Analyzing the Viability of Decentralized Renewable Energy Solutions for Rural Electrification in Marginalized Communities of Pakistan

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Analyzing the Viability of Decentralized Renewable Energy Solutions for Rural Electrification in Marginalized Communities of Pakistan

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Abstract: *Access to electricity is crucial for socioeconomic development, yet many rural communities in Pakistan still lack reliable and affordable energy services. This research paper explores the potential of decentralized energy solutions for rural electrification in Pakistan. It assesses the effectiveness, challenges, and socio-economic impacts of various decentralized energy technologies, including mini-grids and off-grid systems. The study also examines the enabling policies, regulatory frameworks, and financial mechanisms necessary to promote the deployment and scalability of decentralized energy solutions. The findings highlight the opportunities for leveraging renewable energy sources, such as solar PV having cost of energy 0.20$kWh, and provide insights for policymakers, practitioners, and stakeholders to foster sustainable rural electrification in Pakistan.*

Keywords: Pakistan; Rural communities; Punjab; Renewable energy, Solar (PV)

1. INTRODUCTION

Pakistan is a country of 240.5 million peoples and with total installed power capacity of 40000MWs. Access to electricity is a fundamental prerequisite for economic growth, social development, and poverty reduction. However, electrification in Pakistan faces numerous challenges, leaving a significant portion of the population without reliable and affordable energy services. The lack of access to electricity hinders educational opportunities, limits healthcare facilities, and restricts economic activities in rural areas. Electricity is a fundamental driver of economic growth, significantly contributing to a nation's Gross Domestic Product (GDP).

Many, rural communities in Pakistan lack access to electricity, particularly those in marginalized areas. According to the World Bank, only 56% of rural households in Pakistan have access to electricity. This is significantly lower than the national average of 75.4%[1].

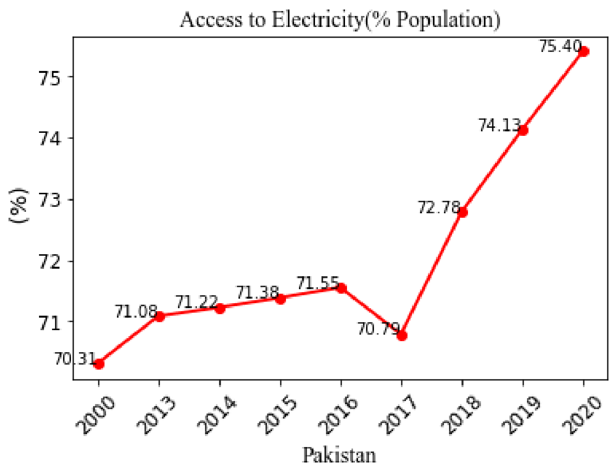

Fig. 1 Pakistan access to electricity (%)

Punjab is the most densely inhabited province in Pakistan, accounting for about 53% of the country's total population. The population of Punjab is growing at a rate of about 2.1% per year and its economy is 1.018 trillion USD. Punjab is a predominantly rural province, with about 66.9% of its population living in rural areas. The agricultural sector is the largest employer in Punjab, accounting for about 42.3% of the workforce and a major source of economic activity in the province []. According to the Pakistan bureau of Statistics Punjab has maximum power installed capacity of 17,257 MW which includes hydel, nuclear Solar, bagasse, wind, and solar each have 25%, 4%, 3%, and 1% of the share, respectively[2].

It is an indispensable requirement in today's digitally connected world, powering essential services like communication systems industries and houses. Additionally, the availability of reliable electricity plays a crucial role in generating employment, reducing poverty, and improving the human development index, particularly in rural areas.

As of 2022, Islamabad Electric Supply company (IESCO) one of power distribution company has electrified over 13,000 villages in Punjab, Pakistan [2]. The total number of rural households with access to electricity in Punjab is estimated to be over 7 million with the electrification rate in rural Punjab is estimated to be around 65% The government of Pakistan has set a target of electrifying all rural households in Punjab by 2025[3],[4].

Here are some of the challenges that faces in rural electrification:

I. The terrain in rural Punjab is often difficult, which makes it challenging to build and maintain electrical infrastructure.
II. Many rural communities are located far from the grid, which makes it expensive to extend the grid to these communities.
III. There is a lack of financial resources to invest in rural electrification.

