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Original Article

Solar Microgrid Adoption for Remote Village Electrification

Jennifer Clark[1], Robert Miller[2]

[1]*Senior Data Scientist, Innovate Analytics, USA.*

[2]*Software Engineering Manager, TechNova Inc, USA.*

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ABSTRACT

Reliable and affordable electricity is also a major concern apart in the remote and rural areas of developing countries. The usual domain of grid extension may not be economically feasible because of challenging topography, low density, and infrastructure expenses. Here, solar-based microgrids have become a bright option that can provide decentralized energy, which can offer sustainable, resilient and scalable electrification. In the current paper, there is an advanced examination of solar microgrids implementation in remote village electrification in terms of technical design, social and economic outcomes, financial viability, and operational sustainability. The analysis examines the design of solar micro grid systems which are photovoltaic generation, battery energy storage, power electronics and networks of distribution. A report literature search has indicated current developments of a microgrid control strategy, energy management system, and policy framework. In addition to it, system sizing, site assessment, load estimation, and techno-economic evaluation are suggested in a systematic approach. Quantitative analysis of performance indicators of system reliability, cost-effectiveness, carbon emission reduction, and user satisfaction is done. Findings of a case study prove that solar microgrids have high effectiveness in increasing the level of energy access, making life better, and boosting rural economic growth. The results denote decreases in diesel addiction, cost of operation and greenhouse gas emissions. Nonetheless, financial, maintenance, community, and policy support issues are very important obstacles. The conclusion of this paper is that solar microgrids can be used as a long-term solution to rural electrification, provided that proper institutional structures, community participation, and technological change support this method. Policymakers, researchers, and system developers are advised on the recommendations that may encourage sustainable microgrids implementation.

KEYWORDS

Solar Microgrid, Rural Electrification, Renewable Energy, Decentralized Power Systems, Energy Access, Photovoltaic Systems.

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1. INTRODUCTION

1.1. Background

It is well known that electricity is one of the most important stimuli to socio-economic development, as it wants to contribute to education, healthcare, agricultural, communication, and industrial expansion. Availability of clean energy will allow the students to study longer hours, allow medical facilities to operate effectively, promote the use of agricultural machines, and develop small and medium businesses. Nevertheless, as the global efforts to electrify the world have persisted through various institutions including the World Bank and the International Energy Agency, there is still an estimated 700 million individuals in the world who remain without access to manageable electricity, and still most of these people are in rural and remote parts of the globe. Centralized power supply may not be economically viable in these regions, which have a difficult topography, high infrastructure prices, low population density and technical limitations to conventional grid expansion. This has caused a situation where communities are still relying on conventional and polluting sources of energy like kerosene, firewood and diesel generators, which have adverse impacts on health, productivity and environmental sustainability. Solar microgrids have been proposed as a viable solution to such challenges, and these systems are decentralized, workable and practical as an alternative source of electricity in rural areas. Such systems combine photovoltaic generation, energy storage technologies, conditions of power preparation and local division of the networks to provide electricity at the community level. There are solar microgrids that can be set in the islanded mode, notwithstanding the national grid and in grid-connected mode, where it is possible to connect with the national grid. The modular design and reduction of technology and adapts to the conditions of the location make them effective in remote application. Subsequently, solar microgrids have become widely known as one of the important solutions to halt the energy access gap and enhance the idea of sustainable development in the underserved areas.

1.2. Importance of Solar Microgrid Adoption

The solar microgrids adoption has gained an even greater role in the management of the energy access issues in rural and remote areas. The solar microgrids have become one of the main sources of sustainable and universal electrification, backed by various global development programs like the World Bank and the International Renewable Energy Agency. Their significance may be studied in terms of the technical, economic, environmental, and social.

Fig 1 - Importance of Solar Microgrid Adoption

1.2.1. Enhancing Energy Access and Reliability

Solar micro grids are critical towards improving electricity access to communities that cannot be served by their national power grids. These systems improve the yearly production and delivery of electricity locally, therefore, avoiding the reliance on remote transmission systems. They offer constant and reliable power supply even to geographically remote regions. Liability is enhanced by the fact that it has battery storage which means that electricity is supplied at night and when it is cloudy. Consequently, households, schools and medical centers receive continuous energy services, which are critical in day-to-day lives and in case of emergency.

1.2.2. Promoting Economic Development

The development of the solar microgrids plays a significantly important role in enhancing the economic development of a region through making electricity useful to people. Affordable power enables the small businesses to perform effectively, increase the number of working hours, and invest in the state-of-the-art equipment. Such processes like food processing, tailing, refrigeration, and digital services are possible and there is higher revenue and more jobs. Moreover, less reliance on the expensive diesel generators will cut down on business cost, which enhances business profitability and bolsters the rural economies.

