

Exploring the Electrification of Rural Areas in Pakistan with Solar Energy

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Abstract

Pakistan’s rural electrification gap remains acute: over 30,000 villages are off the national grid and roughly 40 million people lack any electricity access, with many remote communities facing high fuel costs and poor air quality from fossil fuel use. This study asks whether decentralised solar mini-grids can deliver practical, affordable power for these communities. We combine three pillars: resource suitability, technology fit, and economics. First, we build a national geospatial suitability model using a Random Forest (RF) classifier trained on 492 labelled points derived from Solargis rasters; the model achieves ~0.9 AUC, then scores every 1 km cell across Pakistan. The resulting map highlights a southern belt—especially Balochistan and Sindh—with relatively higher solar suitability. Second, we define a robust off-grid reference system for rural contexts: 50 kWp of crystalline-silicon PV, 200 kWh lithium-iron-phosphate storage, and a bidirectional hybrid inverter. Third, a bottom-up levelised cost of electricity (LCOE) calculation for this reference design yields \$0.24/kWh, competitive with diesel generation (\$0.30–\$0.70/kWh) commonly used in rural areas. We conclude that well-sited, standardised solar mini-grids can close a substantial share of the rural access gap at costs at or below prevailing alternatives. As next steps, on-site campaigns—prioritising high-suitability districts such as Balochistan—should install short-term meteorological measurements, verify vendor and logistics costs, and characterise real demand and community preferences. Such fieldwork would substantially reduce uncertainty in both the RF model inputs and LCOE assumptions and represents the most important limitation to address before programmatic deployment.

Index Terms

Solar energy, rural electrification, Pakistan, mini-grids, LCOE, geospatial suitability, Random Forest.

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I. INTRODUCTION

Pakistan is mired in a chronic energy shortage caused by its rapidly growing population, unsustainable dependence on costly fossil fuels and mounting financial challenges such as the circular debt exceeding \$7 billion in the power industry. Rural areas are disproportionately affected with millions lacking access to reliable electricity. This is often essential, not only for lighting and heating, but for pumping up groundwater from the country's abundant aquifer resources.

Globally, countries are shifting to renewable energy sources to ensure energy security, reduce carbon emissions and meet international targets such as the Paris Agreement and the UN Sustainable Development Goal 7 (Affordable and Clean Energy). Pakistan, recognising these imperatives, has committed to ambitious policies such as the Alternative and Renewable Energy Policy 2019 (ARE policy) which sets a target of 30% of Pakistan's energy to come from renewable sources [1]. To achieve these goals, Pakistan must utilise its abundant natural resources—chief among them: solar energy.

Pakistan possesses the highest average solar insolation potential in South Asia, receiving between 5.3 to 6.0 kWh/m²/day across much of its territory. This means it can generate about 2.9 TW solar energy annually, which is over 20 times its current consumption. The vast majority of this potential remains an immense, untapped natural resource that Pakistan has to take advantage of. Since 2010, the cost of solar photovoltaic (PV) systems has decreased by 82%, dramatically improving the economic viability of solar energy and providing a cost-effective solution to the financial problems that drive the severe electricity crisis.

This research paper aims to evaluate the feasibility of electrifying rural areas in Pakistan with solar energy in a multidimensional approach considering three critical factors: Solar Irradiation, Solar Technology and Economic Viability. The analysis of these three key dimensions via existing literature, predictive machine learning models and available quantitative datasets will determine the extent to which solar energy can bridge Pakistan's rural energy gap. This paper hopes to provide actionable recommendations for government stakeholders, NGOs and energy providers to accelerate rural energy access and reduce reliance on fossil fuels.

II. BACKGROUND

Solar energy is the most abundant energy resource on Earth, and it has been the goal of mankind since ancient times to harness it for its own advantage [2]. About 1.08×10^{14} W reaches the surface of the Earth per second, meaning that the solar radiation reaching the earth's surface in just one year is an order of magnitude greater than all the estimated (discovered and undiscovered) non-renewable energy resources, including fossil fuels and nuclear [3]. Despite this immense potential, only a small fraction is currently utilised, highlighting the urgent need for widespread methods to capture and convert solar energy, especially in the face of growing global energy demands and the escalating impacts of climate change. In particular, developing nations stand to benefit the most from solar technology with solutions that can bypass the limitations of traditional grid infrastructure as well as providing sustainable energy access to marginalised communities.

Approximately 1.1 billion people worldwide lack electricity with the majority of these being found in rural areas [4]. This trend is no different in Pakistan with the majority of those affected located in rural areas which make up 61.64% of the total population; the country's total power demand is 25,000 MW and is estimated to increase rapidly with urbanisation to 40,000 MW by 2030 [5]. Currently, the electricity supply is around 17,000 MW causing an electricity deficit that leads to blackouts known as load shedding that at their peak can impact urban areas for up to 8–12 hours and rural areas for up to 18 hours [6].

