

The Future of Solar Microgrids in Sub-Saharan Africa: How social enterprises can accelerate the spread of renewable energy to off-grid communities

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Abstract

Solar microgrids are an integral part of bringing energy access to the over 1.2 billion people living in off-grid communities globally. This research examines the role of solar microgrids in addressing the issue of energy poverty in sub-Saharan Africa. Part I compares solar microgrids with alternative energy solutions including kerosene, small solar lanterns, solar home systems, other renewable energy microgrids, and the national electricity grid. These technologies are compared in terms of their power, area reached, affordability, common distribution channels, services provided, ease of maintenance, and durability. Part II outlines the ideal conditions for a microgrid installation in an off-grid community in sub-Saharan Africa, taking into account local weather, distance from the nearest urban center, housing density and catchment area, energy requirements of the community, ability to pay, and community dynamics. Insights from solar microgrid installations in Benin and Lesotho supplement findings from the literature. This research concludes that despite higher upfront costs and issues around energy storage, solar microgrids can provide productive energy services to facilitate economic development that other technologies cannot.

Introduction

Energy poverty is a widespread issue throughout the developing world, and is often defined as a lack of access to modern and safe energy services for lighting, cooking, and running appliances in the home.¹ Billions of people throughout the world

¹ IEA, *Africa Energy Outlook*.

do not have basic electricity in their homes, forcing them to use inefficient, and often dangerous, alternative energy sources such as kerosene. This issue is especially prominent in sub-Saharan Africa, where many communities are isolated far enough from the nearest city that the national electricity grid is unlikely to reach their area in the foreseeable future. Of the over 1.2 billion people who live off the electricity grid globally, over half are located in sub-Saharan Africa, where only 32% of homes are electrified by a national grid connection.² This proportion drops to 17% when looking only at rural areas in the same region. In the 2014 Africa Energy Outlook report, the International Energy Agency projects that even with current efforts to electrify Sub-Saharan Africa, 530 million rural people in Africa will still lack access to energy in the year 2040.³

To address this urgent problem, solar energy is widely regarded as one of the most promising solutions. Sub-Saharan Africa has reliable sunlight year-round, and the price of solar panels continues to drop each year. The market for solar is already booming in the region; in the first half of 2016, more than 45.5% of all solar products sold worldwide were sold in sub-Saharan Africa.⁴ Solar products are sold and distributed by retail stores, social enterprises, NGOs, corporations, and governments throughout sub-Saharan Africa. Currently, distributors in sub-Saharan Africa are selling everything from small solar lanterns, to single-family solar home systems, to village-wide solar microgrids.

² Warnecke and Ahitame, *Let There Be Light*.

³ IEA, *Africa Energy Outlook*.

⁴ Peters and Russell, *Global Off-Grid Solar Market Report*.

Renewable energy researchers in Ghana argue that while small-scale solar lanterns can be a good transitional technology, enterprises wanting to make the greatest impact should be looking to expand into larger systems, like solar microgrids, as demand for energy increases throughout sub-Saharan Africa.⁵ Solar microgrids are “distributed systems of local energy generation,”⁶ and typically consist of a set of solar panels in a central location supplying energy to an entire village through a network of power lines. Microgrids are between a solar home system (SHS) and the national electricity grid in size, and provide slightly more power than a SHS and slightly less than the national grid. However, a high-functioning solar microgrid provides more electricity to a home than an unreliable national electricity grid.

With microgrids standing out as a promising solution to bring power to off-grid communities in sub-Saharan Africa, it is important to look at the differences between microgrids and other technological solutions to energy poverty that are currently on the market, as well as to look at where solar microgrids are most viable. Part I of this paper compares the costs and benefits of solar microgrids to kerosene, small solar lanterns, solar home systems, other renewable energy microgrids (i.e. biomass or hydropower microgrids) and the national electricity grid. Part II explores the ideal conditions for a solar microgrid installation in an off-grid community. Interviews conducted with an electrical engineer experienced in installing solar microgrids in Benin, and with the

⁵ Quansah et al., *Solar Photovoltaics in Sub-Saharan Africa - Addressing Barriers, Unlocking Potential*.

⁶ Schnitzer et al., *Microgrids for Rural Electrification*.

founder of STG International, a solar microgrid enterprise working in Lesotho,⁷ provide additional insights to supplement available literature on the subject (see Appendix B for biographies).

