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Analysis of Solar Energy Mini-Grids for Rural Electrification

[1,2]Hitarth Chopra, Aviral Gupta, [3]Dr. JP Kesari
[1,2]Student, Dept. of Information Technology, Delhi Technological University, New Delhi, India
[3]Associate Professor, Dept. of Mechanical Engineering, Delhi Technological Engineering, New Delhi, India

ABSTRACT
This paper highlights the working, principle techniques and applications of Solar Energy Mini-Grids . Mini-Grids are an off-grid electricity distribution network system not dependent on centralised grids involving small scale electricity generation for mostly localised usage. They may also serve as future connections to a network of such grids if and when the need arises but right now they mainly work to bring a stable supply of electricity to far-off places where neither centralized systems nor stand-alone systems are feasible enough. In this paper we also analyze the usage of mini-grids among rural communities. Thanks to new technological innovations resulting in cheaper and cheaper costs for both installing mini-grids and solar energy generation sources, mini-grids have the potential to bring electricity to those remote villages which would otherwise remain without electric power for household use as well as agricultural and commercial use with both efficiency and economically.

Keywords: *Mini-Grids, Solar energy generation, Adoption, Rural Usage*

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I. INTRODUCTION

A mini-grid is an off-grid electricity distribution network which involves small-scale electricity generation.Often consolidated with microgrids, a mini-grid is defined as having a power rating less than 11kW and being disconnected from utility-scale grids. The United Nations Framework Convention on Climate Change (UNFCCC) defines a mini-grid as one with a power rating below 15MW and being disconnected from larger electric grids. Mini-grids are a cost-effective solution for electrifying rural communities where a grid connection would be challenging in terms of transmission and its cost for the end user population density. Although solar home systems are currently more popular and reliant, slowly mini-grids are gaining popularity because of their ability to support basic and productive and commercial loads. However, this doesn't mean there are no obstacles, there are several barriers to their development such as ambiguity regarding regulations, financing constraints for developers, and most importantly lack of affordability. Hence, to overcome these challenges, countries such as Indonesia, Rwanda, and Nigeria along with some states in India have introduced compensation and exit strategies for the mini-grid operators to prepare for their early arrival. For example, The rural electrification program for Rwanda is making provisions to distinguish the areas for grid and mini-grid development. Mini grid development is being limited to areas that don't have the financial situation for grid-electricity.

II. SOLAR MINI-GRIDS

A mini-grid is basically a network of small-scale electricity generators and may also include some energy storage systems connected to a distribution system that supplies electricity to a localised group of people and operates independently from any other transmission grid. They range (in capacity) from a few kilowatts up to 10 megawatts. They are a suitable method to serve various consumers. They may include households, businesses such as shops, ice makers and phone chargers, agricultural uses such as irrigation, cold storages.

Mini-grids can be developed and operated by state, private companies, communities, or different entities such as public-private partnerships. The generation and distribution components can be developed by different players, both public and private. These mini-grids can run on diesel or renewable sources such as solar PV, hydro, wind, biomass etc or as a hybrid of the two. Our focus here will be on the mini-grids which generate their power supply from solar energy.

a. ELECTRICITY GENERATION

The generation of electricity from solar energy in mini-grids is done through solar panels in photovoltaic (PV) generators. The generators consist of several components, such as solar panels to absorb and convert sunlight into electricity, an inverter to convert the output as required, as well as other electrical components to set up a working system. These systems include every scale from small, rooftop-mounted or building-integrated systems with capacities from a few to several tens of kilowatts, to large utility-scale power stations of hundreds of megawatts. The actual voltage and current delivered by such panels depends on the surface of the panel, its orientation and the incident solar radiation and also on the load connected to the system. Due to the growth in usage of photovoltaics as a source of energy, prices for PV systems have rapidly declined. However, there still is much variation by market and the size of the system.

b. ENERGY STORAGE

Due to the unreliable nature of renewable sources, batteries are essential to ensure the reliability of Mini-Grid Renewable Energy Systems by storing excess supply when not required, to be supplied in times of need or when generation is not possible . Neglecting this aspect and only relying on real-time generation of electricity can result in power outages and blackouts, especially in places where environmental conditions are ever changing and have no back-up sources . While in rural areas, fluctuations in load is not a major problem, still the system must be able to meet the peak demand, which can entail large and expensive battery or fuel cell systems. To mitigate these problems, energy storages can be combined with diesel power and introduced to a mini-grid in a series when required or a switched hybrid system can be implemented which enable renewable energy plus storage to supply the base load power supply while the diesel generator helps meet peak loads at the time of increased demand.

