy infrastructure to provide at least 95% of the population with electricity, and that renewable resources will provide at least 20,000 MW of the additional 29,000 MW of electricity needed.[vi] Thus, it is a needed service that the government and community support. Also, the energy situation in South Africa is ideal for developing a renewable-based microgrid, as the rural agricultural communities are too remote to connect to the main grid and have access to renewable energy sources, such as animal waste for a biogas generator and strong solar and wind resources. The communities are also still accessible to construct the microgrid because South Africa is a politically stable country and is more developed than the majority of countries facing energy challenges. In addition, there is more data and information available from South Africa because it is more developed and there is not a language barrier. Finally, coal currently meets over 90% of electricity demand, so investing in clean energy in South Africa is important so that it can become an alternative to coal.

There are two primary methods to provide energy in developing regions: standalone systems and microgrids. While constructing a power plant may take over a decade, a decentralized microgrid has a low upfront cost, quick deployment time, can operate alone or connect to a main grid, and can provide energy access in regions too remote or difficult to connect to the national power grid at present. This speed, flexibility, and low upfront cost makes microgrids an ideal way to bring energy connectivity to developing areas. Microgrids utilize a variety of energy sources, taking advantage of renewable sources in the region such as solar power, wind power, and biogas from animal waste. Further, they provide greater energy security and their construction has a lower environmental cost than connection to a national grid. The grid can be highly unreliable, especially when the regions it connects to are distant and separated by mountainous terrain. When the grid fails, consumers would be left either without electricity or with low quality, expensive fuels like kerosene to power lights. Microgrids therefore can be more reliable for communities.

Our project analyzes the feasibility of developing a self-sustaining micro-grid which could potentially be connected to the national grid in the future in remote regions of KwaZulu-Natal and Eastern Cape in South Africa. We identified parameters specific to this region and optimized a micro-grid system for three ranges of community sizes to develop recommendations for communities in South Africa that fit these characteristics. This process can be applied to other regions.

The microgrid system we modeled runs on PV, wind turbines, a biogas generator, and lead-acid batteries. South Africa has a large solar capacity, so the addition of batteries will enable the system the generate energy and store it in the batteries during the day, then use this resource when little solar energy is available. The wind and biogas will supplement this energy. A biogas generator is ideal for agricultural communities as there is excess waste available from cattle, and it can supply reliable power when the solar or wind resource is too low. If the community lacks sanitation, human waste may also supplement the animal waste.

Powering the micro-grid with renewable energy also has a smaller levelized cost of energy (LCE) than fossil fuels.

We modeled microgrids in communities of 75, 400, and 1250 households to develop recommendations that would fit typical South African communities of all sizes. We focused on the region between KwaZulu-Natal and Eastern Cape as there is a high concentration of households without energy (as shown in Figure 1). The South African energy utility Eskom also analyzed off-grid energy potential for households in each province and found that Kwazulu-Natal and Eastern Cape had the highest potential, with 84,000 and 73,000 potential households, respectively.[vii] We looked specifically at communities that were not along the coast, as the strong coastal wind makes wind turbines the ideal energy option there, unlike in the rest of the country.

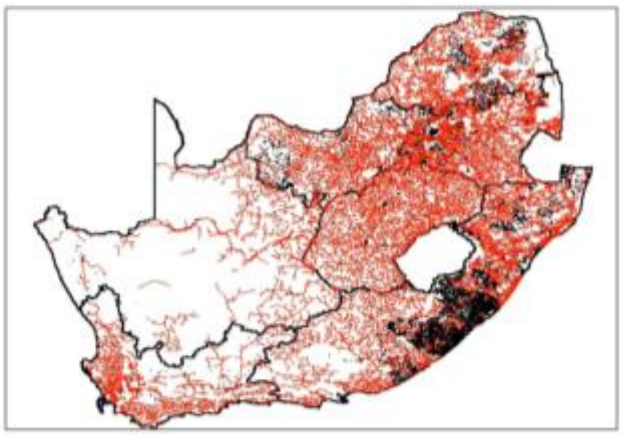

Figure 1: Map showing electrified regions (red), unelectrified populated regions (black), and unelectrified unpopulated regions (white) in South Africa[viii]

Technical Design: Using HOMER

The HOMER (Hybrid Optimization Model for Multiple Energy Resources) Pro[ix], originally developed by the National Renewable Energy Laboratory, is a microgrid modelling and optimization software, that is applicable in a range of sectors: from village power to grid-connected industrial utilities. HOMER allows users to input environmental and geographical data from a particular location, as well as the specificities of the desired grid components, and outputs a ranking of the most optimal grid configurations.

Why did we choose HOMER?

We discovered that HOMER was suitable for our needs after looking into studies that align with our own. We came across a few different papers that both look into the design and optimization of a microgrid for a particular location, and use HOMER to their benefit.

