Techno-Economic Analysis of Photovoltaic Microgrids Using the DER-CAM Optimization System in Rural Andhra Pradesh, India

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ABSTRACT

Rural communities in developing countries continue to lack reliable, universal energy access even as urban areas improve their energy access. Microgrids can help this issue, as flexible systems that efficiently govern onsite distributed power generation, while maintaining a connection with the central grid. In parts of the world that benefit from high year-round solar irradiance, like India, photovoltaic (PV) microgrids combine the environmental and systematic advantages of onsite clean renewable generation in providing reliable power. However, high upfront costs make microgrids an expensive investment. To test the viability of photovoltaic microgrid systems in rural Andhra Pradesh (AP), I used a modified version of the DER-CAM optimization model to compare simulations of energy generation of PV microgrids, and diesel generators. I incorporated local solar irradiation and, local load profiles, into the model. I also compared policies on a local and national level that could subsidize a PV microgrid project in the average rural AP village. Government subsidies and the rising cost of transporting diesel to the site played a significant role in determining that the PV microgrid system was more cost effective than a reliance on diesel generators. However, policy research suggested a need to incentivize standardized microgrid infrastructure development through subsidies that can be paid off over the course of the project. Finally, farmer's willingness to pay more for reliable agricultural power in the state could increase revenue to support these projects in the future.

KEYWORDS

Rural electrification, energy access, subsidies, solar power, diesel generators

INTRODUCTION

36.8% of rural communities in the developing world lack access to electricity, often due to poor service or lack of connectivity (IEA 2011, Palit and Chaurey 2011). Unfortunately, this is unlikely to change dramatically in the near future, even in emerging markets like India and China that are projected to have a 75% stake in world energy markets in coming decades; most of this progress will occur in urban areas (Ojha 2010, Ummel 2010). In an attempt to bridge the gap between electrified urban regions and their rural power-starved counterparts in India, independent organizations like Aurore, Gham Power, and SELCO India, are developing off-grid photovoltaic (PV) solar power systems that harness the abundance of sunlight in the subcontinent for household electricity use (Ojha 2010, Nouni et al. 2008, Palit and Chaurey 2011). These stand-alone PV (SAPV) power systems are a step in the right direction in providing basic power for India's rural communities, but they are limited in the following ways: (1) power for each household is often generated by a separate solar home system (SHS) and, therefore, is limited to the output of one or two PV panels on the roof of the dwelling, (2) due to the small-scale generation, the power is of poor quality, making incandescent lighting the only end-use and (3) SHSs do not efficiently manage the generated power and therefore there may be overall power loss (Rao et al. 2013).

Recent innovations in distributed power systems, in the form of microgrids - which are self-governed onsite distributed generation (DG) power systems- offer chances to improve the functionality and capacity of power systems in rural India. More specifically, microgrids are small-scale power grids that govern onsite DG, leveraging local renewable and traditional generation as necessary; these systems can function independently or in tandem with the central energy grid, optionally buying from and selling power to the grid to optimize cost offering flexibility and independence (Ustun et al. 2011, Rao et al. 2013, Miriam et al. 2013, Balijepalli et al. 2010). At a higher level, multiple microgrids connected with the main grid also lend the central system more stability by ensuring additional power sources to draw upon in case of a rise in peak power demand, which is a big problem for India's spotty and perennially underserved and overused grid (Llaria et. al 2011). However, high upfront costs for distribution and control mechanisms generally make PV microgrid more costly than SAPV systems, but economic incentives in the form of subsidies and tax breaks can affect this to some degree (Loka et al. 2013). The higher cost of PV microgrids results from installation of metering and distribution infrastructure that manage the power among the households. This is not needed for SAPV systems which operate one per household and do not distribute power. Therefore, cost is an important factor to consider when weighing the advantages microgrids provide for off-grid electrification in India, and recent studies have focused on how the additional cost of microgrids and factors into the resulting viability of such distributed energy systems.

Recent studies concerning the economic viability of microgrids in the rural context demonstrate that site-specific data is a crucial part of the economic analysis, generally employing the HOMER optimization program to perform these simulations. Studies addressing the success of PV microgrids bring attention to two principles. The first is the difference between the success of PV microgrids and SAPV (which are considered the next best option to PV microgrids) depend on local energy costs and meteorological data. The second is that incorporating different generation sources, i.e. hybrid power generation, like PV and wind is common to overcome intermittency issues of individual renewable technologies (Turkay and Telli 2011, Prodromidis and Coutelieris 2011). Fewer studies address pure PV generation, which indicates a need for more research in the area. The limited available research about the viability of rural PV generation asserts that higher population density and flatter terrain financially favor microgrid PV, which and is therefore dependent on local characteristics (Chaurey and Kandpal 2010a, Kaundinya et al. 2009). This conclusion is supported by the idea that high population density and accessible terrain allow for heavy use of the power system, leading to brief pay-back period sand making the PV microgrids financially sounder in the long run. Yet, site-specific factors such as costs of transporting and installing materials, and operation costs affect whether SAPV out-competes the PV microgrids and so it is important to factor these in when studying economic feasability. Studies on distributed PV generation in rural India are limited and generally address north Indian regions like Gujarat and Rajasthan that experienced a surge of large-scale solar power government projects in recent decades because they have the highest solar irradiance in the country (Kaundinya et al. 2009).