c. DISTRIBUTION SYSTEM

A distribution system carries the energy produced by the generation source to the consumers. It consists of transmission lines, transformers, and other infrastructure necessary to enable an effective and safe energy distribution to all participants. Transmission lines can be overhead or underground but overhead transmission is preferred because it is cheaper to build. Distributing electric power at medium voltages allows the system to use smaller conductors, thus reducing cable costs. Higher voltages pose greater safety risks for both operators and users, so operators need special training to handle their operations. Different components have different efficiencies, so the choice of voltage, current and transformers determine the energy losses. Cost usually dictates which components the project developers choose to employ in the mini-grids.

III. EXTENT OF USE OF MINI-GRIDS IN RURAL AREAS

To analyse and fully understand the use and extent of solar mini-grids, we must ask ourselves a few questions. What role can solar mini-grids play in rural areas with grid electricity? Does grid extension make them an unnecessary and pointlessly expensive capital expenditure? Can they play an important role in being a complement to the grid? Rural corporations adopt various alternatives to grid electricity at a much higher rate compared to rural households. 50-60% of the surveyed households reported grid-electricity as their primary source of electricity, however, only 25-30% of the enterprises relied on grid-electricity as their primary source which goes to show that while India’s rural electrification programs have improved, their attention or as we could say the implementation for the needs in productive uses has not been given. This impacts the productivity and the profitability of enterprises, and therefore, they are more likely to move towards alternatives of grid-electricity given that they are provided with reliable energy. The one and only drawback that came out was affordability. However, it was not enough to deter their use since the demand and purpose of their use was low, reliable monthly electricity was preferred instead of low cost but less efficient grids. Users were provided mini-grid connections at fixed monthly rates for lighting and cooling, which were the two most common uses of electricity in the villages. Extension of these mini-grid technologies would however require regulation that encourages and protects the investment in mini-grid infrastructure. Though, it is important to note that this development and growth is not solely dependent on electricity provision, but on other ‘complementary’ services and infrastructure also.

Following tables draw a comparison between grid and mini-grid electric systems, the initial cost and the corresponding monthly expenditure in ruraL enterprises and rural households respectively.

d. COMPARISON OF COST IN RURAL ENTERPRISES

Purpose	Grid		Mini grid	
	Initial cost(□)	Monthly expenditure(□)	Initial cost(□)	Monthly expenditure(□)
Lighting only	1950	339	346	178
Cooling and others	1844	463	846	297

High powered appliances	1386	2874	-	-

e. COMPARISON OF COST IN RURAL HOUSEHOLDS

Purpose	**Grid**		**Mini grid**	
	Initial cost(□)	Monthly expenditure(□)	Initial cost(□)	Monthly expenditure(□)
Lighting only	590	333	320	128
Cooling and others	1487	337	236	210
High powered appliances	1361	348	-	-

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IV. MODELLING AND ANALYSIS

There are five key steps in the mini-grid technical design process: Defining the geographic area of the project, Assessing the available resources for energy production, Sizing the system according to requirements, Selecting the system configurations and Designing the distribution system.

The first step in mini-grid design is to define the geographic area and the total number of consumers. A mini-grid may have to supply power to multiple communities, a single village or a cluster of buildings. The number and type of consumers ,residential and/or commercial and industrial are key factors in selecting the resource used for the power generation technology. Terrain, ease of accessing the resource, will also influence the system design.

After defining the scope of the project, developers need to assess the energy resources available locally, including quantity, availability, cost incurred and sustainability. Mini-grids always need reliable and affordable supplies of energy resources that can meet local power needs and different resources have their own distinct benefits and disadvantages. For instance, in drought-prone areas, hydropower may not be a reliable source year round.