Beyond these disruptions, over 30,000 villages in Pakistan remain completely off the national grid, leaving approximately 40 million people, or one-quarter of the population, without access to electricity in any form [7]. Many small rural communities, particularly in Balochistan and Khyber Pakhtunkhwa, are located in remote locations far from existing transmission infrastructure, making it logistically and financially difficult to connect them to the grid. In these poorer areas, households can be forced to invest up to 25% of their monthly income in fuel, kerosene and batteries for necessary tasks such as lighting and irrigation [8].

The current solution to this severe electricity crisis involve relying on expensive foreign oil imports that amount to a financial drain of about \$11.3 billion on Pakistan's economy [9]. Despite this massive expenditure, most of this energy ends up in urban areas leaving rural areas disproportionately affected. Beyond economic inefficiency, the environmental consequences are severe with imported fuels contributing to both greenhouse gases and the intolerable air pollution found in Pakistan's major cities; combustion emissions and air toxics from fossil fuels are major contributors.

III. LITERATURE REVIEW

A. Solar Irradiation

Pakistan is located in the high-potential ‘solar belt’ of the globe, with approximately 300 sunny days a year for adequate sunshine hours (8 to 8.5 hours a day) [10]. This energy source is widely distributed across the region, however there are regions where solar irradiation is more concentrated. This variability is of critical concern when planning solar energy development.

Global Horizontal Irradiation (GHI) is the most important measurement for energy yield calculations and predicting the performance of a flat-plate photovoltaic (PV) module. It is measured in kWh/m² demonstrating the solar power falling on each square meter of land. The Renewable Energy Resource Mapping program, initiated by the World Bank, has a Geographic Information System (GIS) map showing the solar irradiation across the entirety of Pakistan. The World Bank estimates that meeting Pakistan’s current electricity demand would require allocating just 0.071% of the country’s land area to solar photovoltaic systems. This is due to Pakistan’s high average annual solar insolation, measured at approximately 5.30 kWh/m², which translates to a theoretical solar energy potential of around 175,800 GW. While the solar energy sector in Pakistan remains relatively underdeveloped, it holds considerable promise for addressing the nation’s energy needs through its abundant solar resources.

While the World Bank’s maps are widely cited, their use of long-term yearly averages limits temporal resolution. In studies such as Rafiq *et al.* (2021) [11], a finer temporal resolution was achieved using monthly clearness index data derived from satellite inputs, which allowed a more accurate estimation of irradiation across different times of the year. They found that areas in northern Khyber Pakhtunkhwa and Gilgit-Baltistan show significantly lower values during the winter season, highlighting the need for regional adaptation in solar system planning.

Furthermore, these traditional methods don’t utilise machine learning (ML) to predict solar irradiation. Recent literature demonstrates that ML models, most notably: Artificial Neural Networks (ANN), Support Vector Machines (SVM), and Random Forest, outperform conventional statistical models in forecasting solar radiation, especially in heterogenous terrains such as Pakistan [12]. Studies analysing multiple ML models using solar data from across the country suggest that a hybrid ML approach could predict daily solar irradiation with a high degree of accuracy ($R^2 > 0.95$). This idea will be further explored in this paper.

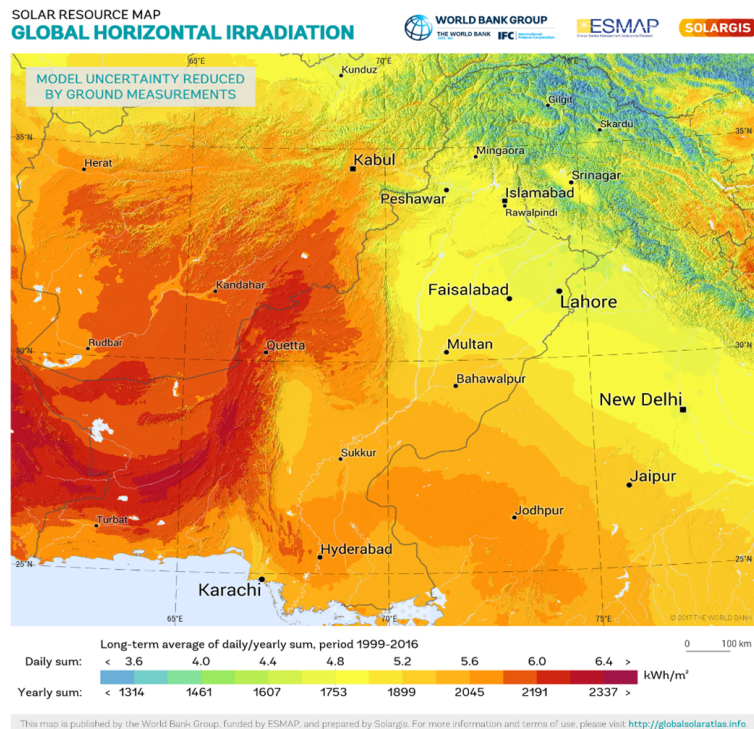


Fig. 1: Solar irradiation map of Pakistan from the World Bank’s Renewable Energy Resource Mapping program

B. Solar Technology

Globally, PV technology has emerged as a viable method to electrify rural villages, offering decentralised energy access that is not reliant on the fossil fuel powered electricity grid. Pakistan, in particular, offers a few different technologies, each with different efficiencies, cost and suitability for working in a rural environment.