The first paper[x] was a case study on the implementation of a microgrid versus grid extension in Ntabankulu Local Municipality in Eastern Cape, South Africa. The paper presented a multitude of benefits of using HOMER, including that it displays a ranked tabular list of microgrid configurations in terms of least total

Net Present Cost (NPC), it limits input complexity, and performs fast computations. The second paper[xi] was a case study on renewable energy microgrid vs. grid extension in Umhlabuyalingana Local Municipality in Kwazulu-Natal, South Africa. This case study presented similar benefits of using HOMER as previous article, however they only consider models with some combination of solar, wind, and batteries, and didn't consider the benefits of biogas CHP. Another paper[xii] explored the design optimization and technological and economic analysis of an off-grid integrated renewable energy system designed to meet the demand of a rural village in West Bengal, India. This paper modelled seven scenarios, each with a different combination of electricity generation (anaerobic digestion with biogas CHP and solar PV) and storage elements (batteries, water electrolyser, and hydrogen storage with fuel cell). This paper used HOMER to do the exact kind of modelling we want to do, which is to determine the best model for electricity generation, just in a different location. The last paper[xiii] we found was a case study in South Africa which looked into the feasibility of a microgrid combining solar, wind, hydropower, biogas (from cattle waste), and biomass (gasification) technologies. The paper employed a completely renewable system, extremely similar to ours, and interestingly enough came to the conclusion that their configuration was infeasible due to biomass limitations. This is insightful because as discussed later, biomass was also a limiting factor to our model, though we did not find our model to be infeasible.

These papers conducted studies extremely similar to the goals of this paper, and except for the last paper, all differed in key points. For instance, one study didn't consider a renewable energy microgrid, while another did use renewable energy sources, but not specifically biogas. Furthermore, while numerous papers used HOMER for similar endeavors, they didn't focus on the region of South Africa that we're focusing on. However, the most significant difference between all of these papers and ours, is that our ultimate goal differs. Instead of stopping at the goal of creating the most optimal microgrid configuration for a particular region, we hope to take this a step further by making our results more usable and our inputs more generalizable, thereby allowing anyone to take our results and easily create the most optimal microgrid configuration for any location and a range of community sizes.

Overview of How HOMER Works

HOMER was developed by the National Renewable Energy Lab (NREL) and ultimately helps model the life-cycle costs of a microgrid system. To do this, HOMER primarily does three things: simulate, optimize, and perform a sensitivity analysis[xiv]. First, the user adds in different elements that they want to include in the microgrid (for example, solar panels, wind turbines, biogas generator, converter, and controller) and after adding all the necessary elements, HOMER models the microgrid for each hour of the year to determine the technical feasibility and life-cycle cost. Concurrently, HOMER is also optimizing the system; in outputting the "most optimal" system to the user, HOMER finds the system that satisfies certain constraints input by the user and has the lowest total net present cost (NPC). The NPC includes all costs and revenues that occur within the project lifetime and discounts future cash flows to the present. To optimize the output, HOMER considers multiple values for several components of the system including: size of the PV array, number of wind turbines, size of the generator, number of batteries, size of the ac-dc converter, and the dispatch strategy. This is the sensitivity analysis which helps increase the accuracy of the model as it creates thousands of different options for the system and models them all before choosing the most optimal one.

Our Three Models

In order to make our results applicable to a wide variety of community sizes, we ran HOMER separately three times. Each run was identical in terms of the specifications of its components. The microgrids each contain some combination of a biogas generator, PV array, wind turbines, batteries, and ac-dc inverter. The values that were input for all four models were specific to the Eastern Cape and Kwazulu Natal provinces of South Africa. The only difference between each model was the community size. The table below displays community size of each model and their respective scaled annual average electric load and available biomass. The biomass values were calculated using the following equation: *num households* x *2.5 cattle/household* x *15 kg waste / cattle / day* x *25% waste reclaimed*. These electric load values were extrapolated from electric load data of a 275 household village in rural Indonesia. In order to scale the value obtained from the Indonesian case study to our model sizes we assumed a linear increase in both electric load and available biomass as the number of households increases.

Community Size (Number of Households)	Scaled Annual Average Electric Load (kWh/d)	Available Biomass (Tons/day)
75	98.1	0.70
400	523.3	3.75
1250	1635	11.72

Table 1: Model community size and relative electric load and biomass (Extrapolated from 275 household recently electrified Indonesian Village (Kamanggih, East Sumba, Indonesia)).

Other key assumptions made in our model include an inflation rate of 6.5%, a nominal discount rate of 8%, and an average household income of $1080.40. The model does not consider the costs of the controller or the transmission infrastructure.

Choosing Inputs

In our model we included parameters for specific technology components that are ideal for the communities' sizes, location, and electric loads. This enabled HOMER to output results that are specific to our system.