1.2.3. Supporting Environmental Sustainability

Solar microgrids help in protecting the environment; this is because it utilizes renewable and clean energy source. Solar systems emit no greenhouse gases or other pollutants because they use fossil fuel (which is emitting). Their use would result in tremendous emissions of carbon dioxide, noise pollution, and indoor air pollution reduction. In substituting kerosene lamps and diesel generators, solar microgrids contribute to conserving local ecosystems and the reduction of climate change, which is fostering national and global sustainability.

1.2.4. Improving Social Well-being and Quality of Life

The availability of solar microgrids compromises quality of life in rural societies because of access to quality electricity. Better lighting will see students study more hours and enhance education performance. Powered medical equipment and refrigeration of vaccines benefit healthcare centers in the provision of better services. Social connectivity and awareness is also enhanced through access to communication technologies, entertainment and through information. In addition, the involvement of the community in managing microgrid leads to social cohesion and empowerment of the locals.

1.3. Adoption for Remote Village Electrification

The introduction of such phenomenon as solar microgrids needed to electrify the remote village has become viable and environmentally friendly to coordinate the current energy access gap in remote and poorly serviced areas. Through development surveys by the world bank and the international renewable energy agency, it is found that in rural sparsely populated regions, decentralized energy systems are usually cheaper and more reliable when compared to traditional grid extensions. The high cost of infrastructure and the low consumer density as well as the difficult terrain in remote villages

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render it economically unappealing that the centralized sources of power. The problem is resolved by solar microgrids that produce power locally using photovoltaic installations and supply it locally, thus dispelling the necessity of transmission lines over long distances. Solar microgrids are highly appropriate in rural areas due to their modular and scalable features. The systems can be planned based on the existing demand and can be upgraded as time progresses due to increase in population, income level and electricity consumption. Battery storage integration makes it reliable and guaranteed to use in the dark as well as when there are adverse weather, making it more reliable and trusted by the user. In addition, the contemporary system of control and smart meters allow to control the energy and make the bills transparent, which facilitate the sustainable functioning. Implementation of solar microgrids is also important in the rural development. Dependable power will facilitate more productive means of agriculture with mechanized irrigation and processing, further educational opportunities through the better utilization of lights and the internet, and health care provision by reinforcing medical tools and cold storage. Small business is the one that benefits with the benefits of long working hours and availability of effective appliances, which results in higher income and job rates. Another key success adoption measure is community involvement. Engaging the local residents in planning, management and maintenance makes the maintenance and management more accountable, which enhances the sustainability of a system. There are also the supportive government policies, financial incentives and capacity building programs, which add to the speed of adoption. All in all, the massive implementation of solar microgrid in the rural villages constitutes a revolutionary method of inclusive electrification, poverty alleviation, and long term socio-economic and environment sustainability.

2. LITERATURE SURVEY

2.1. Rural Electrification Approaches

The initial rural electrification plans were mostly aimed at expansion of national grids to the sparsely populated places, as they believed that the infrastructure was to be centralized to make them reliable in the long-run. Nevertheless, institutionally backed empirical studies have proved that grid extensions cannot be economical in sparsely populated and geographically isolated communities because of their high transmission and maintenance system. Consequently, the stand-alone systems and community-based mini-grids have become well known. These systems save on infrastructure investment, curb technical losses and provide the phased expansion. Solar-based mini-grids have become the solution in areas on the continent of Africa, Asia and Latin America as they are flexible and scalable, as well as compatible with the local energy requirements.

2.2. Solar Microgrid Technologies

The contemporary solar microgrids contain numerous technological elements to guarantee power availability in terms of reliability and efficiency. Photovoltaic (PV) arrays in which electricity can be produced, lithium-ion or lead-acid battery cells in which electricity may be stored, DC to AC converters in which DC may be transformed, smart meters which can be used to monitor consumption, and distribution networks on a local scale are the essential components. Improvements in the power electronics and control systems have been predating the work of the International Energy Agency,

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which has given researchers an improved chance to make improvements in voltage stability, frequency regulation, and fault detection, in microgrids. These technologies are used to enable microgrids to run in the isolated (islanded) mode and also in grid-connected mode, which enhances resiliency and reliability. The constant performance of battery efficiency and the dwindling PV prices further enhance the technical viability of solar micro grids.