More recently, the state government of Andhra Pradesh (AP), a state in southern India, has become interested in developing solar power but the economic feasibility of microgrid PV power systems have not been widely studied in the state (Sahoo 2012). While all of AP's villages have electrical connection available (and are therefore considered officially 100% electrified), more than 1 million rural households within those villages lack access to electricity, creating a need for onsite electrification (Bhattacharya 2011). Furthermore, lack of reliable electrical connection caps the economic potential of local agricultural output in this fertile region; unconnected irrigation water pumps, which already account for 30% of electricity use in rural AP, can increase arable land (Bhattacharya 2011). In performing economic analysis, most studies employ the HOMER optimization model, but I use the Distributed Energy Resources Customer Adoption Model (DER-CAM), which is more easily adaptable for my study site. Similar to HOMER, DER-CAM takes tariffs, end-use power loads (how much power is used), installation and energy costs and yields optimized monthly energy costs to the customer (LBL 2002). Therefore my study addressed the viability of PV microgrids in rural AP, a region in which this has not yet been studied closely, using DER-CAM to simulate energy use.

In this paper, I explore the economic viability of introducing PV microgrids to rural AP, focusing on the overall cost of the system, the cost per kWh and how policies and subsides in the state and country hinder or aid establishment of solar microgrids. To do this, I isolated factors that contribute to successful introduction of PV microgrids into the region. Specifically, I examined: (1) whether PV microgrids are economically competitive with the next best rural alternatives, diesel generators and (2) the state of local policies and subsidies relative to the growth of PV microgrids in the region.

METHODS

Study Site

To test viability of a PV microgrid in AP, I created a model village study system based on the profile of an average village in the rural part of the state. I used census data, studies on agricultural output in Andhra Pradesh, and rural electrification case studies to inform the numerical parameters of this model village and reflect local factors. The parameters include the number of households, an end-use load profile made up of various uses over a 24 hour period, solar irradiance based on weather data, and some assumed and derived cost values. I defined the number of households as 40 based on similar rural electrification study done in rural AP (Loka et al. 2013). As a result of the rural, agrarian setting, electricity loads in this region were defined by water pumps for irrigation, basic lighting, and cellular phone charging.

Data Collection

I collected all available information concerning solar irradiance, and end-use electricity load data as part of my optimization by drawing from government websites, and similar studies that speculate on rural electricity use. I chose these parameters partially because DER-CAM uses them as inputs but also because, logically, electricity use, electricity generation onsite, and competing costs between grid electricity and on-site generated power need to be considered when coming to a sound conclusion about whether solar microgrids would be feasible in AP. I obtained solar irradiation data for Vijayawada, a coastal city in AP, from a tool on 'solarelectriccityhandbook.com' (Boxwell 2013). It returned a solar irradiance for each month based on the angle of the solar panel that optimized energy collection through the day (solarelectricityhandbook.com Boxwell 2013). The values ranged from 4.55 to 7 kWh/m^2/day.

I also formulated an end-use load profile, incorporating all expected uses for electricity in a model rural village in AP. To do this as accurately as possible, I assumed that my model village population was made up of 40 households, based on a similar study done on PV microgrids in AP, which informed the end-use load profile. Since agricultural pumps made up a significant portion of the end-use in a rural setting in AP, I added in the base-load of irrigation 'pumpsets' of 3 kW. Furthermore, I assumed that each household consisted of about 4 people, and that each household had two lights and one cell-phone charging station (Figure 1).