To address these issues one of the best solutions proposed by energy policy maker and experts for clean and cheap sources of electricity in rural areas is,

I. The use of renewable energy sources, such as solar and wind power, to electrify rural communities.
II. The use of microgrids to provide electricity to rural communities that are located far from the grid.
III. The provision of financial assistance to rural communities to help them afford electricity connections.

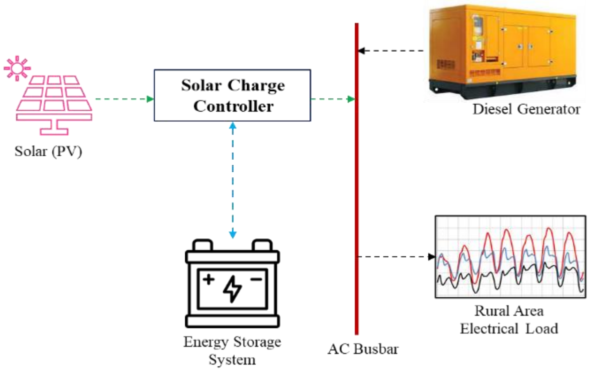

Fig. 2. Off-grid Solar PV system

The decentralized renewable energy solutions have emerged as a promising approach to provide sustainable and inclusive electricity access to marginalized communities. The objective of this paper is to conduct a comprehensive analysis of decentralized energy solutions for rural electrification in Punjab Pakistan. The study evaluates the technical feasibility, economic viability, and socio-economic impacts of decentralized renewable energy technologies in marginalized rural communities. Additionally, the research seeks to identify the enabling factors and barriers to the adoption and scalability of these solutions, providing insights for policymakers, practitioners, and stakeholders to facilitate effective implementation strategies.

2. Methodology

A system in which power is produced at or near the location where it is consumed, utilizing technologies like solar, wind, biomass, and diesel generators. However most suitable is PV solar. The solar electrification feasibility through decentralized solar micrograds is established by conducting demand and supply side analyses. The demand analysis involves eliciting the total load of 3 villages of sub-region district Talagang Punjab, on the supply side, a detailed system cost analysis considers factors such as solar panel costs, batteries, inverters, installation, and maintenance, along with local solar resources and environmental conditions. Combining these analyses allows stakeholders to assess the economic viability, financial sustainability, and potential scalability of the of off-grid solution, ensuring it can provide reliable and affordable electricity access while leveraging local resources and meeting the needs of the target communities.

2.1 Demand and supply assessment

To determine the demand for rural micro-grid. Load is assessed by IESCO survey teams in the remote areas of district Talagang Punjab, Total 101 houses in selected area that were designated as off-grid, they are not covered by the national electricity grid. Total load estimated as 260 kW, out of 101 houses, 70 consumers want to use lights, fan, TV, water pumps were placed in category-1 having load 1-2 kW, while 31 houses willing to use refrigerators and washing machine and AC was taken in 2-3 kW load category-2.

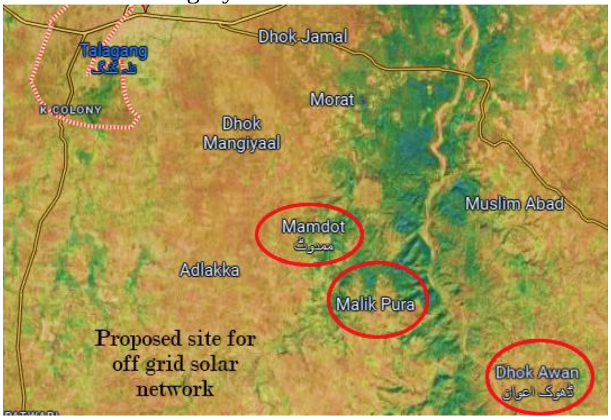

Fig. 3. Location of Villages

2.2 Proposed off grid Solar PV system

The solar radiation and ambient temperatures are important considerations in solar PV power production. The power generated by the PV module in this research is modelled using the equation below[5]:

$$P_W(t) = N_{pv} \text{ x } V_m \text{ x } I_m \qquad (1)$$

Where N_{pv} is the number of PV modules is determined during the optimization process while V_m and I_m are the values of the maximum voltage and current of the PV module[6].

$$P_{PV} = C_{PV} \cdot D_{PV} \cdot \left(\frac{G_T}{G_{T,STC}}\right) \cdot \left[1 + \alpha_p\left(T_C - T_{C,STC}\right)\right] \quad (2)$$

C_{PV} is the capacity of the PV array in kW, D_{PV} is PV derating factor (%) G_T is solar radiation kW/m^2 $G_{T,STC}$ incident radiation at standard test conditions 1 kW/m^2, α_p is temperature coefficient of power (%/°C), T_C is PV cell temperature (°C).