Part I: Comparing solar microgrids with other solutions to energy poverty

At first glance, solar microgrids can seem like the perfect solution to electrifying households off the grid in sub-Saharan Africa. They are large enough to provide power to an entire community and they pollute far less than fossil fuels. However, every technology comes at some cost, and some economic and practical tradeoffs, and it is necessary to understand how solar microgrids compare to other technologies currently working to address the same problem of off-grid energy access. As of now, kerosene, small solar lanterns, solar home systems, other types of renewable energy microgrids (i.e. biomass or hydropower), and the national grid are energy sources present in areas of sub-Saharan Africa. By comparing these types of systems in terms of their power, area reached, affordability, distribution, services provided, maintenance, and durability, the advantages and disadvantages of solar microgrids in the context of the alternative solutions become clear. Microgrids are able to supply clean, affordable and productive energy to off-grid communities. Figure 1, *Comparing Solar Microgrids to Alternative Technologies*, was informed by an interview with Fr. Constant Bossou SJ, an electrical engineer with experience installing solar microgrids in Benin, and was supplemented by outside research of available literature.

⁷ STG International works with concentrating solar power (CSP) technology instead of solar PV, but the factors that go into site selection remain the same.

Power and Area Reached

The power of a system is measured in watts (W), and the area reached describes the area lit or powered by one system. For instance, a solar lantern has a power rating of about 10W on average, and a single solar lantern can light one room at a time. Kerosene lanterns can also only light one room at a time. Their power cannot be measured in watts, but they typically provide slightly less light than a solar lantern. A solar home system can range anywhere from 10-200W, and can reach an entire household, depending on how many bulbs are included in the system and how many rooms are in the house. The power of a solar microgrid varies drastically, since the energy it generates is spread over an entire village. There is no agreed-upon definition, but residential microgrids typically range between 100W-5kW, and utility-scale microgrids can range up to 1MW.⁸ Depending on the size of the village and the size of the system, solar microgrids can supply different amounts of power to individual households, sometimes supplying as much as the national grid would provide. Other renewable energy microgrids, like biomass or hydropower, provide about the same amount of power and reach roughly the same area as solar microgrids, as they are also designed to fit the population of a village. However, both biomass and hydropower microgrid installations are limited by the resources they require. Biomass microgrids require a reliable local source of biomass, such as rice husks, and hydropower microgrids require a local river, unlike solar, which only requires adequate sunlight. The national electricity grid can provide anywhere from 1000-2200W of power per

⁸ IRENA, *Solar PV in Africa: Costs and Markets*.

household, and can reach an entire country, though in sub-Saharan Africa the national grid currently reaches only about 32% of homes.⁹

Price and Distribution Channels

The price and distribution of these technologies vary widely depending on the context. Many distributors do not publicize their pricing, but general estimates of price per kilowatt-hour (kWh) can be used to compare the affordability of each technology. In sub-Saharan Africa, living on less than \$1.25/day¹⁰ is considered poor, between \$2-10/day is middle class, \$10-20/day is upper middle class, and above \$20/day is considered rich.¹¹ While looking at price differences between these different technologies, it is important to keep in mind that even the poorest off-grid households are already using a portion of their income on energy services, such as kerosene or other biomass. If solar products are sufficient to replace these other energy sources, and are the same price or cheaper than the price of kerosene, the household is spending no more money than they were previously or is oftentimes saving money.

Keeping this in mind, kerosene can cost the equivalent of \$20-45 per kWh, whereas solar lanterns cost about \$2 per kWh, making them more affordable poor households.¹² Solar lanterns are often sold in retail stores for a one-time payment, but can also be distributed through social enterprises that sometimes provide payment plans or partner with micro-finance institutions to make them even more affordable. Energy generated by solar home systems can cost households anywhere from around

⁹ Warnecke and Ahitame, *Let There Be Light*.

¹⁰ Incomes are adjusted for purchasing power parity.

¹¹ African Development Bank.

¹² Schnitzer et al., *Microgrids for Rural Electrification*.

60 cents per kWh to \$8 per kWh, but are typically affordable only for upper middle class or rich households in the region due to the high upfront costs of \$500-\$1000 for installation of one system.¹³ If the provider subsidizes the upfront costs in some way, these systems can be affordable for poor households. Solar home systems are sold through either retail stores or through social enterprises, often aiming to provide last-mile distribution to communities far from the national grid.