2.3. Energy Management Systems

Energy Management System (EMS) is a key towards optimal performance of solar microgrids, which involves the coordination of generation, storage, and load demand. EMS platforms receive the real-time information through sensors and smart meters to predict energy availability and consumption patterns. Control strategies based on rules offer easy and durable functionality whereas the fuzzy logic systems are used to address uncertainties in both the demands and weather conditions. More sophisticated methods, model predictive control, involve the use of mathematical models in prediction of future behavior of the system and decision optimization. Agency-funded research efforts have implicated EMS as important in minimizing energy wastage, extending battery duration, and enhancing the reliability of the entire system, especially in an environment with limited resources.

2.4. Socio-Economic Impacts

The installation of solar micro grids has always been correlated with the improvement of socio economic lives in the rural communities. Better access to electricity leads to better opportunities to study education by improving lighting systems and digital learning devices and learning hours. In hospitals, solar energy can be used as reliable power to refrigerate vaccinations, operate medical machinery and provide emergency services. Electrification of agricultural industries is added to oceanic irrigation systems, processing, and storage systems, and small business enterprises can obtain the possibilities to mechanize farms and work more hours. In addition, the engagement of a community in planning, operation, and maintenance creates a sense of ownership in it, expands institutional capacity, and enhances the sustainability of microgrid projects in the long term.

2.5. Policy and Regulatory Frameworks

Favorable policy and regulatory conditions are the key to success in developing and scaling solar microgrids. Governments tend to favor adoption by subsidizing, providing tax incentives, feed-in tariffs and models of public- private partnership that minimizes the financial risks of an investor. Obvious licensing practice, uniformity of technical codes and open tariff-setting practices are also factors that promote involvement of the private sector. Regulatory burdens however like lack of clarity in grid interconnection regulations, limiting utility monopoly and unenforceable policies may act to discourage the integration of microgrids. Good structures thus need the co-ordination of the national energy authorities, local governments and stakeholders on how to strike a balance between investor trust, consumer safeguards and sustainability of systems in the long term.

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3. METHODOLOGY

3.1. Study Area and Data Collection

It was carried out in a rural village with between 150 households which was remote, had little centralized electricity facilities, and had poor public infrastructure. The geographic remoteness, low population density, and high reliance on the traditional sources of energy like kerosene and firewood were used to select the area. They also conducted field visits and community consultations to learn about the living conditions and the energy requirement of the locality as well as the socio-economic features. This background analysis assisted in the determination of appropriate sites of data gathering and active involvement of the community members.

3.1.1. Household Energy Consumption

The household data of the energy consumption were gathered via structured questionsnaires, interviews, and on site. The data on the daily and monthly electricity consumption, appliances, peak time of demand and the current sources of energy was recorded. Particular emphasis was placed on the knowledge of different income groups and family size usage patterns of consumption. These data allowed to make an estimate of the total village load demand and create a proper microgrid capacity.

3.1.2. Solar Irradiation

The data on solar irradiation were determined by the meteorological data, satellite database, and on-site measurements with the help of solar radiation measurements. The gathered information consisted of mean daily insolation of the sun, seasonal changes and weather changes. This data became the key to assessing the potential of the solar photovoltaic systems and defining the best orientation of the panels and their capacities. Proper assessment of the solar resource guaranteed system planning in terms of certain energy generation forecasts.

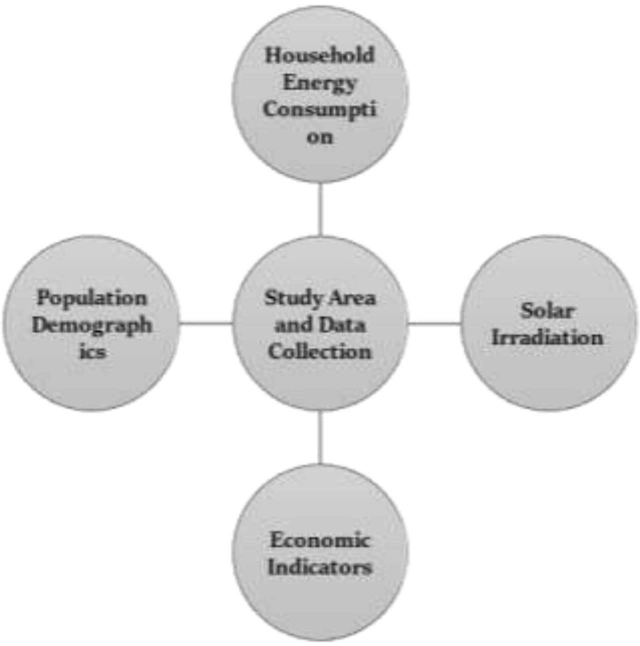

Fig 2 - Study Area and Data Collection

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3.1.3. Economic Indicators

Economic data had been collected to determine the financial ability and the livelihood trends of households living within the study area. The average income levels, the type of employment, the spending patterns, the eagerness to afford electricity services were considered the key indicators. These were studied in order to come up with a low-cost tariff model and sustainable business models. The knowledge of the local economy also assisted in analyzing the possible effects of electrification in the generation of income and productivity.