Unlike solar panels or wind turbines which have a standard power rating and can be multiplied to fit the electric load, biogas digesters and generators are best designed to fit the site-specific load. There are many different types of digester designs, and are best chosen by the site-specific soil, temperature, and biomass characteristics. A single generator can produce a range of power outputs, and generators exist in a long range of power outputs from Watts to Megawatts. As the soil characteristics, building material availability and cost were unknown, we decided to create a composite $/kW figure for both the digester and generator rather than choosing a specific digester design and generator. After researching costs of each, we found that our figure closely matched HOMER's given $3,000/kW figure for a biogas generator, and decided to stick with HOMER's given cost.

We decided to use the CanadianSolar Super Power CS6K-295MS[xv] solar panel because it is readily available for sale in South Africa. In addition, CanadianSolar solar panels are compatible with HOMER. HOMER has the option to choose a specific solar panel from its data base, and links its specification sheet with a range of values that it automatically inputs into the software and uses during calculations. This particular PV panel is a 295 W and after inputting its retail price from the online store where it's sold in

South Africa, HOMER linearly scales the prices for a range of wattages, so that it can select the most optimal cost versus wattage per panel.

We used the Kestrel e400n wind turbine because Kestrel is a South African company, so the wind turbines are locally produced and easily acquired, and operation support is available if needed. The wind turbine also maintains its rated output in excess wind speeds, and its price is comparatively low. A 3.5 kW turbine is also a manageable size for a community to maintain.

We decided to choose the Redflow ZBM battery for several reasons. First, it is environmentally friendly and all of its components can be recycled or repurposed after use[xvi]. Additionally, it is very safe and does not carry the risk of fires or thermal runaway, thus reducing the need for a fire suppression system. Its safety, lifetime, and performance are not affected by temperatures, which is important given South Africa's hot climate in the summer. Finally, its energy capacity and power output are independent which means that the amount of energy it can store is only determined by the concentration of the ions in the electrolyte[xvii]. This means that it allows for greater flexibility in adding capacity and reduces the physical footprint of extra capacity. This is important because once a community is electrified, it will tend to use more electricity later on, meaning there is a high possibility of needing extra battery capacity.

Results and Discussion

After inputting all available geographic data, technology choices, and costs, HOMER calculated thousands of microgrid designs with different technology combinations and costs. While HOMER ranks its outputs by lowest net present cost, we scrutinized results using criteria other than cost, such as installation feasibility, repair feasibility, and social impact. In the smallest community (see Table 2), we selected a microgrid design that only uses solar and biogas, despite its slightly higher cost than a design which uses solar, biogas, and wind. This choice was made out of concern for a small village having to maintain wind turbines in addition to solar panels and a biogas generator. In the largest community (see Table 2), we selected a microgrid design that uses a smaller share of solar than other designs out of concern for land availability for the panels.

In addition to running HOMER to provide a microgrid design for meeting zero demand growth, we used HOMER to design microgrids for the same communities with an expected demand growth of 1.5% per year (see Tables 3, 4, and 5). This raised the cost of energy significantly, and demonstrated the financial and technical challenges in designing for future consumption. As well, we adjusted a significant model input, biomass availability, to reflect a community with a concentrated livestock operation rather than one with traditional farming practices. Using the zero demand growth model, we tripled the amount of waste available. This significantly reduced cost, decreased the share of excess electricity, and decreased space requirements in all three communities (see Tables 3, 4, and 5).

Community Size (households)	Electric Load (kWh/ day)	Peak Load (kW)	PV (kW)	Wind (kW)	Biogas Generator (kW)	Storage (kW)	Converter (kW)	Cost of Energy	Net Present Cost (25 years)	Operating Cost	Initial Cost
75	98.1	13.81	83.1	0	2	79.47	14.5	$0.273	$204,628	$3,364	$134,145
400	523.3	73.68	349	96	10	298.01	68.1	$0.25	$999,365	$13,815	$709,949
1250	1635.0	230.2	874	207	30	1,142.38	228	$0.243	$3,030,000	$38,622	$2,230,000

Table 2: Optimal microgrid for three model community sizes

Model Type	Electric Load (kWh/day)	PV (kW)	Wind (kW)	Biogas Generator (kW)	Storage (kW)	Inverter (kW)	Cost of Energy	Net Present Cost (25 years)	Operating Cost	Initial Cost
Original	98.1	83.1	0	2	79.47	14.5	$0.273	$204,628	$3,364	$134,145
1.5% Load increase per year	144.23 (year 25)	130	0	2	119.16	21	$0.317	$285,797	$4,054	$200,866
75% biomass reclamation	98.1	37.54	0	8	19.86	9.7	$0.194	$145,312	$3,682	$68,178

Table 3: Optimal microgrid for a community of 75 households under three scenarios