Energy from solar microgrids can cost as little as about 20 cents per kWh, and can be affordable for poor households if they are not asked to pay the upfront cost of installing the equipment. Most often, a developer will price the energy so that the villagers pay back the initial installation costs over time. Since solar microgrids are installed for an entire village, they are often distributed by social enterprises and other organizations that either front the cost of the equipment, find outside funding, or divide the upfront payment among the villagers over time until they eventually own the system. Other types of renewable energy microgrids, such as biomass or hydropower microgrids, can cost customers up to 60 cents per kWh, or double the price of energy from a solar microgrid. This price disparity is mainly due to the low cost of solar panels, as the different types of microgrids are usually distributed in the same ways. The national electricity grid is the cheapest option, at around 10-20 cents per kWh, and is typically affordable for anyone living where there is a power line connected to their house. The national grid is provided by the national government of any given country.

¹³ Madamombe, "Solar Power: Cheap Energy Source for Africa."

Services Provided

While all of these technologies are aimed at providing light to households, some come with additional services such as USB charging and outlets. To truly address energy poverty, solar power has to provide enough energy for the household to discontinue the use of kerosene for lighting. One study found that 92% of solar electrified households in Ghana continued to use both solar and kerosene to meet their energy needs.¹⁴ Solar lanterns provide only the most basic service, lighting, meaning many households do not get sufficient energy from these lanterns to power their other activities. The minimum standard for lighting as an energy service is 300 lumens per household, with four light bulbs and four hours of light per night.¹⁵ Solar home systems often provide lighting to multiple rooms as well as USB charging, so households can keep their cell phones and any other small devices charged.

Solar microgrids typically provide lighting and USB charging to households, but can also provide outlets, depending on the size and design of the system and the payment options provided. Outlets are beneficial for running larger appliances, but make it more difficult for distributors to prevent one household from pulling too much electricity from the system. This problem is largely avoided if a pay-as-you-go system is installed, since the system can automatically shut off the supply to any house attempting to use more energy than it purchased. Solar microgrids also have the distinct advantage of being able to power small industry in villages.

¹⁴ Amankwah-Amoah, "Solar Energy in Sub-Saharan Africa: The Challenges and Opportunities of Technological Leapfrogging."

¹⁵ Leiberman, *Universal Energy Access*.

With enough storage capacity, solar microgrids can power commercial activities such as mills or small businesses, which can be a reliable source of revenue for the microgrid developer.¹⁶ These “anchor tenants” are often convenient places to install the panels and house the equipment, and can contribute to the economic development of a village. In Kenya, researchers found that energy access from a microgrid enabled a community to use tools and electric equipment in their work, resulting in productivity increases of 100-200% and income growth of 20-70% per person.¹⁷ Additionally, schools, water pumps and markets powered by the microgrid were able to offer improved services to the villagers with reliable electricity. Some developers and researchers claim that the presence of industry in a village is a vital factor to the success of a microgrid, because it provides a reliable source of revenue for the microgrid enterprise and increases the villagers’ ability to pay for energy.¹⁸ The capacity to supply productive energy—in addition to the typical lighting and charging provided by other technologies—makes solar microgrid enterprises stand out as important players in the economic development of off-grid communities.

Other types of renewable energy microgrids can provide the same services as solar and face the same difficulties with preventing overuse. The national grid also powers lights, outlets and industry, but is often not reliable 24 hours per day in many developing countries.

¹⁶ Schnitzer et al., *Microgrids for Rural Electrification*.

¹⁷ Kirubi et al., “Community-Based Electric Micro-Grids Can Contribute to Rural Development: Evidence from Kenya.”

¹⁸ Schnitzer et al., *Microgrids for Rural Electrification*.

Maintenance and Durability

Maintenance and durability of the various technologies are important factors to consider as well, especially for communities located far from the nearest urban center. Kerosene lanterns do not require much maintenance, but households often have to restock on kerosene frequently as they can use about half a liter per night for lighting.¹⁹ Solar lanterns are relatively easy to maintain, and the owner of the product does most of the maintenance. If the product breaks, it can usually be taken back to the retailer to be fixed. Solar lanterns typically last between 3-5 years before they need to be replaced. Solar home systems are slightly more difficult to maintain, as the owner has to care for and clean the panels, and the distributor of the product has to be able to repair any serious issues. The distributor, who often collects payments regularly from the customer, has an incentive to keep the home system running smoothly either by contracting a maintenance provider or servicing the technology in-house. Solar panels and controllers can last 20-25 years when taken care of properly, and batteries can last around 4-5 years, so as long as these parts are replaced when they need to be, the system can last many years. Energy storage is a major topic of discussion for microgrid developers, since lead-acid batteries are not the most efficient storage option, but are often the most affordable and widely available option on the market. Another option is lithium ion battery storage, which is more expensive and less prevalent in developing countries, but much more efficient at holding a charge than lead-acid batteries. Lithium ion prices are dropping, however, and some developers are choosing to switch to this