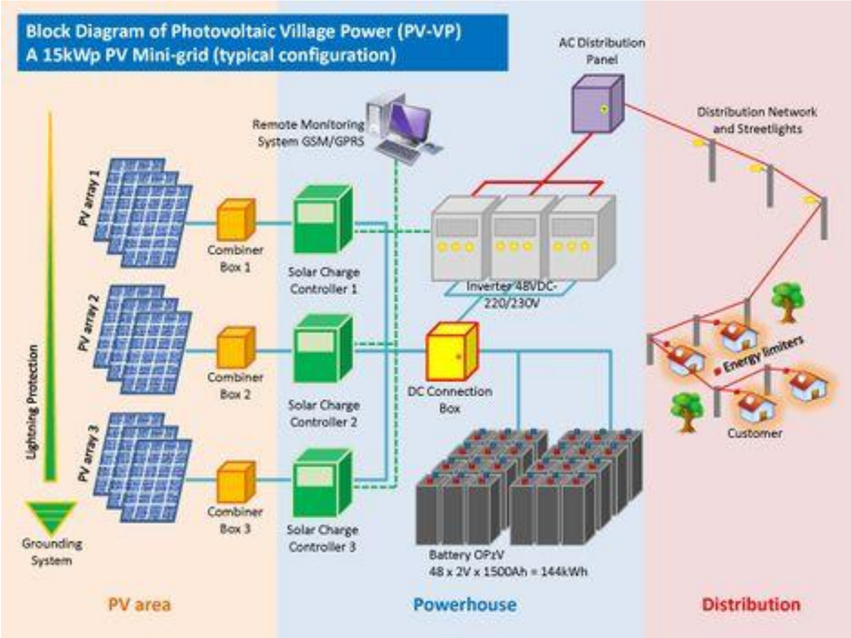
During the assessment, developers need to work with local communities together. The women and men who use these local natural resources can provide important information about the availability and potential pitfalls regarding their uses.

After identifying the resources with the most potential, developers select the energy generation technology. Developers can choose from among different technologies for each energy resource according to the situation on the ground and what technologies might provide the best efficiency.

A mini grid's size determines its maximum power output. The power generation system installed should have sufficient capacity to meet the demand loads. Planners must calculate variations in loads in intervals and also predict future load growth to determine the size of the system . Calculating and planning for present and future loads is a very critical step, especially for the financial viability of the whole project.

Mini-grid developers estimate electric current loads by surveying present and potential customers. Anticipating future loads is a difficult task. The demand for electricity supply grows hand in hand with demographic changes and economic expansions, which are very difficult to predict. Well-thought models give planners an insight on how to use different fuel sources efficiently and those decisions impact resource usage, consumption and cost.

Figure 1: Block Diagram of Photovoltaic Village Power (PV-VP).



Source: 131114 Inspection Guide for PV-VP (EnDev Indonesia 2013)

Ideally, mini-grids should be scalable in their operations, allowing operators to add generation capacity as demand for electricity grows. A mini-grid that can meet increased demand over time is more financially sustainable and also more time efficient since the developers would not have to begin anew . The best size for a mini-grid also depends on whether it is likely to be connected to a standard grid in the future.

Mini grids can have three basic configurations for power supply: alternating current coupled, direct current coupled or hybrid. Energy generation technologies, system sizing and battery use are the primary factors in deciding which configuration to use.

For designing the distribution system, developers first need to design the system layout and select system specifications. Then the next step is to make a model of system performance based on the preliminary layout and system specifications. Once they have defined the model for the distribution system, they can consider different conductor sizes based on the load allowed across the distribution system. Once project developers have completed the base case model, they can introduce model variations like single- versus three-phase service and loads.