PV modules are broadly divided into conventional, first-generation crystalline silicon (c-Si) and newer technologies such as thin-film panels that use different materials like amorphous silicon (a-Si) and cadmium telluride (CdTe). Currently, c-Si panels dominate both the global and Pakistani markets due to their generally higher efficiency (18–20%) and longer lifetime. In case studies for rural Pakistan, c-Si microgrids were found to provide stable power that was relatively durable in the high temperature and dust. However, thin panels provide a lower temperature coefficient with a 0.22% per degree rise in temperature [13].

Another key technology for efficient solar panels is batteries which store excess energy for use during periods of low or no sunlight. This is critical in decentralised systems that don't have backup in the form of an electricity grid. The most common battery types for PV systems are lead-acid and lithium-ion batteries. Lead-acid batteries, including flooded and sealed types, are the most commonly found in Pakistan due to their low upfront cost and widespread availability despite their shorter lifespan. Globally, however, lithium-ion-phosphate (LiFePO₄) batteries are increasingly being used for energy storage due to their much longer lifetimes and higher temperature durability. In a case study for an off-grid rural solar system, Polymer-Gel Valve-Regulated Lead Acid (VRLA) batteries are used in the simulation to prove that a rural system using lead batteries is feasible, producing 729 kWh annually at a cost of \$2,468 [14].

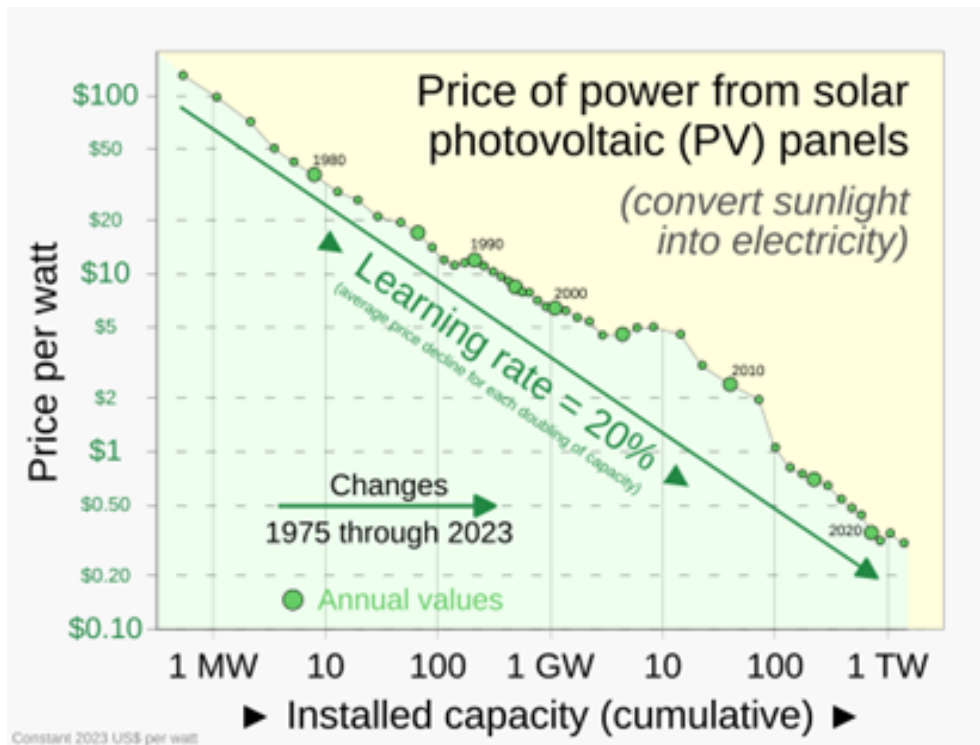


Fig. 2: Illustrative trend of falling PV module costs [15]

Additionally, inverters are used to convert the DC electricity produced by solar panels into usable AC electricity that powers homes. The type of inverter used is crucial in improving the efficiency of a rural, decentralised system. There are three main types of inverters used in solar applications: string inverters, microinverters, and hybrid inverters.