Power storage of the battery system[6],[9],[12]

$$E_{bat(t)} = E_{bat(t-1)} + \left(E_{gen(t)} - E_{L(t)}\right) \quad (3)$$

The constraint of battery modelling can be expressed as [6],[11],[12]

$$E_{bat\_min} \leq E_{bat(t)} \leq E_{bat\_max} \qquad (4)$$

The SOC of a battery can be determined as[6]

$$SOC_{(t)} = SOC_{(t_o)} - \frac{1}{P_{bat-disch}} \int_0^t I_{bat(t)} dt \qquad (5)$$

Figure 1 shows the off-grid standalone PV-battery DG system for any remote community which quite easy to design and install as per load requirement. ESS is an energy storage system and DG is for back supply. Systems size

As per NEPRA electricity connection criteria load can be calculated either by the area of house or how much customer intended to connect load to electricity point through energy meter, however minimum allowable limit is 1kW up to 4.5kW a single phase domestic rural area consumer can get approved by IESCO under regulator laws [7], [8].

3. On-grid rural electrification plan and cost

According to the consumer demand and area weather conditions On-grid system is proposed for three villages and the estimated cost of electrical network infrastructure including three distribution substations, HT/LT lines with steel structure poles is $2.18 million for three villages named Malikpura, Mamdot and Dhok Awan located in Talagang district Punjab location map is displayed in figure 3 , adding 22% installations, shipment and contract charges gives total cost $ 2.65 million USD process are taken from BoQ of IESCO construction manual. Daily load in kWh is given in Table 1 and Figure 4.

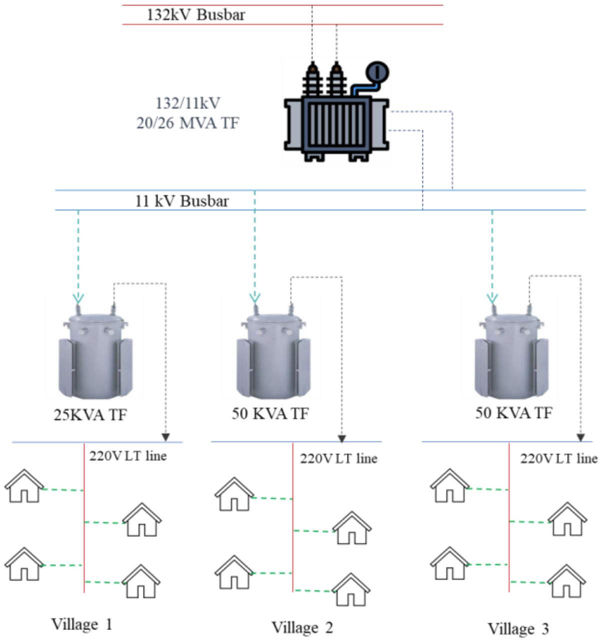

Fig. 4 On-Grid HT/LT network

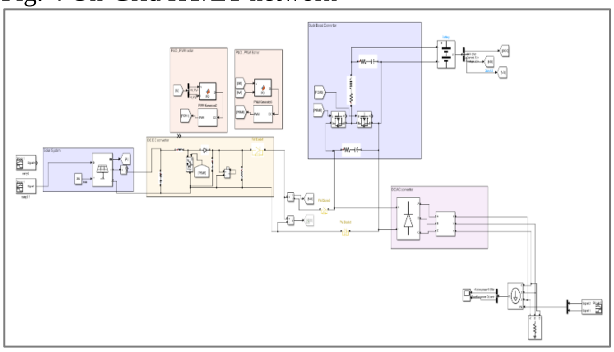

Fig. 5 MATLAB SIMULINK Model

Table. 1. TF capacity and estimated electricity demand

TF Capacity	Houses	Load kWh
25KV	26	348
50KV	32	326
50KV	48	690

Houses' electricity load is assessed as 6 hours peak, 12 hours normal and 6 hours 30% and according to distribution transformers capacity when connected only to on-grid system.