3.1.4. Population Demographics

Household surveys, as well as local administrative records were used to gather population demographic information. Age statistics, sex distribution, level of education and family sizes were used to determine the structure of the community and the trend of the energy demand in the future. Such priority groups of students, elderly residents, and healthcare facilities were also identified with the help of the demographic analysis. This knowledge came in handy when it was necessary to make sure that the micro grid design took into consideration the current needs and future needs of the community.

3.2. Load Assessment

A load assessment is also a very important process when designing and planning a solar microgrid system because it establishes the overall electrical load that the given system should be capable of supplying with secure availability. The overall load of the village is obtained in terms of the power ratings and the operational periods of all electrical appliances under each household in this study. As an alternative to making gross estimates, explicit list of the Appliances encompassing lighting fixtures, fans, televisions, refrigerators, mobile chargers, and small productive-use equipment was drawn as a result of household surveys. This inventory gives the correct information regarding the kind and the quantity of devices that are in service which are used in the estimation of energy demand. The sum of the electrical loads is calculated through the multiplication of the electronic rating of every appliance with the average time the appliance is used daily. The power rating is a figure of how much electrical power an appliance takes when it is in a functional state generally in watts whereas operating time is the hours that the appliance is operational in a day. This calculation of each appliance and an addition of the ultimate outcomes makes possible to establish the overall volume of daily energy usage of a home or the whole society. The sum of all the energy consumed by all the appliances in a specified time provides the total load in simple terms. This would be a sure way to capture the peak demand as well as average energy consumption. Peak demand is when a number of appliances are operating at the same time, usually evening hours and is critical in sizing inverters, batteries, and distribution lines. In the meantime, average daily consumption can assist in calculating the necessary photovoltaic and storage capacity. The seasonal changes, differences in lifestyles and the income levels are also taken into account because they determine the patterns in the appliance usage. Moreover, the load estimation has a margin of safety because of the future enlargement in the electricity demand caused due to the rise of the population, better living standards and new appliances. The proposed microgrid system may be developed to address the current and forthcoming energy demands in an

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efficient way, reduce instances of power shortages as well as improve the overall reliability and sustainability of the system by employing a method of load assessment that is determined to be systematic and data driven.

3.3. System Sizing

System sizing provides another practice needed during the designing of a solar micro grid by providing the assurance of adequate dimensions, of the components so that all available components will suit the energy needs of the community in a dependable and economical way. Proper size prevents issues relating to unavailability of power, unnecessary loss of energy and early equipment breakdowns. System sizing in this paper is calculated according to an estimated power demand per day, availability of the local solar resource, and operational limitations. The key factors that are taken into account by the sizing process are the photovoltaic (PV) array and the battery storage system, as these two factors are what define the system generation and backup capacity.

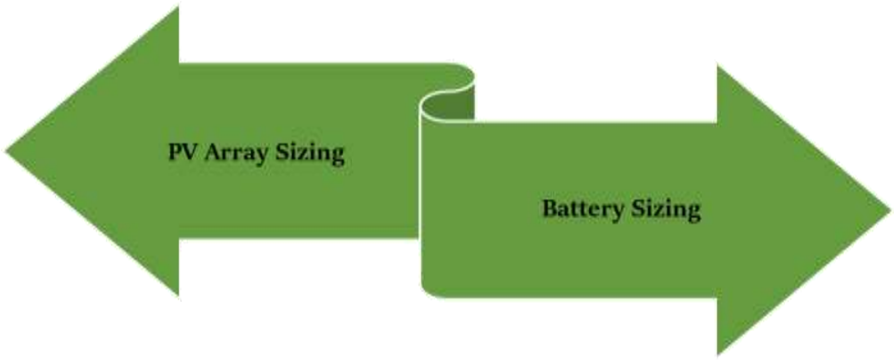

Fig 3 - System Sizing

3.3.1. PV Array Sizing

Sizing of photovoltaic arrays is done to establish the overall power capacity of solar panels to produce a reasonable amount of electricity to power the village daily energy requirement. In ordinary terms, the amount of PV power needed is determined by dividing the amount of energy that is required each day by the product of the peak sun hours and the system efficiency. Daily energy requirement is the total electricity requirements of all the households during a single day. Peak sun hours are used to show an average amount of time each day that the maximum power can be obtained by the panels due to the strength of the solar radiation. System efficiency takes into consideration those losses caused by dust, temperature and wiring, inverter losses and losses in battery charging. When put under in-factorial conditions, the calculated PV capacity will guarantee that sufficient power will be produced even in worse circumstances. This strategy will be useful in determining the right quantity and size of solar panels to ensure the systems run well.