String inverters connect a series of solar panels together and are the most widely available in Pakistani markets. However, literature suggests that performance is constrained by the lowest-performing panel in the array, making them vulnerable to shading and dust which can be common in certain parts of Pakistan's rural areas [16]. Microinverters on the other hand operate on individual panels which maximises efficiency for systems affected by partial shading [17]. Hybrid inverters combine the functions of both solar and battery inverters, enabling them to simultaneously convert solar-generated electricity into usable AC power for household consumption while also facilitating energy storage in batteries. According to certain literature [18], this is essential for off-grid decentralised systems due to their reliance on battery systems to store energy.

C. Economic Viability

Economic constraints are one of the most decisive factors when determining the feasibility of energy initiatives. Half of Pakistan's rural community live in poverty which the World Bank defines as living below \$3.65/day [5]. This low wealth shows the importance of governmental policies and cost-effective materials. In addition, this situation is further exacerbated by a 65% rise in energy inflation in recent years, increasing the necessity that an economical solution to their energy access be found quickly. These communities face two problems: requiring a project that is financially accessible at the point of implementation while also ensuring long-term operational viability with minimal maintenance requirements.

a) Simple form:

$$\text{LCOE} = \frac{\text{Total discounted costs}}{\text{Total discounted energy output}} \quad (1)$$

b) Detailed form:

$$\text{LCOE} = \frac{\sum_{t=0}^n \frac{I_t + O_t}{(1+d)^t}}{\sum_{t=1}^n \frac{E_t}{(1+d)^t}} \quad (2)$$

where I_t is capital expenditure in year t , O_t is annual operating and maintenance costs in year t , E_t is electricity generated in year t (kWh), d is the discount rate (WACC), and n is the lifetime of the power plant (e.g. 25 years for PV).

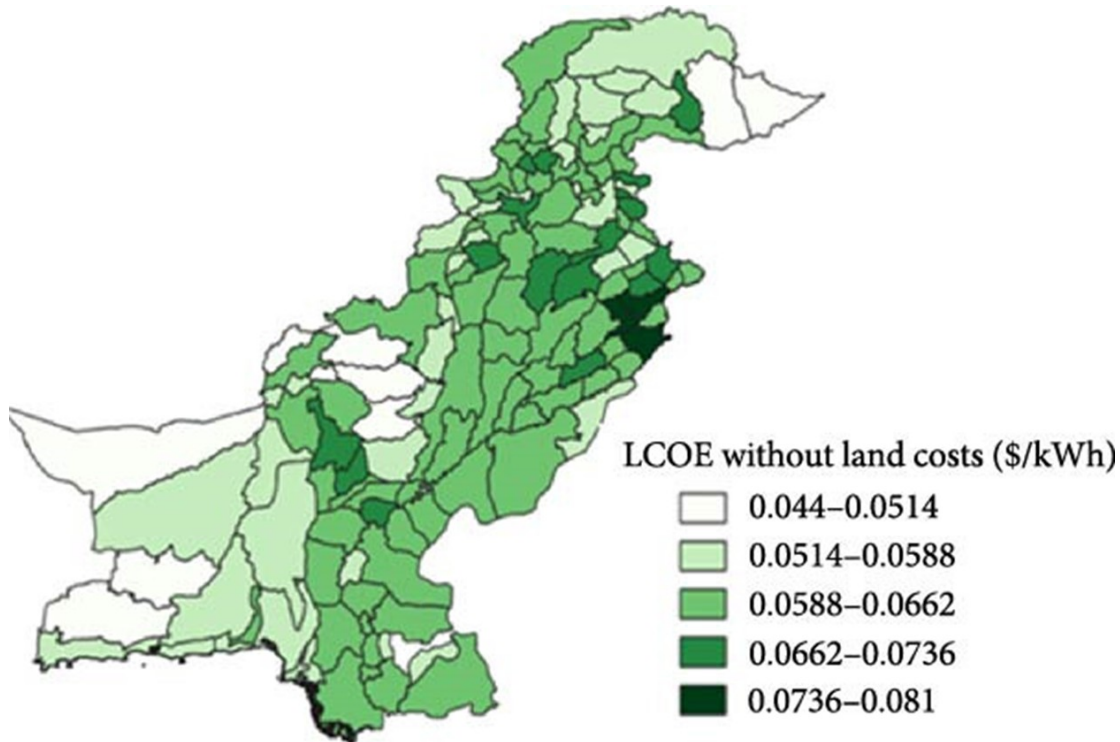


Fig. 3: LCOE variation by region [19]

Numerous studies have been conducted before to estimate the LCOE of Pakistan's solar energy, from off-grid households to larger PV plants. For example, a study [8] simulated an off-grid solar photovoltaic system with the electricity at price of PKR 6.87/kWh (\$0.04/kWh) compared to traditional energy source which was about 20.79 PKR/kWh (\$0.12/kWh). However, this study was focussed on Sindh specifically and failed to take into account a critical component of off-grid systems: battery storages systems. This is a gap in the literature my research can address.