2.3 PV-battery System Sizing

The proposed system size is 910 kW solar PV and 790 batteries of 200AH capacity**.**

Table 2 PV battery cost

Solar PV Cost	704.62 $/KW
Battery Cost	188 $/ Battery
O & M Cost	20 % of the Initial Cost
PV Regulator Cost	102.09 $/KW
Invertor Cost	645.69 $/KW

PSO optimization is an optimal sizing and cost, and simulation is performed in MATLAB Simulink[8]

3. Results and discussion

The results show that the total 54.6031MWh of electricity is generated against the 49.7860 MWh load in one year, figures 5 and 6 show the PV-battery balance of demand and supply for proposed model, which is satisfying the demand of the three villages. The results shows that batteries are supplying required energy during night without any need of diesel generator.

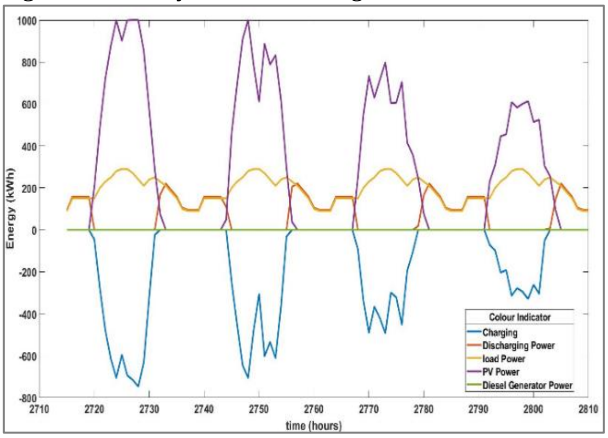

Fig.5 Power balance for 4 days May

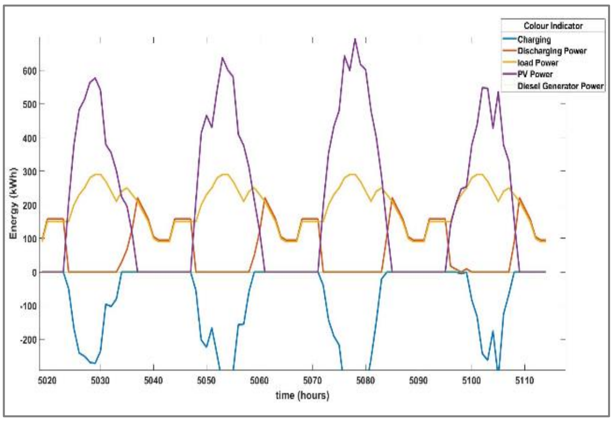

Fig. 6 Power balance for 4 days August

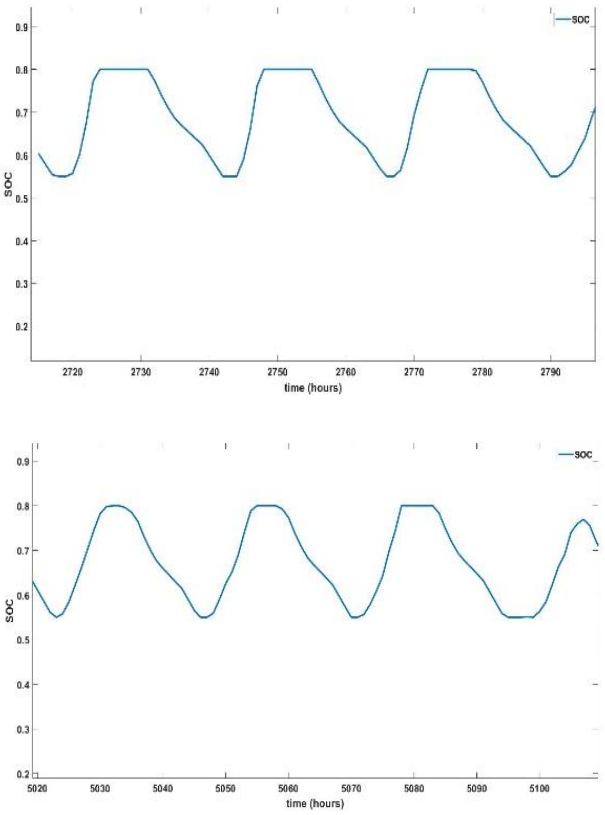

Fig. 7 SoC of Energy storage system

The state of charge (SOC) of batteries is displayed in figure 7 shows that energy storage system is supporting demand during nighttime.