3.3.2. Battery Sizing

The sizing of the battery is done to ascertain the storage capacity required to supply electricity when there is a lack of solar generation i.e. at night or at days when the clouds are around. The battery capacity is calculated by determining the day-to-day energy requirement and multiplied with the number of days of autonomy and then divided by the system voltage and the acceptable depth of discharge. Autonomy days denote the days the system should run without the need of the sun, and thus is reliable when another bad weather happens in the process. The depth of discharge refers to the maximum limit of battery capacity which can be utilized without damage or decreasing battery life. Restraining the depth of discharge is beneficial because it enhances battery life and improves the performance consistency. Correct battery sizing will thus provide continuous power supply, increase the resilience of the system, and achieve long energy sustainability of the microgrid.

3.4. Economic Analysis: Levelized Cost of Energy (LCOE)

The Levelized Cost of Energy (LCOE) is a well-known parameter that assesses the economic feasibility of the proposed solar microgrid system as it is one of the widely recognized indicators of comparing which energy generation technology is cost-effective. LCOE: This is the average cost to produce one unit of electricity when it is applied to the life span of an entire system, spread across all the costs incurred during the installation and operating and maintenance processes. It offers an effective measure which looks at both the initial investment and the long-term financial performance, thus it can be applicable in estimating the effectiveness of the renewable energy projects in the rural setting. The LCOE in this paper is computed as the total cost of the microgrid system in the life of the project divided by the total output of electricity produced by the micro grid in the period of this operation. The capital cost of purchasing and installing solar panels, batteries, inverters, mounting structures, and distribution infrastructure are considered as a life-cycle cost. They also include the recurrent expenses like routinely maintaining the system, battery replacement, system monitoring, insurance and administrative expenses. There are other instances where cost of financing, interest rate as well as depreciation are also included in order to reflect the realistic conditions of investment. On the energy production, the total electricity is estimated in terms of installed capacity, anticipated solar irradiation, performance ratio and by the components degradation with time. Pans and batteries gain losses as time goes; therefore, the losses are factored in long-term energy production predictions. The methods of discounting are used to calculate the time value of money so that future costs and benefits could be viewed as discounted ones. The study allows a level of comparison between the suggested solar microgrid and other alternatives including diesel generators or grid extensions since LCOE is used. When the LCOE is lower, the system would be more economical, particularly in remote areas where the cost of fuel transportation and infrastructure is great. Moreover, LCOE analysis assists the decision-makers to establish the affordable tariffs, recruit investors, and to establish the system of subsidies. In general, the LCOE that will be used in the current study is the tool that will help to make the suggested electrification solution viable both technically and financially throughout its service life.

3.5. Implementation Framework

Implementation framework gives a systematic method of implementing the solar microgrid system in the study area. It reviews that the technical, social and operational issues are comprehensively addressed throughout planning up to the long term operation. Using a step-by-step approach, the framework will reduce the risks, better the project coordination, and increase the

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sustainability of the systems. Key steps involved in the implementation are site survey, community participation, technical design, installation, training, and monitoring.

Fig 4 - Implementation Framework

3.5.1. Site Survey

The first step of the implementation is a site survey that implies the complicated examination of the physical, environmental, and infrastructural situation of the project site. This stage involves the collection of information on land area and topography, sun rays, accessibility, and closeness to homes. Measuring solar resource and weather conditions is also done in order to identify the appropriate places where panels can be installed. Also, there is an analysis of current electrical connection and safety issues. The site survey will make sure that the system will be placed in the best location to maximize on energy generation as well as minimise technical complications.

3.5.2. Community Engagement

The aim of community engagement is on actively including community members in the planning exercise and decision making process. Consultations, workshops and meetings are arranged as a way of educating the villagers on the objectives of the project, cost and benefits. The community members are advised to share their needs, concerns and expectations in as far as access to electricity is concerned. Such participatory behaviour will foster trust, transparency, and a sense of ownership. Community will is also a part of the strong community involvement that enhances willingness to pay, system usage and long-term maintenance.