Model Type	Electric Load (kWh/day)	PV (kW)	Wind (kW)	Biogas Generator (kW)	Storage (kW)	Inverter (kW)	Cost of Energy	Net Present Cost (25 years)	Operating Cost	Initial Cost
Original	523.3	349	96	10	298.01	68.1	$0.250	$999,365	$13,815	$709,949
1.5% Load increase per year	759.3 (at year 25)	420	90	10	297.9	90	$0.276	$1,100,000	$14,190	$805,204
75% biomass reclamation	523.3	196	N/A	40	158.94	48.9	$0.197	$786,398	$18,497	$398,883

Table 4: Optimal microgrid for a community of 400 households under three scenarios

Model Type	Electric Load (kWh/day)	PV (kW)	Wind (kW)	Biogas Generator (kW)	Storage (kW)	Inverter (kW)	Cost of Energy	Net Present Cost (25 years)	Operating Cost	Initial Cost
Original	1635.0	874	207	30	1,142.38	228	$0.243	$3,030,000	$38,622	$2,230,000
1.5% Load increase per year	2372.7 (at year 25)	1600	375	30	1,490.38	350	$0.304	$4,560,000	$53,726	$3,440,000
75% biomass reclamation	1635.0	408	66	140	367.41	310	$0.194	$2,430,000	$10,046	$1,260,000

Table 5 : Optimal microgrid for a community of 1250 households under three scenarios

Environmental Analysis

When thinking about the actual implementation of these three microgrid options, it is also important to consider their potential environmental impacts. The most relevant impacts associated with this project are possible emission changes in the local area associated with using biomass to produce electricity and the impacts of actually installing the system.

First, we considered the carbon emissions associated with producing biomass. We wanted to calculate the amount of emissions our proposed microgrid would produce and additionally consider the amount of CO_2 emissions created if the same amount of electricity were produced by connecting these communities to the grid or connecting them to a diesel generator-based microgrid (which is currently one of the most popular options in developing countries). In calculating the CO_2 emissions from our proposed microgrid, one study[xviii] computed the possible amount of electricity produced from all the cow manure in the US. While the size of the cows in the US and South Africa is different, we assumed that the average amount of CO_2 produced from generating biogas would still be similar since it would be scaled for the amount of manure actually collected. They calculated two different numbers for amount of electricity and amount of CO_2 produced assuming different efficiencies of the biogas generator so we took an average of both and divided the two numbers to get a value of 0.000829 tonnes of CO_2 per kWh produced. We then multiplied this number by the number of kWh that our biogas generator was producing. When considering connecting these communities to the South African grid, it was found that the country's average carbon grid intensity is 0.94 tCO_2/MWh[xix]; given this, the number of kWh per community was converted to MWh and multiplied by this number to obtain the total tonnes of CO_2 emitted. Finally, for the diesel generator-based microgrid, it was found that diesel fuel produces 161.3 pounds of CO_2 per million British thermal units (Btu)[xx]. This number was converted to tonnes of CO2 per kWh and multiplied by the number of kWh needed per community. All three results are shown below in Table 6.

Load Size (kWh)	CO_2 Emissions from microgrid (tonnes of CO_2)	CO_2 Emissions from South African Grid (tonnes of CO_2)	CO_2 Emissions from diesel microgrid (tonnes of CO_2)
98.1	0.00166	0.092	0.0245
523.3	0.0083	0.492	0.131
1635	0.0249	1.537	0.408

Table 6: CO2 Emissions for 3 Different Sources

The numbers in the table do not include the emissions associated with construction of the microgrids or the emissions associated with transporting the diesel fuel to the communities.

Next, emissions associated with cattle manure are considered. Cattle are often associated with methane emissions and a 2013 study determined just how much methane that cattle in South Africa were producing. The target community for this project falls under emerging and subsistence farming which was categorized under communal beef cattle emissions in this study. To determine methane emissions, Table 1 below was used.

Animal class	Weight (kg)	MEF_{entric} (kg/h/year)	MEF_{manure} (kg/h/year)
Bulls	462	83.8	0.017
Cows	360	73.1	0.015
Heifers	292	62.5	0.013
Oxen	344	72.6	0.015
Young oxen	154	41.6	0.010
Calves	152	40.9	0.010

MEF: methane emissions factor; kg/h/year: kg/head/year.