¹⁹ Schnitzer et al., *Microgrids for Rural Electrification*.

technology to improve the efficiency of their microgrids.²⁰ Distributors of both solar home systems and solar microgrids can monitor the status of their systems from a central location if they install inverters that send them information to help anticipate maintenance issues. STG International takes advantage of this technology with their microgrids in Lesotho.

Solar microgrids also require maintenance by the owner and a repair technician if necessary. Depending on the type of batteries in the system they can require different amounts of maintenance by the owner, in addition to keeping the panels clean. If one battery in the system goes out, the entire battery bank stops working. While panels can last up to 25 years, batteries typically only last around 5 years (10 is about the best case scenario, but in developing countries 1-3 years is more typical), which means the provider must replace them every few years. Other types of renewable energy microgrid technologies are more difficult to maintain than solar, as solar panels are relatively easy to clean and maintain as compared with technologies such as water turbines or biomass gasifiers. The national grid is the most difficult to maintain, but the maintenance is done by the government. This can be beneficial when the government is on top of maintenance, but a serious issue if problems go unresolved.

Advantages and Disadvantages of Solar Microgrids

By comparing solar microgrids to other technologies, some advantages and disadvantages become clear. First, compared with other solar technologies, solar microgrids are typically able to provide more power to a household at a lower price. The

²⁰ IRENA, *Solar PV in Africa: Costs and Markets*.

initial installation costs of solar microgrids are higher than other technologies, but they also generate more revenue and can recoup the cost of the initial installation over time when the customers start paying for energy, if the installation was not already funded by an outside source. In addition, solar microgrids can provide energy to an entire village with one system, instead of installing individual systems on the roof of each household or selling individual lanterns. Solar microgrids are also able to provide lighting, USB charging and sometimes outlets, making them attractive to households looking for multiple energy services.

Beyond residential uses, microgrids can also power commercial activities within a village, increasing the overall economic output of the village and ensuring a reliable revenue stream for the microgrid developer. While maintenance is required to keep the microgrid solar panels and batteries working smoothly, providers can monitor the health of each system remotely, anticipating maintenance issues before they break the system. Solar panels on microgrids have a lifespan of up to 25 years,²¹ and can provide energy to villages unlikely to be reached by the national grid during that time. Clearly, villages far from the national grid are the most logical place to install a solar microgrid, but what other conditions must be met in order for a solar microgrid to be the most effective solution for a village without access to energy? Part II will explore this question.

²¹ Maehlum, Mathias. "The Real Lifespan of Solar Panels."

Figure 1: Comparing Solar Microgrids to Alternative Technologies²²

Technology	Power of System (Watts)	Area reached by one system	Price per kWh (affordability)	Distribution channel/ Provider	Services provided	Maintenance (How difficult: By whom?)	Durability (life expectancy of product)
Kerosene	N/A	1 room	\$20-45 (kWh equivalent) ²³	Local supplier	Light	Easy: Owner	.5 liters per night
Solar lanterns	~10W	1 room	\$2: Poor/middle class if on payment plan	Retail stores	Light	Easy: Owner of product	3-5 years
Solar home systems	10W -200W	1 household	60+ ¢: Upper middle class/rich	Retail stores and enterprises	Light USB charging	Moderate: Owner or provider of product	Batteries: 5 years Panels: 20-25 years
Solar microgrids	100W+ per village	1 village (50-500 houses)*	20+ ¢: Poor if not asked to pay equipment cost upfront	Enterprises and other organizations	Light USB Charging Outlets Industry	Difficult: Owner or technician	Batteries: 5 years Panels: 20-25 years
Other microgrids (wind)	100W+ per village	1 village (50-500 houses)*	60+ ¢: More expensive than solar	Enterprises and other organizations	Light USB Charging Outlets Industry	More difficult: Owner or technician	Batteries: 5 years Panels: 20-25 years
National grid	1000W -2200W per home	1 country	10-20 ¢: Everyone living where there is power line	Government	Light Outlets Industry	Most difficult: Government	Indefinite

²² Interview with Father Constant Bossou.