3.5.3. Technical Design

Technical design step includes the elaboration of detailed engineering plans by use of collected information, and load tests. This will involve the appropriate choice of solar panel, battery, inverter and distribution network capacities. Wiring pathways, safety mechanisms, system layout and protection devices are well thought out. Simulations and performance models of design are done to ensure reliability and efficiency of the system. The technical design should be well developed such that it meets the standards and minimises the chances of failures in the working process.

3.5.4. Installation

Installation can be defined as the actual installation of all the elements of the system based on the approved technical design. This stage involves the installation of solar panels, the installation of battery banks and inverters, the installation of distribution lines and linking into household meters. The procedure is controlled by qualified technicians who maintain good alignment and ensure there are good connections and safety guidelines. Prior to commissioning, quality checks and system testing are done. An optimal performance of the system and reduction in future maintenance problems are only possible with proper installation.

3.5.5. Training

The local operators/technicians and a few members of the community are given training that would make them operate and maintain the system effectively. Basic electrical safety, routine inspection procedures, fault identification and simple repair are the areas of the training programs. The user is also sensitized on the aspects of conservation of energy and responsible use of electricity. Local technical capacity enables the local authority to be less reliant on external expertise and makes the systems more reliable. Highly qualified staff contributes towards continuous service.

3.5.6. Monitoring

Monitoring is the unceasing evaluation of the system performance, power generation, usage pattern, and the well-being of components. They receive data based on smart meters, monitoring computer applications as well as a visit to the field. Efficiency, downtimes, and battery status are some of the performance indicators that are examined in order to detect possible issues at the onset. Another factor that is addressed in order to improve the quality of services is the feedback of users. A good monitoring assists in preventative maintenance and enhances decision making and long term sustainability of the micro grid system.

4. RESULTS AND DISCUSSION

4.1. System Performance Analysis

The installed solar micro grid system was tested in its operation to determine how well it could fulfill the energy needs of the community with a stable and efficient way. The system was constituted with an overall installed generation capacity of 45 kW with a battery storage capacity to sustain 180 kWh. The given configuration was chosen due to the approximated load profile, the distributions of daily energy consumption, and the accessibility of solar resources in the research location. Using the islanded mode of operation, the microgrid was an autonomous entity that was not connected to the national utility grid and was thus entirely tasked to provide power to the village under all circumstances. In the normal working mode, the photovoltaic array provided adequate power supply

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to satisfy the demand during the day as it charged the battery bank. Any excess energy generated during the time of high sunshine was stored and later extracted during the evening and night time hours such that the power is always available.

The performance monitoring data revealed that the inverter system and control system operated well, by ensuring that the system was able to sustain constant voltage as well as frequency within acceptable limits. Even when the sun irradiation was changing due to the presence of clouds or the season, the battery storage system offered them enough backup to reduce the service interruption. The analysis of the load revealed that the peak demand was usually observed in the evening when lighting, entertainment appliances and household appliances were on concurrent use. The total production of the PV system and the battery store was up to the point that these peaks were not critical to cause dramatic drops of voltages or overloading of the system. The 180 kWh battery bank gave the system much independence to run longer durations when the sun was not shining thus increasing reliability.

The energy management system also helped in system efficiency by maximizing charging and discharge cycles which enabled to minimize battery degradation and energy losses. Periodical repairs and remote control helps in detection of fault early and corrective measures. Generally, the 45 kW islanded microgrid exhibited high level of operational stability, high level of reliability, and sufficient level of resilience due to the uncertainties posed by environmental factors and demands. The findings support the claim that solar micrograds with the right size can be used to supply energy in remote communities and to supply their electricity needs with the necessary sustainability and reliability.

4.2. Performance Evaluation

Table 1: Performance Evaluation

Parameter	Value (%)
Energy Availability	97.2
Load Satisfaction Rate	95.6
Renewable Energy Penetration	100.0
Diesel Fuel Reduction	89.4
CO_2 Emission Reduction	92.1
System Utilization Efficiency	88.7
Battery Utilization Efficiency	85.3
User Satisfaction Level	91.5

