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Exploring the Electrification of Rural Areas in Pakistan with Solar Energy

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Context

Pakistan's rural electrification gap remains acute: tens of thousands of villages sit off-grid and millions lack reliable power. Dependence on costly diesel, volatile fuel logistics and poor air quality worsens outcomes for remote communities. This study asks whether decentralised solar mini-grids can deliver practical, affordable power by combining geospatial suitability modelling using machine learning with a transparent LCOE analysis.

Are decentralised solar energy systems the key to solving Pakistan's energy crisis?

Methodology

Overview (3 pillars)

- **Resource suitability:** nationwide RF classifier on Solargis-derived features (GHI, temperature, elevation, slope).
- **Technology fit:** available literature analysis to determine best reference technology stack for LCOE estimate
- **Economics:** bottom-up LCOE (CAPEX, OPEX, replacements), 25-year life, real WACC 12%.

Solar Irradiation (ML & GIS)

Objective: Classify relative PV suitability nationwide.

- **Inputs:** Solargis rasters (GHI), temperature, elevation, slope.
- **Model:** Random Forest; training on 492 labelled points; 1 km grid inference.
- **Feature insight:** GHI dominates (+); temperature (+); elevation/slope (–).

Reference Technology

Table 1: Summary of why technology stack was chosen

Choice	Reasoning
Solar Panel Type: c-Si material	High efficiency; durability; resistance to dust
Battery Type: Lithium-ion	Long lifetime; high temperature durability
Inverter Type: Hybrid inverter	Enables simultaneous battery charging and AC supply in off-grid systems

Results

Solar Irradiation Model

Model performance

- RF classifier achieves **AUC 0.9** (strong separability in **90%** of cases)
- Robust to heterogeneous terrain; key driver: **GHI**.
- **ROC curve** shown below. A curve closer to the **top-left** corner indicates a more accurate classifier.

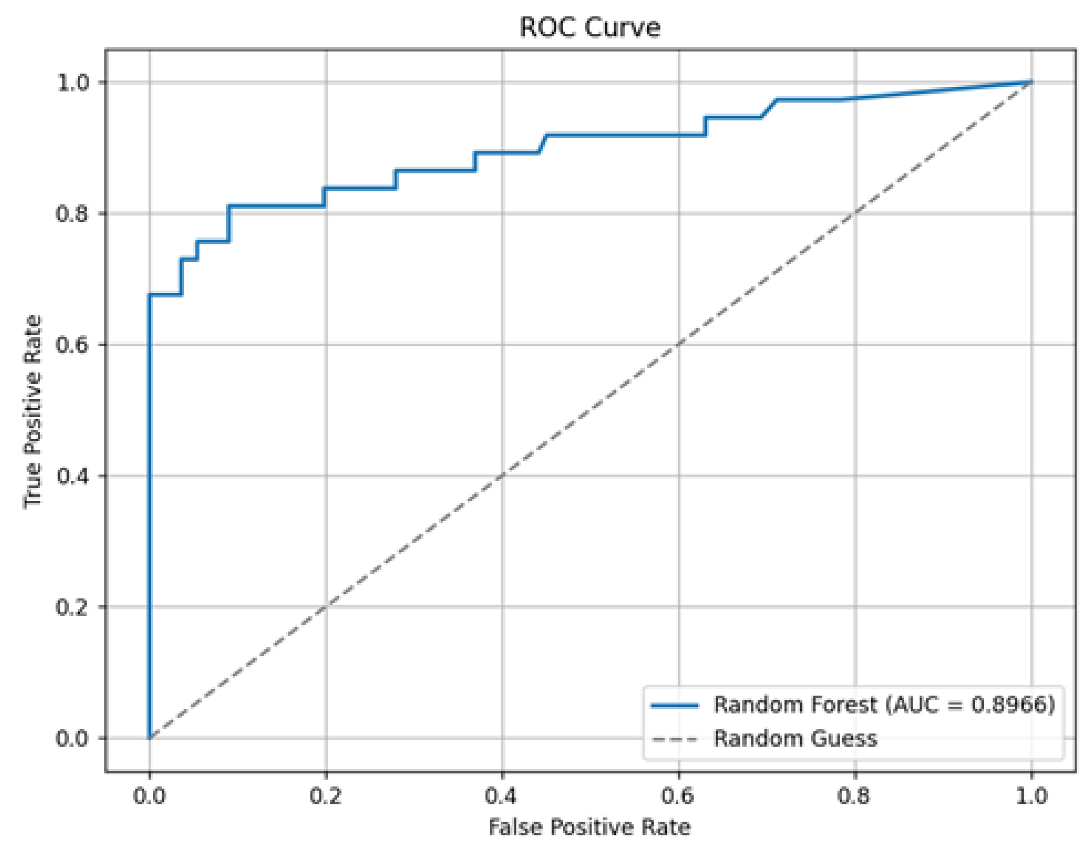

Figure 1: Plot illustrating the performance of the model by comparing the true positive rate (TPR) against the false positive rate (FPR)

Suitability map

- Model run at a resolution of 1Km on map of Pakistan
- **Southern belt** (Sindh, Balochistan) scores higher
- Lighter areas = relatively less suitable (not necessarily "poor" sites)

LCOE Estimate

Assumptions (compact)

Table 2: LCOE summary (reference 50 kW PV + 200 kWh LFP).