²³ Schnitzer et al., *Microgrids for Rural Electrification*.

Part II: Ideal conditions for solar microgrid installations

There is no one-size-fits-all solution to energy poverty. Not every technology is successful in every context, so it is important to understand where and under what conditions solar microgrids are most viable when looking into scaling their presence in sub-Saharan Africa. To understand where solar microgrids are the most effective solution, insights from Fr. Constant Bossou and Matt Orosz, in addition to insights from relevant literature, were compiled to develop a set of ideal conditions for a solar microgrid installation. The various factors for a social enterprise to consider when assessing a community include local weather, distance from the nearest urban center, housing density, catchment area, energy requirements, ability to pay, and community dynamics. Analysis of each factor includes an *Example from the Field* to illustrate its importance in past microgrid installations.

Local Weather

For solar microgrids, the local weather affects the availability of reliable energy. Luckily, sub-Saharan Africa has plentiful sunlight. In fact, most of sub-Saharan Africa receives in excess of 2000 kWh/m² of solar irradiance, or power per unit area from the sun, per year.²⁴ The key for solar microgrid enterprises then, is to ensure there is an appropriate place in the village to install solar panels where they will receive sunlight throughout the day. The more hours of sunlight per day, the more energy produced by the panels. Batteries can store energy for use during times when the sun is not shining, but depending on the capacity of the batteries, they may not last throughout the night

²⁴ Quansah et al., "Solar Photovoltaics in Sub-Saharan Africa - Addressing Barriers, Unlocking Potential."

without sufficient sunlight during the day. If there is no centrally-located roof or other surface in the village to install the panels, where someone could feasibly maintain them on a daily or weekly basis, a solar microgrid may not be viable in that particular location.

Example from the Field

In 2015, Father Constant Bossou advised two Santa Clara University electrical engineering students, Nico Metais and Jacob Leatherberry, on their project to design and install a solar microgrid in a rural community in Alafiarou, Benin. They chose solar as an energy source for this microgrid because Benin receives adequate sunlight year round. Because of its location near the equator, the shortest day in Benin is only 45 minutes shorter than the longest.²⁵ Benin also has a high solar irradiance, at 6kWh/m²/day. The engineers installed the solar panels on the roof of a centrally located enclosed structure, facing south to ensure high energy yields, and placed the rest of the equipment (batteries, charge controller, etc.) within the enclosed building. They protected the equipment with a steel locking door to prevent theft, and gave access to the local technician, Parfait, who is responsible for maintaining the microgrid and collecting payments.

Distance from Nearest Urban Center

For electrification purposes, solar microgrids are not necessary in places where the national grid is already installed and providing a reliable source of energy to households. In these places, solar microgrids could be installed for backup power or in

²⁵ Metais and Leatherberry, "Bringing Electricity to Alafiarou: The Solar Microgrid Project."

case of emergency, but they would not be solving the larger issue of energy poverty.

Solar microgrids are most necessary in areas unlikely to get access to the national grid in the near future. For many sub-Saharan African countries, it is prohibitively expensive to extend the grid to all areas of the country.

In villages close to the existing grid it does not make financial sense to install a solar microgrid because it would cost significantly less for the government to expand the grid to that area. However, once you move further from the national grid, even about 5km away, the price of the national grid expansion exceeds the cost of installing a solar microgrid and it becomes more economical to invest in a solar microgrid. Even so, there is always the possibility that the national grid reaches a village with a solar microgrid installation. In this case, it makes particularly good sense for an enterprise to build their microgrid to the local grid code, so when the national grid does arrive they have compliant infrastructure.

Example from the Field

In Lesotho, where STG International works, it costs up to \$20,000 to extend the national grid 1km. At the same time, it costs around \$50,000-300,000 to install a solar microgrid in a village.²⁶ Matt Orosz explained that there is no fine line, but if a village is located far enough from the national grid, it makes more sense to install a microgrid if the government is unlikely to pay to extend the national grid to a rural village. However, as explained, the national grid always has the potential to reach these villages after a microgrid installation. Although STG International has yet to face this situation, Orosz

²⁶ Interview with Matthew Orosz.

suggested that two possible scenarios would be to turn over the infrastructure to the utility for market rate compensation, or buy electricity from the national grid and resell it to the microgrid community, essentially becoming the utility provider.