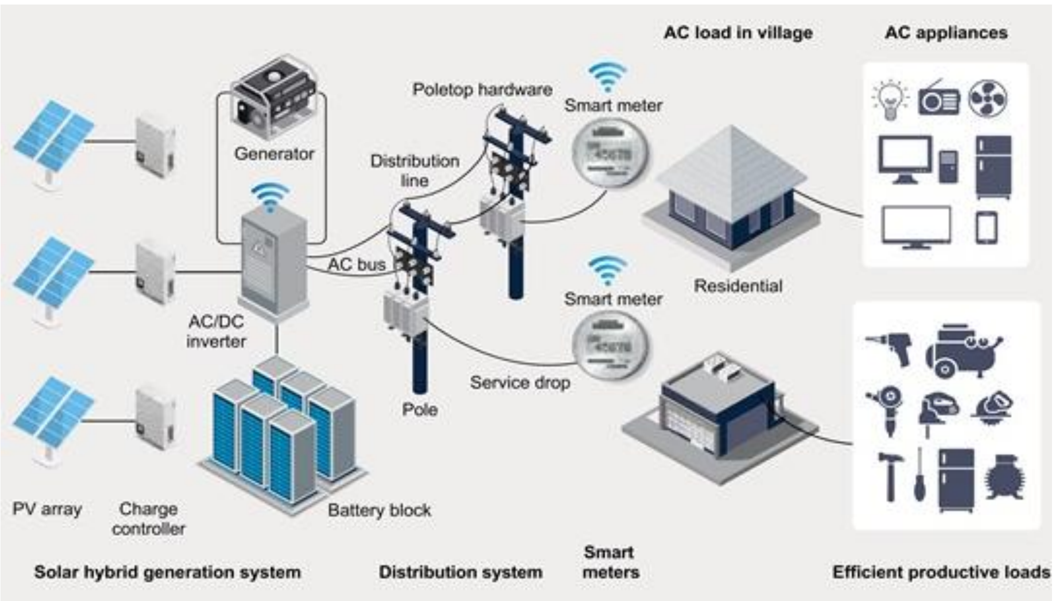


Figure 2: Features of a third-generation mini-grid system

Source: Mini Grids for Half a Billion People: Market Outlook and Handbook for Decision Makers.

When planners have finalized system layout and specifications, design planners determine the structural and design features of the distribution system. The design planners produce a list of materials based on benchmarks for the type and number of pole-top structures required for the line length and then determine the total length of the distribution line. They perform a final survey of the distribution system adjustments to determine pole locations, structures and other requirements.

Mini-grid distribution systems are often more complex than those of standard grids because of the nature of power supply and generation. Mini-grids may have two directional power flows and multiple energy sources unlike standard grids, where the flow is unidirectional. This complexity in operational procedures requires extra controls and software. In switched hybrid systems, each power source requires their own separate controllers, and the mini-grid must have an overall management master control to integrate the different power sources.

The following were the system's cost considerations. The costs have been converted in rupees:

PV panel—1 Watt = 106 □

Converter—3 KW = 104545 □

Battery—1 battery = 93344 □

Generator—16 KW/20 kVA = 224025□

In this paper, only the capital and replacement costs were considered leaving out the operation and maintenance since they vary with time considering the project duration hence difficult to predict future financial trends.

V. CONCLUSION

Our results suggest that rural enterprises have adopted alternatives to grid-electricity at a higher rate than rural households. While about two-thirds of the surveyed households reported grid electricity as their primary source of electricity, only about one-third of the enterprises relied on grid electricity as their primary source. This is because, while India's rural electrification programs have improved electricity infrastructure for rural households, the same amount of attention has not been given to the needs for productive uses. Therefore, mini-grids can play a role in providing electricity especially to rural enterprises as they provide electricity on a reliable monthly basis. But on the basis of the table above and general surveying we found that the use of mini grids was mainly limited to cooling and lighting purposes in rural households and given the high cost of operation of mini-grids, increasing their use to meet motive load is still a challenge. Also, a significant share of rural enterprises in the surveyed villages were unelectrified, despite having the luxury of grid and mini-grid solutions. This goes to show the low productivity and profitability of rural enterprises in India. Which draws an important conclusion that while it is important to improve electricity access, only the extension of electricity services alone won't steer growth and development of rural enterprises.This can be done by the promotion of energy- driven activities. Hence, it's important to link rural electrification programs with the rural development plans. The performance of grid-interactive mini-grids requires a lot of attention.

Mini grids do provide a better solution in remote areas however this paper highlights that customers should use and adopt mini-grids even in areas that are grid-electrified because of the sheer reliability. To ensure that customers are able to access reliable power supply at affordable rates, rural energy planners should pay more attention towards providing reliable grid-based electricity. Mini-grid based solutions can replace grid-connected areas at least in the short term, though it's still hard in the long term. We hope that our study helps energy planners be creative with the use of solar mini-grids in different conditions, and not interpret this paper as being a study for mini-grids to be a simple substitute for the grid where the extension of the grid is too expensive.

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