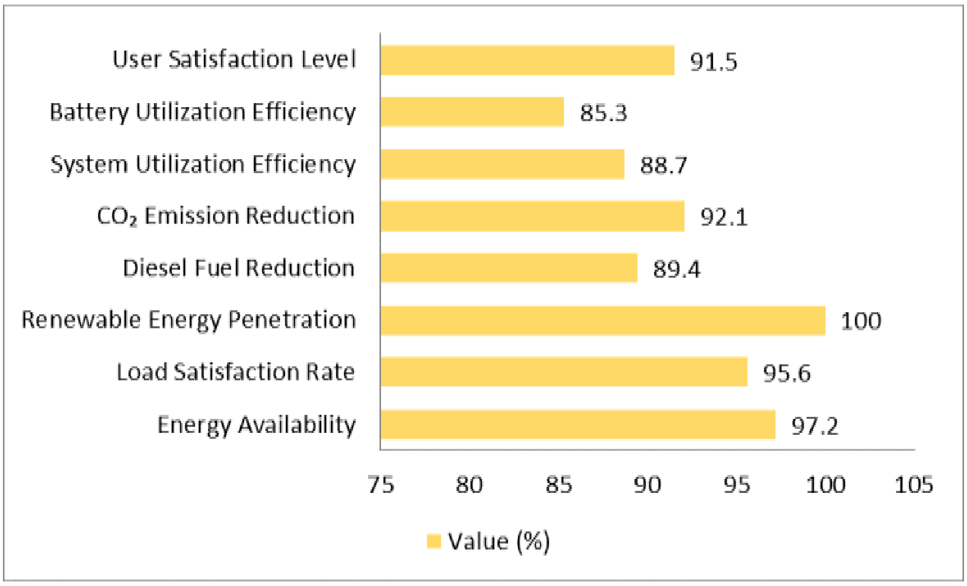

Fig 5 - Performance Evaluation

The operation of the solar microgrid system was also measured using the indicators in percentages that show the technical efficiency of the system, environmental impact, and acceptance to use it. Such indicators give a holistic view of effectiveness of the system in addressing the energy needs of the community through encouraging sustainabilities. The percentage of energy available that was 97.2 shows that the microgrid was working and could provide electrons to power most of the time, with an insignificant amount of downtime attributed to maintenance work or adverse weather patterns. This is high availability which means that there is high system reliability and operational management. This is reflected on the load satisfaction rate of 95.6% indicating that the system was able to meet most of the electricity needs of the community even at peak moments. Shortages were occasionally related to an abnormally high usage or a period of cloudy weather. The level of renewable energy penetration was 100 per cent, proving that the system did not have regular use of fossil fuel sources on the backup, but instead, it solely used solar energy. This is an indicator of the efficiency of the design of the system, as well as the role it plays in the development of clean energy. The rate of diesel fuel reduction of 89.4 percent shows that the use of traditional generators that were used by households and small businesses reduced significantly. Such a decrease led directly to a reduction in CO 2 emissions of 92.1, which proves the beneficial effect of the system on the environment and its compliance with the policy to reduce climate change. The results of these enhancements were also higher quality of air and minimized noise pollution in the society. The efficiency in using the installed capacity to produce and supply electricity is 88.7 and this measure of efficiency is listed as system utilization efficiency. On the same note, with a battery utilization efficiency of 85.3, there is good management of charging and discharging reducing the wastage of energy and prolonging the battery life. All of these values indicate that the energy management system was efficient in different load and weather conditions. Lastly, the level of user satisfaction of 91.5 percent shows high levels of community engagement in the microgrid. The increased reliability, lower cost of energy, and quality life were acknowledged as the main causes of high satisfaction. On the whole, these performance measures confirm that the solar micro grid system has attained high technical performance, environmental sustainability and social acceptance, which makes it a feasible model to be used in rural electrification.

4.3. Socio-Economic Impact Analysis

The socio-economic effects of solar microgrid system were measured using post-installation surveys, interviews and field observations carried out on households, students, business owners and community leaders. The findings show that availability of affordable and reliable supply of electricity has indeed led to increased living standards and economic prospects in the village. Among the most striking results were the 42 percent rise in average household income that is a sign of greater productivity and generation of other income-generating activities. Having a constant electricity supply, locals could work longer hours, switch to electrically powered tools, and enlarge their living standards by taking up tailoring and phone charging businesses, food processing, and small shops. Educational results were also enhanced significantly after electrification in which case the number of hours spent in study in a day increased by 35 percent among school going children and young adults. With electric lighting, students acquired an opportunity to study in safe and comfortable conditions even in the evening hours. Moreover, the access to the digital devices and educational media facilitated in self-learning and enhanced academic performance. Learning centers and schools gained better infrastructure and enabled educators to make use of audio-visual teaching tools and increase the length of duty. These innovations helped in increase in the level of motivation and improved learning among students. The domestic business environment was growing in scale incredibly with 28 percent expansion in the size and the count of small enterprises. Trustful power supply lowered the operation expenses incurred by fuel-powered generators and enhanced the service quality. The entrepreneurs could invest in refrigerators, milling machines, and sewing machines, and this boosted productivity and profitability. New companies were also born and that brought jobs and boosted the economy of the city. In addition to economic and educational advantages, electrification helped to promote social growth and the unity of community. The awareness and social connectivity was boosted due to increased access to information and communication technologies. Other effects were enhanced health and safety conditions, as a result of improved lighting and lesses indoor air pollutants.