Table 7: Methane emissions factors for communal beef cattle[xxi]

Since the breakdown of the cattle within each target community is unknown, the average amount of methane, measured in kg CH_4/head/year/kg weight, was taken based on Table 7. These calculations came to show that for each kg of weight, each head of cattle contributed 0.225 kg of enteric methane and 0.0496 g of manure methane per year. Based on the assumption that each head of cattle weighed approximately 200 kg, this means that each head of cattle emits 44.96 kg of enteric methane and 0.0099 kg of manure methane per year. Further, with the assumption of 15 kg of dung per head of cattle per day, this means that each kilogram of manure is responsible for 0.0272 g of methane per day. Using the assumption that inputs to the biogas digester are responsible for 25% of the total dung produced, this would eliminate 0.00679 g of methane per day or less than 0.01% of the methane per day. It is clear that because enteric methane is the overarching cause of cattle methane, implementing this microgrid by using biogas from cattle dung does not have any significant impacts on reducing methane emissions.

Manure left in pastures due to subsistence farming also necessitates examining nitrous oxide emissions. A 2004 study looked into the nitrous oxide emissions from manure in South Africa and assumed that subsistence cattle manure management was 10% drylot, 80% pasture, and 10% manure with bedding greater than 1 month. Although this study calculated N_2O emissions for each type of cattle, these numbers were calculated for all cattle across South Africa. Thus, to calculate nitrous oxide emissions, the nitrogen excretion rate given for subsistence cattle was used to calculate the annual nitrogen excretion. This rate, given in kilograms of Nitrogen per 1000 kg of animal per day, was 0.63 for all subsistence cattle. Given the assumption that each head of cattle weighed 200 kg, this means that each head of cattle produces 45.99 kg of N_2O annually from their dung. Assuming 25% of the dung is collected each day for the biogas digester and assuming none escapes before it is collected, this would reduce emissions to 34.5 kg of N_2O annually per head of cattle.

It is important to consider that the physical components of the microgrid might also have environmental effects. With a zinc bromide flow battery technology, there are little environmental impacts as discussed in the "Microgrid Components" section. The other impact would be the physical space that the microgrid consumes. With the larger communities, there are large amounts of solar panels needed, which could potentially impinge on space already being used for agricultural purposes. Wind turbines were not as prominent in our final designs but also take up space that needs to be taken into account.

Social Impact

One major advantage of tackling the issue of energy access in developing communities is the expected social and economic impacts on that community. Having access to energy provides a range of new opportunity for communities, from improving basic household operations like cooking and lighting to allowing for the creation of new businesses and the improvement of current ones. Amongst other benefits, energy access can fuel economic growth, job creation, and female empowerment, all of which can help an area achieve equitable and sustainable development.[xxii] Implementing this microgrid model in any of the three theoretical communities outlined could have similar effects on the unelectrified region of KwaZulu-Natal and Eastern Cape, allowing these communities to develop their economies and making their communities more prepared for potentially connecting with the larger South African grid in the future. However, in assessing the social impacts of implementing a microgrid and bringing energy access to communities in this region, it is important to study the impact of the community on the success of the microgrid as well as the impact of the microgrid on the success of the community.

Having the support and involvement of the community when planning the installation of the microgrid is essential, because without the community's support and understanding, the microgrid and the energy it provides is likely to be underutilized and less successful. First and foremost, this is true because the community's cooperation is necessary to provide a key input and limiting factor to the system, the biomass that fuels the biogas generator. Without the biomass from the community's livestock, running this type of system would not be possible, and in order to be willing to provide that biomass, the community must buy into the value of the system.[xxiii] It is also crucial to have community members' support because without it, they are less likely to make full use of the system once it has been implemented, limiting some of the potential positive impacts on development.[xxiv] A study conducted on different methodologies to improve community involvement with and acceptance of new microgrid systems suggests that NGOs or other groups planning to bring energy access to a community focus on opening community members up to the diverse uses of the system, building consensus on solutions with the community, and focusing on the sustainability of the system.[xxv] Taking these steps should ensure that the community positively impacts the success of the microgrid system, allowing them to later reap the most benefits possible from the system.

After the community has been included in the development of the microgrid and has "bought into" the potential of the system, they can begin to experience some of the economic growth and development that energy access can bring. Based on a 13 year study of the effects of installing a diesel-powered microgrid in a rural, unelectrified area in Kenya, we can anticipate some of the key economic outcomes of installing our system in a rural, unelectrified area in South Africa. Despite the differences in primary energy sources between these two systems, the two communities are still similar enough for it to be reasonable to expect similar economic growth as a result of electrification. Both the Kenyan village and the theoretical villages described used in this model are in rural, largely unelectrified area with limited potential to connect to the larger grid at the time of the microgrid installation.[xxvi] Additionally, the Kenyan village consists of 105 households, a size that falls between our small- and medium-sized communities, so the village is of a comparable size to those examined in this model.[xxvii] Because this Kenyan village meets many of the parameters we used to define the theoretic South African villages, this long-term study of the economic impacts of electrification can be used to predict the outcomes of implementing this microgrid system in a rural, unelectrified village in South Africa.