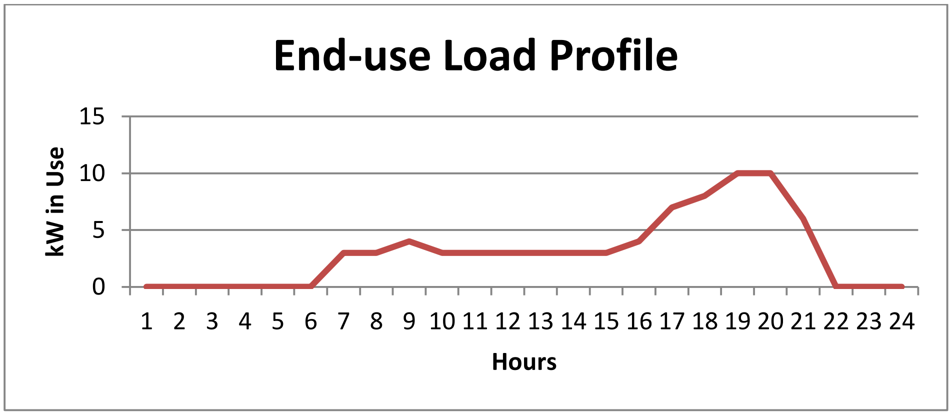

Figure 1. End use load profile I created an end use profile by incorporating a base of 3 kW of irrigation pumpsets with light bulbs and charging stations, whose use increases into the evening.

Data Analysis

Model Modification

The DER-CAM program that I used takes inputs of preferred energy generation technologies, load profiles, and local environmental conditions to optimize the best energy mix for on-site generation based on the lowest cost scenario. Since I was working in the lab that developed the DER-CAM program and therefore had access to the source code to modify it to fit my site-specific needs, I chose it over the popular NREL-developed HOMER model; both models offered most of the same optimization functions, so I did not lose out on functionality, and gained the ability to closely collaborate with the developers in my lab to understand the program better.

Before running my data through DER-CAM 4.40, I modified the program constraints that included the values of solar irradiance, the load profile, and costs calculated for PV, and diesel, incorporating costs of transport and installation, which are uniquely high for rural regions due to remote location. Specifically, I based my costs on assumptions drawn from a study done in coastal Andhra Pradesh for a group of tribal villages (Loka et al. 2013).

Policy Research

To get a better understand funding opportunities for this mode of rural development in India, I performed a literature search on all government solar programs. Specifically, I focused on the biggest solar subsidized programs in India and AP, the Jawaharlal Nehru National Solar Mission (nation-wide), Andhra Pradesh State Solar Subsidy, and other programs that came up in the literature. Specifically, I looked at subsidies the programs could offer towards rural microgrid projects.

Simulations

After modifying the model to reflect the case study site's constraints, I ran the simulations, with the PV microgrid as one option for technology and the diesel generator as the other. I ran three different simulations to gather financial metrics such as net present value (NPV), payback period, and levelized cost of energy (LCOE). First, I ran the PV microgrid, with inverters and battery storage, and then I ran the diesel generator that would service the same load profile. Finally I ran both together and allowed the model to use its own internal optimization to pick the most viable option, based on cost (Table 1).

Table 1. Scenarios of optimization runs in DER-CAM I ran three separate optimizations through DER-CAM to collect information on each system's performance costs and finally to see which one is considered more economically viable by the program.

Generation Technology Tested in Optimization	Data Recorded From Optimization
PV microgrid	NPV, LCOE
Diesel Generator	NPV, LCOE
PV microgrid and Diesel Generator	The technology that was deemed viable

RESULTS

The DER-CAM program outputs levelized cost of energy, net present value, and payback period of the system to give users a better idea of the economic metrics of the final power system that was selected as economically feasible.

I found that the PV microgrid system's LCOE was cheaper per kWh and was also selected as the economically viable generation technology. This was important because the LCOE takes into account the lifetime and the operational costs (e.g diesel transport and purchase) which give the PV microgrid an edge.

Table 2. NPV, Pay-back Time, LCOE of Proposed and Alternative Systems DER-CAM calculated the Net Present Value, Pay-Back Time, and the Levelized Cost of Energy of the proposed PV system and the alternative diesel system.

Load Scenario	Net Present Value ($)		Pay-BackTime (yr)		LCOE($/kWh)	
	PV	Diesel	PV	Diesel	PV	Diesel
Base Case	$250,000	$300,000	5	3	$2/kWh	$1.2/kWh

Given that irrigation and pumpsets formed such a large portion of the end-use profile, analysis of agricultural power subsidies and policies was also crucial and revealed that rural power supplied for agricultural use was practically free, but very unreliable, making it impossible for the government to recoup the cost of transmission (Chowdhury and Torero 2007). I found that farmers demonstrated a willingness to pay for more reliable power to protect their equipment from damages caused by regular outages (Dossani and Ranganathan 2004). Information about irrigation and power policies helped inform my understanding of how PV microgrids could be funded and incentivized.