IV. METHODOLOGY

As stated earlier, this paper focuses on three key factors: (i) Solar Irradiation, (ii) Solar Technology, and (iii) Economic Viability.

- 1) **Solar Irradiation:** This study utilises publicly available geospatial data and a machine learning model developed by the author specifically for this study. This approach combined with the traditional review of existing literature will enable a more accurate estimation of energy generation potential across Pakistan's varied landscapes and climatic conditions.
- 2) **Solar Technology:** The availability and efficiency of solar technology such as PV panel materials, charge controllers and inverters will be assessed to determine the technical feasibility of solar energy in these regions.
- 3) **Economic Viability:** Pakistan already suffers from dire economic issues; any solution will have to be truly affordable for it to be used by rural communities and fulfil obligations like UN SDG 7. An estimate for LCOE will be calculated from quantitative data and compared to trusted sources to determine whether it is economically feasible for Pakistan's rural areas to run on solar energy.

A. Solar Irradiation ML Methodology

The goal of the ML model is to predict the places where there are ideal conditions for PV sites due to high solar irradiation, temperature, elevation and slope. To achieve this, a detailed geospatial dataset was developed. Figure 4 contains an overview of how the data was processed.

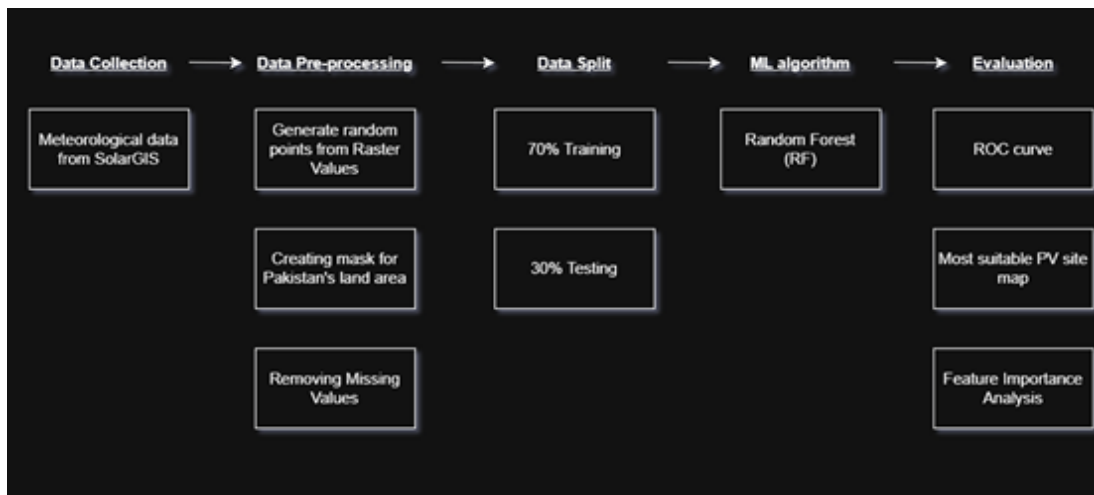


Fig. 4: Overview of data processing pipeline

The data was sourced from Solargis in the form of geospatial raster values; representative satellite-derived datasets are used in related work on Pakistan [20]. Following this, the data was then cleaned, resampled and split into training vs testing data. The chosen ML algorithm was Random Forest (RF), widely reported to be strong and simple to use for solar radiation/suitability prediction in heterogeneous terrains [12].