13 years after the studied microgrid was implemented in Kenya, the community experienced a 100-200% increase in productivity per worker, depending on the task they were completing and the sector they worked in.[xxviii] Additionally, community members experienced a 20-70% growth in income levels, also depending on what part of the economy the person was engaged with.[xxix] Students in this community also had a better education experience, and had more access to continuing their educations in the future in other parts of the country. The two sectors that experienced the largest growth in this village's economy were agriculture and small and micro enterprises, so one could expect to see similar growth in this model's villages' agricultural and small and micro enterprise sectors. Electrification could assist with agricultural growth in both of these communities by mechanizing labor and improving their ability to clear land for planting, in order to increase yield on existing land and make other land developable. Additionally, electrification allows for refrigeration, meaning that community members can reduce food waste by keeping food fresh longer. The combination of these effects of electrification on agricultural yield and the longevity of food promote growth in the agricultural sector.[xxx]

However, energy access can do more than just change the economic landscape in this area: it can also empower women in the community, which typically leads to further improvements in the community's education, health, and economy. Although quantitative studies demonstrating the effect of energy access on women's empowerment are lacking, a review conducted of all the studies on and anecdotal evidence of this phenomenon shows that electrification typically does improve women's situations in rural, developing villages.[xxxi] Electrification provides lighting in households, cleaner cooking processes, and makes many household tasks, which are typically assigned to women, much easier.[xxxii] This means women can spend less time on household tasks and more time pursuing an education, improving their access to other opportunities outside the home. Since an expansion in small and micro enterprises can be predicted with energy access, women could also gain more opportunities in this growing sector as their time spent completing household duties is reduced. On the whole, we can expect the implementation of this microgrid to have a positive impact on the overall economy in the community, as well as on women's empowerment and the overall future of the community, as long as the community is fully included throughout the process of installing this project.

Basic Business Plan

Corporate Structure

This microgrid would best be implemented through a company under a partially subsidized public/private model. Large portions of capital costs would be subsidized by NGO and governmental grants, and the operation and maintenance costs would be covered by both government subsidies and a customer pay-per-period payment system. The micro-grid will not be community-owned, as there have been cases of corruption due to competing-interests in some communities. However, it will be community-operated, with clearly defined expectations, training, and employees in charge of collecting the payments and collecting the animal waste.

Payment Structure

We analyzed three potential payment methodologies in determining the feasibility of the microgrid for a community of 75 households, as shown in table 7. The cheapest option for the community would be if households paid the average cost of energy (COE) in South Africa, $0.100. However, at the end of the 25-year system lifetime, this payment scheme would still fall $129,613.62 of the NPC, a cost that is likely too high to be covered by subsidies. The second option would be if every household paid 8% of its income, for a COE of $0.181. This payment scheme would fall $68,822.15 short of the NPC, which again would have to be covered by subsidies. The third payment scheme is if each household paid enough to meet the NPC without external subsidies. The COE in this option is $0.273, which is unrealistic for these communities to afford. The most realistic option is to have each house pay a COE equal to 8% of its income, and rely on government subsidies energy and external investors.

Payment Methodology	$/kWh	Annual Revenue	Present Value (25 Years)	NPC-PV
Avg HH Paying Avg SA COE	$0.100	$3,581	$75,014	$129,613.62
Avg HH Paying 8% of income	$0.181	$6,482	$135,806	$68,822.15
Avg HH paying enough to meet NPC	$0.273	$9,775	$204,789	-$161.26

Table 8: Potential payment methodologies to support a microgrid

Households will prepay for each given period or multiple periods at a time. This payment structure is flexible to accommodate irregular incomes, as many households receive lump-sum payments coinciding with seasonal harvests and it may be easier to pay in bulk for several months of power. After demonstrating the use and benefits of the system to the community, payments would start immediately to promote community ownership from the outset and keep communities from rejecting it as a "donor gift."

For households with extremely minimal electricity usage, a monthly flat rate will be calculated by number of lightbulbs and/or outlets for small appliance charging. There will also be a "lifeline" tariff for the poorest households so that they can afford lighting. This system ensures that all households are able to take advantage of some electricity usage and improve their financial status regardless of their current state.

Community Participation

First, the company will educate and train the community about the microgrid's benefits and how to use it. This step is necessary to ensure that the community understands what to expect from the system and how to properly use and maintain it.

Second, the company will have an employee collect payments from households. This employee will be a trusted member of the community so that the community members feel comfortable trusting him or her with their energy payments.

Third, there will be an employee who collects animal waste. In this third step innovative business strategies can be developed that help community members and work with their customs. One option is for community members to bring their cattle waste to a collection site by the digester and receive compensation, whether it is direct compensation or a reduced cost of energy. If not enough waste is reclaimed, the employee may travel through the farmland the cattle graze in and collect the waste. Also, there is the potential to utilize human waste. An outhouse can be set up by the digester, and the waste people produce can be collected and used for energy. This setup would also assist with possible sanitation issues in the community.