I found that support for PV microgrids was not widespread, and that SHSs were favored, because of their discrete, independent nature, making them easier to sell and install oer house. However, these subsidies and financial assistance come with conditions about the types and categories of the generation systems and limits on the capacity to be considered home systems. More specifically, I found that the Andhra Pradesh government has offered a 20% increased subsidy on top of the 30% existing Central Government subsidy on establishing up to a 1 kW capacity SHS because they are small units that independently installed on homes and do not require extensive network wiring (Sahoo 2013). However, a PV microgrid do not qualify as an SHS and that means that PV microgrids would not be able to receive funding through this subsidy.

DISCUSSION

The simulations of PV array microgrid and diesel generator using DER-CAM demonstrated that the PV system had an overall lower cost per kWh, making it the economically viable option over the diesel generator. However, this result depended heavily on two factors: (1)

that subsidies would contribute to alleviating the high initial capital cost and (2) that the cost of buying and transporting diesel at regular intervals to generate the same amount of power was significant enough to make the PV microgrid cheaper, overall. Policy and literature research concerning PV microgrids and agricultural power use suggest that new financing mechanisms are a key part of encouraging growth in this sector and in providing reliable onsite power (Dossani and Ranganathan 2004).

Implications

The DER-CAM output results show that the PV microgrid was more cost effective and therefore reveals the cost benefit behind switching to solar power in rural areas of India, especially since diesel is rising in cost. The lower LCOE demonstrates that power generated by this system is cheaper over the lifetime of the system, largely because of no maintenance costs. The cost of a constant supply of diesel played a big part in making the generators more expensive in the long run as there is no cost to for fuel for PV. However, the subsidies that cover about 40% of capital costs of the PV offset capital costs significantly and this demonstrates a strong emphasis on government support for the system to be viable. This may not play out well in the long run, as policy research demonstrates that the government is looking to reduce direct subsidies to recoup costs (Jamil et al. 2012, Dossani and Ranganathan 2004).

Policy Outcomes

As the results demonstrate, the feasibility of the PV microgrid system relies, perhaps too heavily, on a large percentage of capital funding coming from subsidies and programs supported by the government. While this support can be politically justified by arguing that rural areas are receiving their access to basic electricity far behind their urban counterparts, policy changes in AP and on a national scale in India demonstrate that large capital subsidies are not economically sustainable. To that end, some studies have explored how to structure funding and financial incentives for rural development projects to optimize lifelong performance and reliability, as some institutions build unreliable systems that fail before their expected lifetimes but are able to cash in on heft subsidies upfront (Jamil et al. 2012). These changes would make for more robust growth and faith in the microgrid field.

Furthermore, AP has developed better grid-scale solar policy incentives that encouraged recent establishment of 1MW-2MW solar array plants to supply urban populations, but less is being done to incentivize rural microgrid development. Government reports demonstrate that SHS and solar lantern subsidies are a large part of rural energy development, but the inverters, and controllers associated with governing and distributing the power effectively (the role of the microgrid) are not part of this policy incentive, as they should be (Bhattacharya 2011). Studies comparing stand-alone and microgrid solar scenarios indicate that since the grid connection is very costly (and this is already available to most villages in AP), microgrid development in AP would be easier and more beneficial if policies were to incentivize and standardize the installment and operation of rural microgrids that are standardized, to encourage new industry players to get involved (Jamil et al 2012).

The need for subsidies, while helpful in relieving upfront financial pressure, does not bode well for overall financial robustness of the investment and growth model of rural energy access. In some cases, such as the Jawaharlal Nehru National Solar Mission project that was meant to expand energy access policy in the solar field, I found that the equipment had to be SHSs, which are not controlled together to function as a microgrid. I found that, given the constraints placed on the size and origin of the systems, finance supports and micro-lending schemes, other than subsidies, might be more helpful in helping spread the access to rural electrification.

Looking Ahead

The literature concerning power and irrigation subsidies in AP and other parts of India suggests that a rural power subsidy restructuring needs to take place in order to incentivize more reliable power supply and discourage wasteful overuse of power, placing more emphasis on solar power as a reliable onsite power generator. A study from neighboring Karnataka state mentions that farmers are actually willing to pay more for their highly subsidized irrigation power, if the power quality were better and caused fewer pumps to fall out of commission (Bose 2006). A survey of AP farmers also demonstrates need for more revenue for the state government and farmers willingness to pay more for agricultural power so long as it is more reliable (Dossani and Ranganathan 2004, and Chowdhury and Torero 2007). These two key findings demonstrate that PV mircrogrids could work with the developing rural infrastructure and changing agricultural power structure setup to offer good quality, onsite power that would take advantage of the farmer's willingness to pay more to protect the investment in their pumps.

On a larger scale, studies such as this one help gauge the benefits and feasibility of new onsite renewable energy generation in parts of the developing world that do not yet have access to electricity. Encouraging renewable DG from the beginning provides the area with great independence, and reliability in power.

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