Fr. Bossou recommends solar microgrid installations at least 10km from the nearest urban center to avoid this overlap and reach communities that are unlikely to receive energy access in the near future. From his experience in Benin, the government is skeptical of buying microgrids, so it may be best to avoid areas with a high likelihood of electrification until there is some precedent for how to deal with that situation. In the installation he oversaw in December 2015, the village had been promised grid connection from the government for over 20 years, but nothing had come of it. Therefore, the village had a low likelihood of electrification and stood to benefit from a solar microgrid installation.

Housing Density and Catchment Area

For a solar microgrid developer to reduce installation costs and energy losses, it is ideal to have a high housing density in the village over a relatively small catchment area. This reduces the cost of the infrastructure and wiring required for the solar microgrid to reach the necessary number of households. Some enterprises prioritize electrifying entire villages, and are more flexible in extending their microgrid beyond the denser center of a village, but other enterprises either choose to connect only a portion of households in a village or supplement the solar microgrid with solar home systems for houses on the outskirts of the community.

Example from the Field

In Father Bossou's experience in Benin, less than 20m between houses is the most appropriate housing density, and the maximum catchment area, or total area covered by the microgrid, is around 500x500m. There is flexibility on this measurement, though, depending on the enterprise's budget for infrastructure. Microgrids can grow until they are utility-scale installations, in which case the catchment area would be much larger than 500x500m.

Part of STG International's approach to planning installations includes using Google Earth to estimate housing density of potential villages, ranking sites based on their housing density, then performing walk-throughs of the villages to understand the makeup of the different buildings seen on Google Earth. For example, two roofs viewed on Google Earth could be two houses, one house with a shed, two small shops, or any other combination of buildings, all with different energy requirements. During the walk-throughs, STG also collects data on the number of people in each household to get a better understanding of potential energy requirements.

Energy Requirements

Solar microgrids can range in strength and size, and each unique community requires a different amount of energy than the next. One of the most crucial preliminary steps for an enterprise is determining the energy requirements of a particular village in order to design an appropriate system. This is a difficult task, because demand for energy often increases over time as communities become more comfortable with

greater access to energy.²⁷ Enterprises are faced with the decision to either build a microgrid that can grow as the community demands more energy, or manage demand so households do not use more than their share of the energy provided by the microgrid. Managing demand is most effective when houses do not have outlets because households cannot plug in appliances that will draw too much energy. To prevent overuse after deciding on the size of the system, enterprises often put limits on the amount of energy each household can consume per day, and either charge customers using a pay-as-you-go model or a flat monthly fee. Enterprises must decide whether they will penalize households for overuse, install load-limiting devices that prevent households from pulling too much energy, or increase the size of the system to meet growing demand.

Example from the Field

In Alafiarou, Benin, the SCU electrical engineering students estimated the amount of power their initial installation would require. They weighed the pros and cons of using AC versus a DC transmission, and ultimately decided on DC to minimize costs both for the installation and for households. The DC system does not require the purchase of an inverter, and limits the appliances households can use because it does not support standard plugs, only lighting and cell phone charging. An AC system would allow for use of televisions and other appliances, but ultimately would have required the addition of at least an additional 300 watts per household to the system, which the villagers could not afford.

²⁷ Schnitzer et al., *Microgrids for Rural Electrification*.

STG International estimates the energy requirements of a particular village by analyzing comparable data from a similar community. After their initial assessment of buildings and population, they are able to calculate the approximate amount of energy the village would require from the microgrid. This allows them to design and build a solar microgrid that fits the needs of the specific population. After initial estimates, the STG team does a site visit of each village and connects with a local “informant” so show them around. During this visit, the team asks the informant to rank the relative energy consumption of each building as “low, medium, or high” consumption to get a deeper understanding of energy requirements.

Ability to Pay

Generally, solar microgrids are relatively affordable compared to other solar technologies. Even so, the price of energy from a solar microgrid can vary widely depending on the business model and technology used by each social enterprise, so it is necessary to ensure that any given community has the ability to pay for the energy they receive from their solar microgrid. As discussed in Part I of this paper, nearly all households are spending some portion of their income on energy services, whether in the form of kerosene, wood, solar, or national grid connection. Therefore, households are typically willing and able to spend money on solar microgrids if they see it as an improvement to their current energy supply. While a social enterprise determines the price they are going to charge for energy from the solar microgrid in a particular community, they must take into account local income levels and whether they want to prioritize supplying all households energy at a low price, or fewer households energy at a higher price if the entire village does not have the ability to pay for the energy.