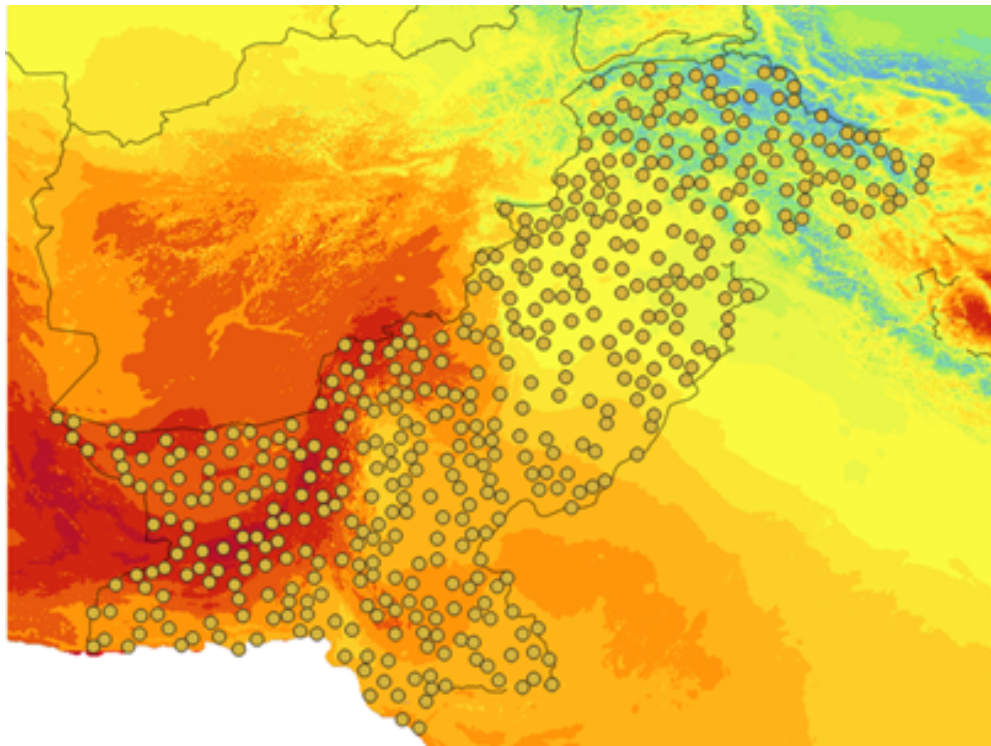


Fig. 5: Points extracted from the dataset to create the ML model

B. LCOE Estimate Methodology

Estimation of the Levelised Cost of Energy (LCOE) for solar power has been investigated previously across a range of applications, from utility-scale 100 MW photovoltaic (PV) plants to smaller, household-level systems [21]. However, the objective of this paper is to assess the feasibility of solar deployment within a rural context in Pakistan. To this end, we adopted a reference model based on a self-sufficient PV mini-grid, which represents the most viable long-term solution for delivering reliable and sustainable electricity to rural households.

The analysis will focus on a reference configuration comprising a PV mini-grid 50kW PV with 200kWh battery storage. The battery storage is necessary in order to ensure reliability since solar generation is inherently intermittent. Additionally, it is needed for the mini-grid to function autonomously and self-sufficiently without the need for an external infrastructure. The estimate relies on a number of assumptions in both the technology used and costs incurred. These are outlined below and are based on the methodology commonly used by literature when making LCOE estimates.

Technology assumptions (summary):

TABLE I: Reference technology choices and reasoning

Choice	Reasoning
Solar Panel Type: c-Si material	High efficiency relative to other types of solar panels; durability; resistance to dust commonly found in rural areas
Battery Type: Lithium-ion (LiFePO ₄)	Long lifetime; high temperature durability
Inverter Type: Hybrid inverter	Enables simultaneous battery charging and AC supply in off-grid systems

V. DISCUSSION & RESULTS

A. Solar Irradiation ML Model

The ROC curve below plots the True Positive Rate (TPR) against the False Positive Rate (FPR) and is a crucial metric in classification. The higher the graph is above the random guess line, the better the model performance. The overall metric AUC gives a quantitative value to the model's performance suggesting that the model can predict if a particular site is suited for PV in around 90% of cases.

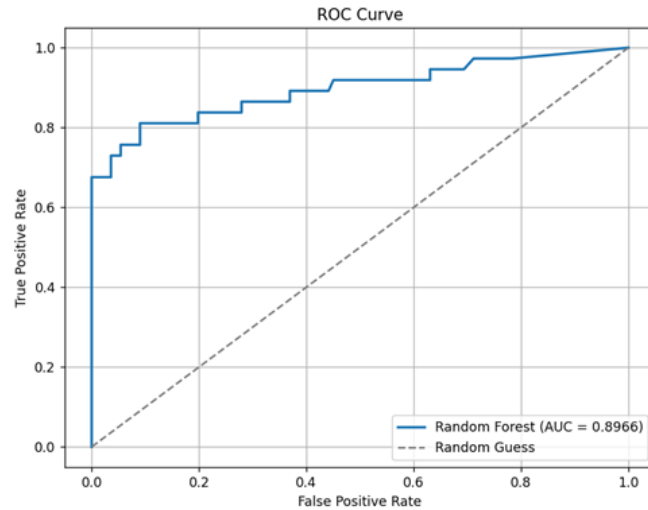


Fig. 6: ROC curve of the RF classifier.

Using the model, at a resolution of 1 km, each point in Pakistan was inputted into the model and received a probability relative to other points demonstrating its suitability for good PV site. This means that the most suitable PV sites according to meteorological data and the model were highlighted. It is important to note that the lighter shaded areas do not correspond to poor PV sites but rather relatively less suitable compared to the darker shaded areas on the map.