The batteries and generator as backup. There is alternate solution to connect the DRE with grid which is quite expensive. Moreover, results shows that the cost of energy off grid DRE system is nearly equal to grid supply however it is source of green energy having cost of energy $0.2 per kWh and main advantage of off-grid energy supply system is continuity of supply, reduced line losses that are currently more than 8%, when these transmission losses are combined with grid electricity price it is a huge burden of govt. The actual cost of energy supplied to this remote area become more expensive.

The cost of system maintenance is another factor as distribution company must appoint permanent skilled worker to handle HT/LT distribution network day and night, line patrolling and tracing faults, transportation and replacing malfunctioned equipment. The issue of energy meter recording, bill distribution and bill payment can also be reduced.

Solar PV systems are the most common type of DRE solution in Pakistan. They are relatively easy to install and maintain, and they do not require a grid connection. This makes them a good option for rural communities that are located far from the grid.

4. Socio-Economic Impacts

The socio-economic impacts of DRE have been the subject of much research. Off-gird renewable power supply can have a positive impact on a wide range of indicators, including:

I. Household Earnings: DRE can be used to power small businesses, which can create green jobs and boost the local economy.

II. Education System: It can lead to an improvement in education system. This is because DRE can be used to power lighting and electronic devices like computer labs in rural schools, which can improve learning outcomes for students.

III. Health Facilities Improvement: It can be used to power rural health units, medical apparatus, such as refrigerators for vaccines and incubators for premature babies, helps to reduced rates of infant mortality and other health challenges in remote areas.

IV. Small Industry: It is an important sector in rural communities, like small flour grinding mills, vegetable processing and packaging plants, carpet and stitching units can easily be shifted to renewable system, this will reduce the price product price and quality.

5. Policy Implications

The findings of this research have several important policy implications:

- The government of Pakistan should promote the use of RE solutions for rural electrification as one of the cheap solutions. This can be done by providing financial incentives to the private sector and developers by simplifying the regulatory environment for DRE projects.

- The govt should focus on funding DRE systems installations instead of on-grid electricity network distribution which is quite expensive for remote areas.

- The government should invest in research and development of DRE technologies. This will help to improve the performance and cost-effectiveness of DRE solutions and make them more accessible to rural communities.

- The government should work to raise awareness of the benefits of DRE among rural communities. This can be done through public education campaigns and by providing information about the benefits of the DREs system.

- The government should encourage the farmers and small industries to installed more renewable energy system that can supply bi-directional energy to local communities which will enhance the energy efficiency, self-generation, and clean energy production.

As a part of policy implementation DRE is best solution for remote areas, RE power systems is viable and can provide desired energy to cover the demanded energy.

6. Conclusion and future work

It is very clear that an off-grid DRE system is one of the best solutions for rural electrification where grid-to-village distance is higher than 20kms mostly people living in these areas consume less energy and due to distance voltage drop is a big issue during summers, the low power factor generates line losses. The government of Pakistan bears these losses and operational maintenance costs every month.

The recovery is another issue people usually do not pay their electricity bills so generating a huge circular debt and financial burden. In the proposed DRE model, the electricity is around $.20 kWh which is suitable as compared to the cost of network and annual o & m cost incurred by a power distributor.

As cost can be fully covered by the govt under Pakistan's development of rural areas PWD-I-II as the same fund is used to electrify the rural areas so the cost of energy can be subsidized by govt to give more benefits. However, people who want to install their PV power system are also allowed to connect to the same off-grid PV system and bidirectionally can sell their extra energy to local grid.

Currently, the ratio of accident due to electrocution is increasing mostly these accidents are occurred in remote areas and on high voltage transmission lines, workers as well as public is victim as they touched the electric poles during rainy season. The implementation of DRE can enhance the safety of systems and humans by using low voltage transmission system.

Further the areas where wind and water potential are available like in coast of northern area of Pakistan wind power and Micro-hydropower systems are also DRE solution for rural communities. They are more expensive to install than solar PV, but they can generate a lot of electricity. This makes them a good option for rural communities with a high demand for electricity.

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