Enterprises need to take into account that the price they charge customers must be enough to eventually cover the installation costs, if necessary, as well as additional recurring costs to the enterprise including battery replacements, routine maintenance, and any other operational costs.

Example from the Field

To ensure that the community had the ability to pay for the microgrid energy in Benin, Father Bossou, Nico and Jacob set up meetings with the patriarchs of each family in the village. The engineers asked for information regarding how much each family would be willing and able to pay for energy services, and how much they were currently paying for lighting and charging using other sources. Through these meetings they came to the conclusion that families could afford to pay 500CFA (0.85 USD) per light bulb per month. This was the initial pricing structure when the microgrid was installed in 2015, but in the summer of 2016 a pay-as-you-go system was installed to allow the villagers to pay for energy how they pay for other services, such as their phone plans, using mobile money.

STG International designs their microgrids with the ultimate goal of minimizing the price of energy for the villagers, otherwise known as their cost recovery tariff. In deciding where to install a microgrid, STG takes into account the cost of the initial installation, since that has a direct correlation with how much they would have to charge villagers for energy to pay back the cost of the installation. According to Matt Orosz, STG's solar microgrid installations can cost between \$50,000-\$300,000. Currently, STG is able to price its microgrid electricity at around \$0.27/kWh for a village of around 200

people. Energy from the national grid in Lesotho is priced between \$0.10-\$0.20,²⁸ so STG's energy is between 2-3 times the price of the most affordable energy source in Lesotho.

Community Dynamics

Social enterprises prioritize community involvement at different levels, but no matter what, the community has to be accepting of the technology in order for the installation to be a success. Unlike in India, where residual issues from the long-standing caste system create dynamics that can inhibit communities from being cooperative enough to share a solar microgrid, sub-Saharan Africa typically does not face the same intra-community hostilities. However, communities still must be willing to work with the enterprise, be somewhat involved in the maintenance, and pay for the energy.

Again, depending on the business model, different levels of community involvement are necessary. Some enterprises need to recruit and train local villagers to do everything from maintaining the solar panels to collecting the payments from customers. This requires higher upfront costs for the enterprise, but can increase the chances of long-term success of the microgrid if the community is fully on-board with the project.²⁹ Other enterprises handle all maintenance and operations themselves, and simply need assurance from the community that they are willing and able to pay for the energy services. Either way, the enterprise must ensure a long-term commitment from the community members, as a solar microgrid can last over 25 years.

²⁸ Lesotho Electricity and Water Authority.

²⁹ Schnitzer et al., *Microgrids for Rural Electrification*.

Example from the Field

Since Father Bossou has connections in Alafiarou, Benin, he was able to connect with the local people first to ensure they were interested in having a solar microgrid. During these initial communications, a local electrician, Parfait, was identified as the operator and maintenance provider for the microgrid. During the installation he accompanied the engineers when they were buying components, installing the microgrid, and trouble-shooting problems so he could keep the system running after they left. A portion of the payments from villagers is used to pay Parfait for his work, and the rest is deposited in a bank account as savings to use to expand the microgrid in the future.

The engineers also met with the local patriarchs during December 2015, before the installation of the microgrid. They discussed the concerns of the villagers and payment options to ensure the microgrid worked for everyone. However, the engineers realized in later discussions with villagers that women's preferences were not brought up in these meetings. The women of the village had desires for where to install the light bulbs that the patriarchs had not told the engineers. The engineers tried to make adjustments, but with a short installation schedule, they could not meet every desire. This highlights the importance of understanding community dynamics during the design and installation of a solar microgrid.