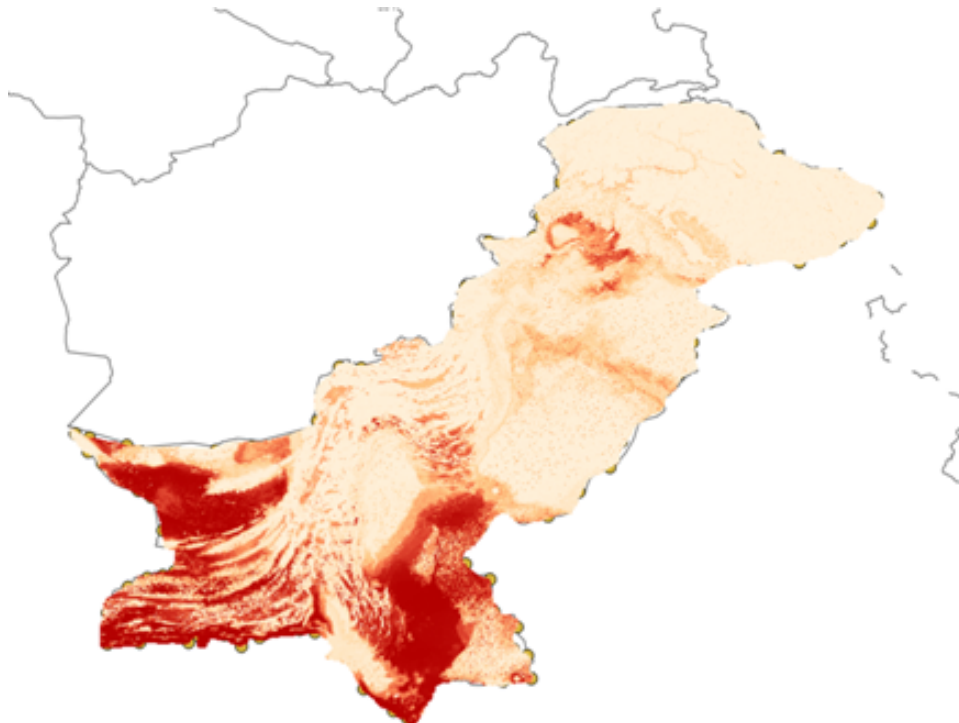


Fig. 7: Model-derived relative PV suitability heatmap

Feature correlations show GHI as the dominant positive driver, with temperature moderately positive and elevation/slope tending negative—patterns consistent with physical intuition and prior analyses.

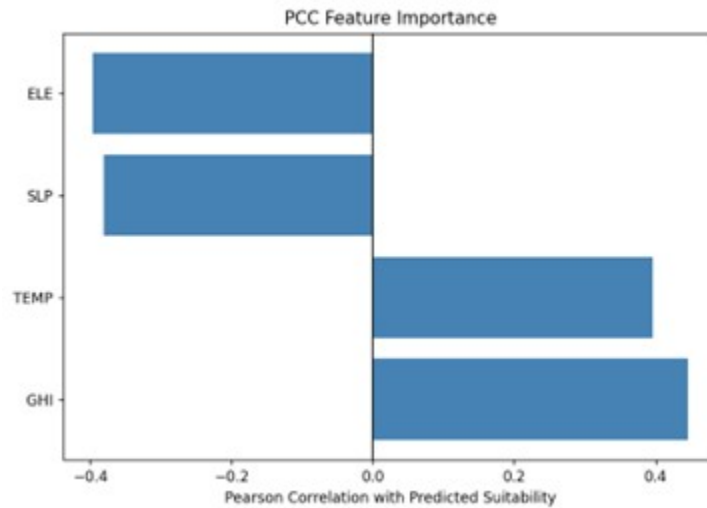


Fig. 8: Feature correlation with suitability label

B. Economic Viability

Following the technology assumptions earlier, these are the economical assumptions that we are making for the LCOE estimation model. The breakdown of the CAPEX and OPEX values further below can be seen. This model is based on the above equation of LCOE.

TABLE II: Reference design and economic assumptions

Parameter	Value
PV Size (DC)	50 kW _p (c-Si)
Battery	200 kWh Lithium-ion (LFP)
Inverter	Hybrid inverter (bidirectional)
Project Life	25 years
Real WACC	12% (base)
Solar Yield (PVOUT)	1,650 kWh/kW _p /yr (Pakistan range: 1,500–1,800)
PV Degradation	0.5%/yr
Battery Round-Trip Efficiency	90%
Initial CAPEX (sum)	\$104,655
Annual OPEX	\$1,095/yr

a) Initial CAPEX breakdown (C_0): Table III presents the detailed breakdown of initial capital expenditure components for the 50 kW solar PV system with battery storage.

TABLE III: Initial CAPEX components

Component	Quantity × Unit Cost	Sub-Total
PV modules	50 kW × \$274/kW	\$13,717
Hybrid inverter	50 kW × \$119	\$5,954
Battery energy storage	200 kWh × \$400/kWh	\$80,000
Owner's costs & contingency (5%)	—	\$4,984
Total initial CAPEX		\$104,655

b) Replacement CAPEX (over lifetime): The replacement costs over the system's lifetime are summarized in Table IV, accounting for scheduled replacements. Important to note that discount rate d has a large effect.