Future Expansion

There are multiple ways the company can expand past the initial microgrid implementation. First, more microgrids can be implemented in other communities to continue to increase the population with energy access. After several years of a microgrid's operation, the company will run a financial and social impact analysis on the community and compare it to unelectrified villages to demonstrate to investors the benefits of investing in this venture. Second, more services can be added to the microgrid to increase the level of energy usage and consequently community financial success and well-being. One such option is to add a leasing contract for devices such as refrigerators, radios, and televisions, as most households are not be able to afford the upfront cost of such devices. Another option is to incorporate electricity into business and agricultural operations, such as land-clearing and irrigation. Third, the company can improve the operation of the system by adding technology for electronic payments and a smart-meter for the system to optimize electricity storage and distribution. Moving payments to an electric process can ward against corruption from the employee collecting them.

Evaluating the Success of a Venture

According to the 2014 UN report on Microgrids for Rural Electrification, the reliability of a microgrid is the most necessary component for financial viability and sustained operation, as it is in this situation where households are most likely to follow payment rules and take full advantage of the electricity. Reliability is impacted by good operation and maintenance, high rates of tariff collection, high cost recovery, load limit compliance, and schedule adherence.[xxxiii] Our company has factored in these components through its efforts to educate the community and use a flexible payment structure and a trusted community members for payment collection until an electronic platform can be developed. The excess solar energy produced during the day will also protect against slight overuse of the system, and overtime adding in a smart meter can limit household energy consumption to what they have paid for so as not to exceed the system's capacity. Since the company will be based in the region and have several microgrids it is responsible for, employees will be in the area to quickly respond to calls about maintenance issues. Consequently, we expect the microgrid's operation to be successful after community acceptance.

Target Market Analysis

We choose to focus our study on the Kwazulu-Natal and Eastern Cape provinces of South Africa because they fit target market archetype for the microgrid model we've developed. South Africa, unlike many other African countries, is farther along the electrification process. At 83% electrified[xxxiv], it doesn't initially seem like the target market for this project. However, in reality, it is the ideal country because it is so close to total electrification. With a lifetime of 25 years, the microgrid we assessed would work best for a country that already has a well-established national power grid that our microgrid could, in the near future, be connected to.

Furthermore, our target market must consist of a government that is interested in funding rural electrification, specifically with an emphasis on doing so sustainably, in addition to containing a region with the type of agriculture that could support a biogas generator. South Africa's government in particular has been the primary motivator in increasing its energy access from 35% to 85% between 1990 and 2011, largely the result of the transition from apartheid to a democratic government. This shows that the South African government has had a recent and very relevant interest in funding energy growth. One major reason for the success of their electrification program is that the national utility Eskom has had access to capital, well qualified staff, and good infrastructure[xxxv]. Additionally, Eskom participated in the World Business Council for Sustainable Development's microgrid program in 2015[xxxvi], further proving that South Africa's government and utilities are interested in funding electricity initiatives, making it the ideal candidate for our microgrid.

Taking a closer look at the province of Kwazulu-Natal in particular, the Department of Agriculture and Rural Development has set a goal for the province to achieve 100% energy access by 2030. This would provide an additional 600,000 households with energy, or another 3 million people, and that's just Kwazulu-Natal. This initiative is the ideal opening in the market for microgrid technology, to help the province bridge the gap to total electrification. Furthermore, the government has already shown interest in employing renewable resources, and avoiding harmful energy sources such as paraffin, candles, and firewood[xxxvii]. The fact that the South African government has already shown interest in sustainable enterprises shows that they would be more likely to implement completely renewable microgrids. Furthermore, Kwazulu-Natal contains 6.5 million hectares of farmland, 82% of which is suitable for extensive livestock production[xxxviii]. In other words, 5.3 million hectares of land for cattle waste production, the fuel source for the microgrid's biogas generator. Eastern Cape, a bordering province, shares similar characteristics that categorize it as our target market. It is also close to being fully electrified but still the least electrified in South Africa, also has governments who are interested in the growth of sustainable energy technologies, and also has the agriculture and lifestyle that could support our microgrid. In this way, our microgrid could be applied to a range of locations across the world that fit this profile.

In addition to the government, other groups including private corporations and NGO's are incentivized to fund energy growth in South Africa and elsewhere. For instance, the companies Specialized Solar Systems[xxxix] and ABB[xl] have already built solar microgrids in South Africa. Accenture Development Partnerships in association with the University of Notre Dame and the Rural Development Company built a solar microgrid in Kwazulu-Natal to power irrigation equipment as recently as in 2017[xli]. The important takeaway here is that largely purely solar microgrids are being built right now, and some aren't even being used to electrify households, which suggests an opening in the market for a multipower renewable microgrid like ours. Thus companies like these as well as NGOs like the Energy and Environment Partnership and Solar Electric Light Fund who already fund such projects, could easily be interested in investing in our microgrid.