Figure 2: Criteria for ideal conditions of a solar microgrid installation

Criteria	Explanation of criteria	Significance for site selection
Local weather	Local weather affects the availability of reliable energy.	Need a location with adequate sunlight to keep the panels producing energy throughout the day.
Distance from nearest urban center	Expanding the national grid becomes prohibitively expensive further from existing urban centers.	Rural areas far (over 10km) from urban centers are ideal to avoid overlap between microgrids and the national grid.
Housing density and catchment area	Housing density and the size of the village affects installation costs and energy losses over power lines connecting buildings.	Communities with a high housing density and smaller catchment area can have more buildings connected to the microgrid at a lower cost.
Energy requirements	Energy requirements include how much energy a community demands and for what services.	Communities with an “anchor tenant” are ideal, and microgrids should use a pay-as-you-go system to manage demand.
Ability to pay	Each household must be willing and able to pay for the amount of energy they want to consume.	Households currently purchasing more expensive energy services (i.e. kerosene) likely have the ability to pay for more affordable energy.
Community dynamics	Communities must be willing to work with each other and the developer to install and maintain the microgrid.	Developers must include community leaders throughout the planning process and ensure someone local is trained and responsible for maintenance.

Conclusion

Nations in sub-Saharan Africa face the enormous challenge of sustainably providing energy access to over 600 million people in the context of a world desperately in need of a shift to renewable energy. To simultaneously combat energy poverty and climate change, small-scale solar is insufficient, and centralized fossil-fuel power plants are unsustainable. Taking into account the available resources, social context, and geography of sub-Saharan Africa, solar microgrids stand out as an optimal solution to address these issues. While solar microgrids are not the solution for every community, where they are viable they stand to bring energy access to entire villages, accelerating the spread of renewable energy throughout sub-Saharan Africa.

As compared with other technologies and energy sources, solar microgrids tend to be more affordable and often provide more energy to households. They also have the added benefit of being able to provide productive energy to power industry within a village, ultimately bringing economic development to the area. The size and reach of solar microgrids can vary depending on the size of the community, and enterprises can work with communities far from the national grid who are unlikely to be electrified by the national grid. If the national grid does reach these villages, the solar microgrids can be integrated into the national grid, giving it more renewable and distributed sources of energy. If enterprises find a suitable location for an installation and take the time to ask the right questions and understand community dynamics and energy requirements, solar microgrid installations can provide much-needed energy and development to much of the rural population in sub-Saharan Africa.

Appendix A: Interview Guide

Research questions:

1. How do solar microgrids stack up against other technological solutions to address energy poverty?
2. Under what socio-economic and geographic conditions are solar microgrids likely to succeed?

1. How do solar microgrids compare to other solar products (lanterns, solar home systems), to other types of microgrids (diesel, wind, hydro, hybrid models), and to the national grid?

Technology	Power of System (Watts)	Area reached by one system	Price per kW	Distribution channel/ Provider	Services provided	Maintenance (By whom? How difficult?)	Durability (life expectancy of product)
Solar lanterns							
Solar home systems							
Solar microgrids							
Other microgrids							
National grid							

2. Where are microgrids most effective?

A. Ideal conditions

- a. Housing density:
- b. Local weather:
- c. Ability to pay:
- d. Energy requirements:
- e. Catchment area:
- f. Community dynamic:
- g. Distance from nearest urban center:

B. Social questions to be answered by an enterprise

- a. Will the community accept the microgrid?
- b. Willingness/ability to pay?
- c. Will the grid reach them in the future?
- d. Who will be the entrepreneur?

Appendix B: Interviewee Biographies

Father Constant Bossou: Fr. Bossou was born in Togo and raised in Benin in West Africa. He is currently a Resident Jesuit and graduate student at Santa Clara University pursuing his master's degree in Computer Engineering. Fr. Bossou advised two senior electrical engineering students in 2015-2016 on their project to design and install a solar PV microgrid in Alafiorou, Benin. This microgrid was installed in December 2015. Fr. Bossou advised another engineering senior design project in 2016-2017, which also focused on designing a solar microgrid for a village in Benin that will be installed in the summer of 2017. Both his experience living in sub-Saharan Africa and with his expertise in electrical engineering, and solar microgrid installations in particular, made Fr. Bossou instrumental in this research.

Matt Orosz, Founder of STG International: Matt Orosz is the founder of STG International, a solar microgrid enterprise working in Lesotho. He is the lead engineer and project coordinator of all of STG International's microgrid installations in Lesotho. He holds a doctorate in Civil and Environmental Engineering from MIT, and has been an Echoing Green Fellow, a Switzer Environmental Fellow, and a Fulbright Scholar. STG International has been working in Lesotho since 2007, scaling up from institution-sized solar installations to village-scale microgrids to power homes and business alike. STG works with Concentrating Solar Power (CSP) and Solar PV technologies.

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