TABLE IV: Replacement CAPEX assumptions

Component	Quantity × Unit Cost	Sub-Total
Battery replacements (every 10 years)	200 kWh × \$300/kWh × 2	\$120,000
Inverter replacements (every 12 years)	50 kW × \$120 × 2	\$12,000
Total replacements (gross)		\$132,000

c) *OPEX*: Annual operational expenditures are detailed in Table V, calculated using the rule-of-thumb estimate of approximately 1% of relevant CAPEX components.

TABLE V: Annual OPEX (rule-of-thumb $\sim 1\%$ of CAPEX components)

Component	Annual Cost
PV OPEX	\$295
Battery OPEX	\$800
Total annual OPEX	\$1,095

d) *LCOE result*: The final Levelized Cost of Energy calculation is presented in Table VI, showing the present value analysis of both energy production and system costs.

TABLE VI: LCOE summary

Metric	Value
Present value of energy	588,767.45 kWh
Present value of costs	\$140,717
LCOE	\$0.24 / kWh
Totals	Costs: \$140,717; Energy: 588,767.45 kWh

The LCOE according to the quantitative estimate is **0.24 USD/kWh** which suggests that solar energy has achieved grid parity in the context of rural mini-grid applications. This is highly advantageous when compared to the prevalent alternative of diesel generation (LCOE of 0.30–0.70/kWh) that is commonly found in rural areas. This reference configuration demonstrates the economic viability of solar energy in rural areas.

VI. CONCLUSION

A. Key Insights & Recommendations

- Pakistan possesses more than enough solar irradiation, particularly in the mainly rural areas of Balochistan and Sindh, to start implementing wide-scale solar projects
- Prioritise development of solar technologies in the high-suitability region identified by the ML model (southern belt of Pakistan).
- GHI is the dominant driver of suitability; temperature is moderately positive, while elevation and slope tend to reduce suitability
- Standardise on c-Si modules + hybrid inverters + lithium-ion (LFP) storage for off-grid mini-grids due to both economic viability and technical advantages
- Adopt the 50 kW PV + 200 kWh LFP mini-grid as a reference design; expected LCOE \approx \$0.24/kWh, already competitive with diesel

This study examined the feasibility of electrifying rural areas with solar power by looking at three factors: the solar energy resources, the technology stack, and the economics. Using geospatial data and a Random Forest-based suitability model, we find consistently strong solar resources nationwide with the highest relative suitability concentrated in the southern belt (Sindh and Balochistan). On the technology side, a standardised off-grid configuration—c-Si PV modules with LFP storage and hybrid inversion—emerges as the most reliable fit for dusty, high-temperature rural conditions. Bottom-up costing of a reference 50 kW PV + 200 kWh LFP mini-grid yields an LCOE of \approx \$0.24/kWh, already at or below typical diesel generation costs in comparable contexts.

Looking ahead, NGOs and other organisations such as energy providers can use these findings to start on-site studies in key areas to determine PV suitability. In particular, the province of Balochistan would particularly suit the reference configuration this study has examined. This is due to its high solar suitability according to the Random Forest model and the significant proportion (almost 78%) of inhabitants that live in rural areas. In addition, Balochistan is the largest province in Pakistan but has the smallest population density with 43 people per square kilometer. Its extensive mountainous terrain and arid, water-scarce climate means that often villages and towns are far from the typical grid network and would benefit enormously from the decentralised, self-sufficient off-grid systems proposed by this paper.

Limitations of the study include the finite training sample used in the RF model, reliance on one geospatial dataset that measures inputs as yearly long-term average and economical assumptions for the LCOE estimate and analysis. Future work should test a wide range of ML algorithms with as many temporally diverse geospatial datasets as possible. In addition, uncertainties in component prices should be reduced by checking with local vendors.

Perhaps the most consequential improvement on this study would come from extended fieldwork in Pakistan. This would allow for the installation of short-term meteorological stations, resulting in accurate meteorological data. Regular site visits would also allow for checking terrain, land cover, access roads, and actual grid proximity while replacing generic price assumptions with verifiable local vendor quotations. Complex assumptions would be able to be made after with this wealth of data leading to a more fine-tuned model for both economic viability and solar irradiation analysis. Crucially, fieldwork would allow for community attitudes towards solar power to be accounted for allowing an extra dimension in feasibility to be analysed. The absence of this on-the-ground evidence is the principal limitation of the present study; addressing it would significantly strengthen the conclusions and help realise mapped potential into actual solar mini-grids in high-priority regions such as Balochistan.

Despite these caveats, the evidence suggests that solar energy in the form of mini-grids is a practical, feasible pathway to universal, reliable, and affordable electricity access in rural Pakistan, advancing energy security and UN SDG 7 while reducing the expensive dependence on imported fuels and diesel generators.

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