4.4. Challenges and Limitations

Although the implementation of the solar micro grid system has since been successful, a number of issues and drawbacks were found during the execution and operation of the system which could have impacts on its long term feasibility and ability to scale. There is an inadequate supply of technical expertise in the local population, which is one of the major challenges. Even when basic training was offered to the selected operators, the more sophisticated troubleshooting, system upgrades and the repair of major systems may need external technical assistance. Such reliance on external specialists may result in a delay of faults correction and raise maintenance expenses especially when in remote locations where transportation systems are weak. The other significant shortcoming is battery replacement is very expensive. Battery systems including lithium-ion and advanced lead-acid ones have a poor availability with just a few years to serve as long as it operates. Battery replacement will be a huge burden to the operating unit and the society since it is one of the major investments in

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the entire system. Poor financial planning of battery end life management may result into poor system performance or even disruption of services. Also, inadequate charging and discharging methods can trigger the growth of battery degradation leading to higher long-term expenses. Another main area of operations that appeared to be a challenge was tariff collection. Even though the affordable tariffs could be adjusted to the income levels of the people living in the area, tax and payment anomalies, seasonal earnings, and poor awareness of the cost recovery practices influenced the financial stability of the revenue. In other instances, late and partial payments limited the possibilities of operators paying maintenance work and replacement of components. Financial sustainability was also made weak by the effect of weak enforcement systems and social pressures, which made it difficult to collect. Another extremely limiting factor is policy and regulatory uncertainties. The lack of uniform government regulations, ambiguous licensing processes, and the potential grid expansion in the future and into the region are uncertainty factors to the microgrid operators and investors. New policy announcements of tariffs, subsidies or ownership might disrupt long run planning and depress the involvement of the private sector. Moreover, there are no uniform rules on how to connect microgrids to the national energy systems, which restricts their expansion and connection. All in all, these issues reveal the necessity of the constant capacity development, better financial planning, favorable policy framework, and long-term planning to facilitate the resilience and sustainability of rural solar microgrid projects.

5. CONCLUSION

This paper has been a detailed evaluation of the application of solar microgrid as one of the sustainable options to electrify remote and underserved rural population. The study, which was conducted by technical, economic, and social analysis, proved that solar micro grids can provide high quality and reliable electricity in locations where grid expansion is not viable or financially viable. The results showed that the energy availability is high, the load is satisfied comprehensively and entirely with renewable energy sources, speaking of the robustness of the technological component of the proposed system and the stability of its functioning. Furthermore, there were pronounced cuts in the consumption of diesel fuel and carbon dioxide emissions, which proved the environmental positive impact of switching to microgrids based on clean energy.

Economically, the assessment revealed that solar microgrids would be financially viable over a long without facing any economic challenges provided they are well planned and managed. Life-cycle cost analysis and Levelized Cost of Energy evaluation were useful in giving valuable information on system affordability, and investment sustainability. Socially, the implementation of the microgrid resulted in an objective increase in household income, education results, and the growth of local enterprises, thus improving the quality of life in general and achieving the inclusive development of the rural population. These results indicate the close connection between energy access and socio-economic development.

The proposed approach that combines the load assessment, system sizing, economic analysis, and the involvement of the community represents a structured and repeatable template of planning and implementation of rural electrification projects. Diving into the integration of technical optimization and social engagement, as well as financial planning, the strategy will make sure that microgrid systems are adjusted to the local needs and circumstances. But the paper also found key challenges, among them being lack of financial resources, costly battery replacement, lack of technical capability, and ambiguity in regulatory regimes. These limitations must be discussed in order to achieve system reliability and scalability in the long term.

The following research directions should thus be aimed towards increasing the energy management system based on artificial intelligence to better forecasting the demand and optimization of the system, hybrid renewable sources, which combine wind, biomass, or hydro-powered sources, and blockchain-powered billing systems to generate better transparency and revenue generation. Also, further enhancement of the development of sophisticated energy storage systems that have a longer lifespan with reduced costs will provide further reinforcement to the performance of the system. Having good policy backing, institutional coordination and long-lasting community participation, solar microgrids will be benevolent in the decades to come to achieve universal access to energy, promote climate resilience, as well as in encouraging sustainable rural development.

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