Government Incentives and Regulations

South African electricity generation faces delays due to the relationship between the government (DOE), the regulator (NERSA) and the supplier (ESKOM). This is mainly due to the change of status of these entities from being a parastatal to profit-motivated businesses.[xlii] Realistically, little can be done to solve this issue directly in the short term, but in the long run this can be fixed by encouraging independent power producers (IPP) to get into the generating industry, reporting to an independent transmission authority. The South African government encouraging private companies to get into power generation by microgrid installation would achieve this goal in a 20-30 year time period. [xliii] In a long-term plan, advancements in technology will likely lead to cost reduction of renewable energy sources used in this project such as solar. This would increase the role of renewable energies in microgrid systems and makes our model look more conservative in terms of cost.

South Africa currently relies on cheap coal as it has a large amount of coal power plants. This is proven to be a weak strategy for energy security and the gap should be filled with renewable energy sources; such as those introduced in microgrids. There are programs available to encourage the use of renewable energy sources in South Africa, like those used in microgrids.

South Africa introduced a non-grid electrification program involving microgrids in 2001.[xliii] This program addressed areas that weren't going to be electrified in the next three or more years. Since 2001, energy access in South Africa has been improved greatly. For the non-grid service to work, the customer was required to pay a connection fee towards the installation followed by a small monthly fee which covered lifetime running costs and support. The government subsidized 80% of the capital costs of the systems. [xliv] However, in our analysis we have found that one of the most important factors in limiting the spread of energy access was education of the community to increase acceptance of the new systems. For communities that haven't been exposed to electricity, it is unlikely that a potential customer would pay any fee initially; thus, the government should work with private companies directly and free the users of all the cost for installation and perhaps the first couple of months as a demonstration of how helpful electricity could be to the community.

Achieving country wide grid connection was accepted as a goal that was hard to achieve in the short run. The government put further importance on supporting off-grid electricity systems in 2013 with the "New Household National Electrification Strategy". The strategy identified 300,000 households to receive electricity access by non-grid solutions by 2025.[xliv] The plan was in alignment with the National Development Plan to achieve universal energy access (97% of the households) by 2030.[xliv] Minister of Finance further recognized the importance of electricity accessing South Africa in an economical growth and development standpoint.

However, the government subsidies were hard to reach because of departmental formalities. The coordination of Department of Cooperative Governance and Traditional Affairs (COGTA) and Free Basic Energy (FBE) represented challenges. Optimizing the communication between consumers and government agencies and even the communication within government agencies should be prioritized. Despite the inefficiencies, between 2002 and 2015, 9600 households were supplied with off-grid solar energy. [xliv]

South Africa has recently agreed to work with the European Union to cooperate on a program focusing on rural electrification, taking concrete steps in towards the goal set by the "New Household National Electrification Strategy" of 300,000 households.

South Africa is also eligible for some initiatives taking action towards African electrification. Power Africa was launched by the Obama administration in 2013 which works to expand electricity access in Africa.[xliv] US committed around 7 billion dollars as financial support, providing loans with a guarantee to investors.[xlv] Since microgrids are usually introduced locally to small communities, they intend to not be as appealing to investors as other projects because of their narrow profit margin, but eliminating some financial risks such as loans draws more investors and introduces private power producers to the market.

Conclusion

Rural microgrids using combinations of wind, solar PV, and biogas combustion for this region of South Africa are technologically feasible, but will require subsidization from government or NGO sources to be economically viable. However, all three models produce high quantities of excess electricity given their dependence on variable wind and solar coupled with storage. If communities were able to take advantage of unpredictable excess electricity through flexible manufacturing operations that generated income, the systems may become economically viable without subsidization. Likewise, the high likelihood of grid connection throughout SA within 25 years presents opportunities for communities to sell excess electricity to the grid, increasing the economic viability of the systems.

All models are highly sensitive to the availability of cattle waste. In areas that have concentrated livestock operations, the higher availability and lower cost of biomass alter the composition of energy resources to favor biogas combustion, lowering the system cost. Consequently, a company that implements this microgrid should device an innovative strategy that works with the community's current animal waste practices to optimize waste collection.

Our models also demonstrate that a renewable solution to increase energy access is possible, and this method can be extended to unelectrified rural areas outside of Africa. Globally over 80% of the unelectrified population lives in rural areas, and many of these communities will also have animal waste available for a biogas generator and thus can benefit from this system. Our process can be replicated using different technology inputs and solar and wind resources based on the community of choice to develop a microgrid for one of these areas. Implementing many of these microgrid systems can help with building economy of scale, lessening the cost of energy and the start-up cost barrier for future developments.

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