Parameter	Value
PV size (DC)	50 kW_p (c-Si)
Battery	200 kWh (LFP), RTE 90%
Inverter	Hybrid (bidirectional)
Lifetime	25 years
Real WACC	12%
Solar yield (PVOUT)	1,650 kWh/kW_p/yr
Initial CAPEX	$104,655
Annual OPEX	$1,095/yr
PV of energy	588,767.45 kWh
PV of costs	$140,717
LCOE	**$0.24/kWh**

Headline

- Reference mini-grid LCOE: **$0.24/kWh**.
- Competitive vs diesel: **$0.30–$0.70/kWh**.

Table 3: LCOE Summary (Present Value, 25 yrs)

Metric	Value
Present value of energy	588,767.45 kWh
Present value of costs	$140,717
LCOE	**$0.24 / kWh**

Key Findings & Next Steps

Key Findings

- **Feasability:** Pakistan's **solar resource + decentralised mini-grids** can close a large share of the rural access gap.
- **Economic parity:** Solar mini-grid **LCOE** ≈ **$0.24/kWh** vs diesel **$0.30–$0.70/kWh**.
- **Geospatial target:** Southern belt (Sindh/Balochistan) shows highest relative suitability.
- **Reference design:** Standardised mini-grid design such as: 50 kW c-Si PV + 200 kWh LFP + hybrid inverter is key.

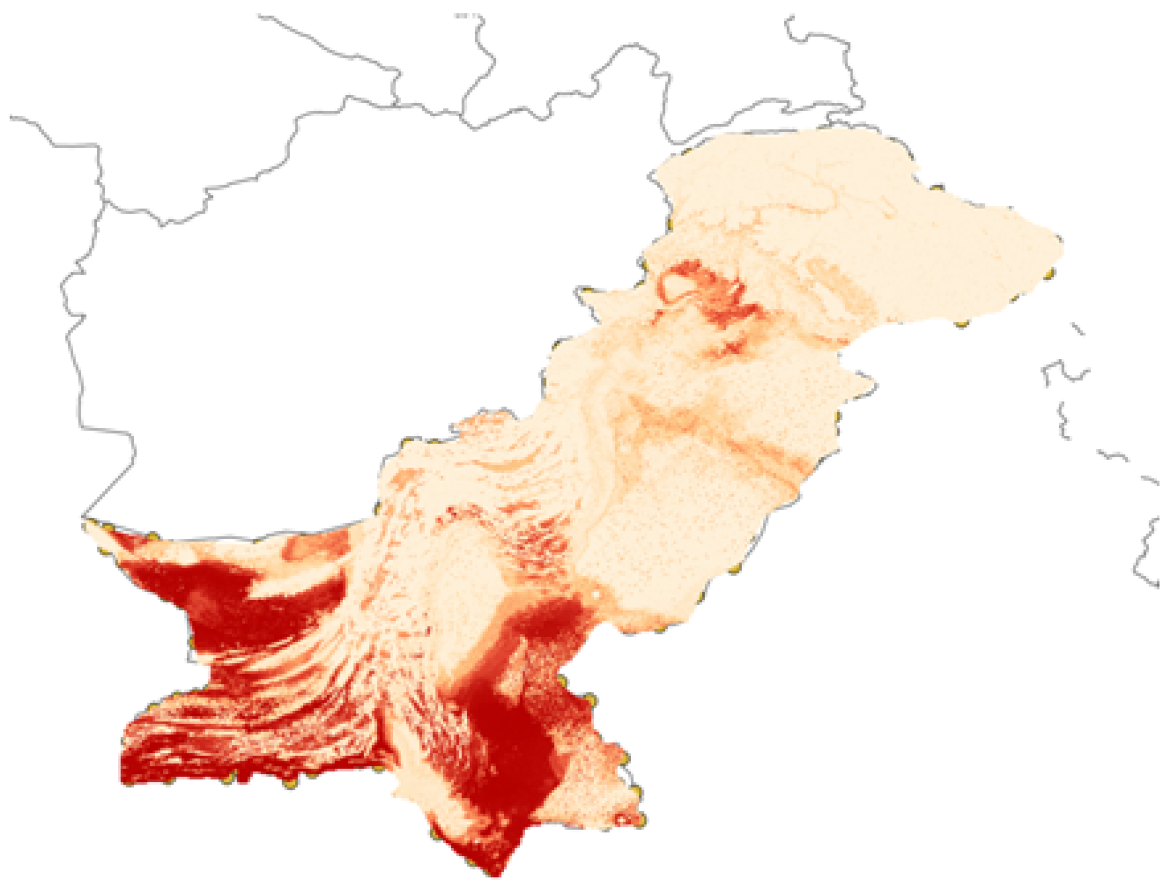

Figure 2: Model-derived PV suitability heatmap (1 km resolution). A southern belt—especially **Sindh** and **Balochistan**—stands out as most suitable.

Next Steps

- **Pilot sites:** launch mini-grid pilots in high-suitability districts (Balochistan, Sindh): verify vendor and logistics cost
- **Field data:** Deploy short-term met stations for more accurate data; account for community attitudes towards solar power
- **Modelling upgrades:** expand/seasonalise datasets; compare other ML algorithms with temporal features; refine battery replacement strategy & financing (WACC) assumptions.