PRIED
Policy Research Institute
for Equitable Development

Bridging the Energy Gap

Navigating Decentralized Microgrid potential in off-grid areas of Pakistan

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Abbreviations and Acronyms

AEDB	Alternative Energy Development Board
ARE Policy	Alternative and Renewable Energy Policy
BESS	Battery Energy Storage System
BRI	Belt and Road Initiative
CPEC	China-Pakistan Economic Corridor
CSR	Corporate Social Responsibility
DERs	Distributed Energy Resources
FDI	Foreign Direct Investment
GDP	Gross Domestic Product
GHI	Global Horizontal Irradiance
GOP	Government of Pakistan
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IRR	Internal Rate of Return
KPK	Khyber Pakhtunkhwa
LCOE	Levelized Cost of Energy
Li-Ion	Lithium-Ion
MW	Megawatt
NEPRA	National Electric Power Regulatory Authority

NREL	National Renewable Energy Laboratory
NPV	Net Present Value
O&M	Operations and Maintenance
PPPs	Public-Private Partnerships
PV	Photovoltaic
QASPPL	Quaid-e-Azam Solar Power (Private) Limited
RE	Renewable Energy
ROI	Return on Investment
SDG	Sustainable Development Goal
SEZs	Special Economic Zones
SWOT	Strengths, Weaknesses, Opportunities, and Threats

Executive Summary

Pakistan faces a significant energy access challenge, particularly in its remote and rural regions where the national grid has limited reach. According to a 2018 study, approximately 37% of Pakistan's rural population lacks access to electricity1, and decentralized microgrids present a promising solution to close the energy access gap. Microgrids offer a localized, reliable, and sustainable energy solution for off-grid populations and communities., in areas where extending the national grid is impractical. They enhance energy access, reduce transmission losses, and support socio-economic development through the integration of renewable resources. This report examines the role of microgrids in enhancing energy reliability and sustainability, particularly in regions underserved by Pakistan's national grid.

The National Electric Power Regulatory Authority (NEPRA) Microgrid Licensing Framework (2022) has laid a foundation for promoting microgrid adoption, aiming to encourage investments from local and foreign stakeholders, particularly in off-grid areas across Baluchistan, Khyber Pakhtunkhwa (KPK), and Sindh. Despite their potential, microgrids in Pakistan encounter several barriers. Regulatory complexities, high initial capital costs, limited technical expertise of the workforce, and the lack of established operational models hinder their widespread adoption. Moreover, challenges in ensuring affordable tariffs while maintaining investor profitability pose significant obstacles. Socio-political factors, including resistance from local/indigenous communities, and insufficient policy incentives, further complicate deployment efforts, especially in remote and underserved regions.

The report analyzes the feasibility of renewable energy-based microgrids in four regions of Pakistan: Sindh, Balochistan, Punjab, and KPK using HOMER software, each tailored to local resources and energy needs. In Jam Nawaz Ali, a sub-district in Sanghar, Sindh, a combination of solar PV and battery system supports a low Levelized Cost of Energy (LCOE) of $0.07433/kWh. In Girote, a village in Khushab, Punjab, solar and biomass offers high reliability and a LCOE of $0.0707/kWh. Sakhra, a town in Swat, KPK leverages solar and hydro resources for year-round energy, with a 1,041% PV penetration and an LCOE of $0.118//kWh. Wadh, a sub-division in Khuzdar Balochistan combines solar and wind with a low LCOE $0.1733/kWh to meet fluctuating agricultural demands, reducing grid dependency. These case studies show that region-specific microgrids ensure reliable, affordable, and sustainable energy solutions for rural Pakistan.

Apart from the feasibility assessment, the report also discusses two billing mechanisms for microgrids in Pakistan: Private Company-Owned Models and Public-Private Partnerships (PPPs). Both models aim to attract investment while ensuring sustainable and equitable energy solutions. In the private model, companies manage generation, distribution, and billing, ensuring operational efficiency and profitability. PPPs involve shared responsibility between public entities and private investors, balancing risk while promoting affordable tariffs and broader energy access.

The proposed framework also presents significant opportunities, particularly for Chinese investors under the Belt and Road Initiative (BRI) and the China-Pakistan Economic Corridor (CPEC). China's expertise in renewable energy technologies, combined with its interest in strengthening cooperation within South Asia makes it a valuable partner for Pakistan in expanding electricity access to off-grid areas through microgrid development. Potential collaboration between Chinese companies and local stakeholders could lead to enhanced energy access, technology transfer, and economic growth in off-grid areas, as a result expanding rural electrification of unserved and underserved strata of society there by promoting socio-economic development.

To overcome challenges hindering microgrid deployment in rural Pakistan and attract foreign investment, especially from China, targeted policy recommendations have been proposed. These include revising NEPRA's 5

1 *https://lidc.ac.uk/how-can-rural-pakistani-communites-electricity-needs-be-met/*

MW capacity cap, introducing clear regulatory frameworks (IEEE 1547.4 and ISO/IEC 27001) to ensure seamless grid integration and cyber-security. Extending licensing tenure to more than 15 years with clear renewal criteria, ensure 5–7 years of tariff stability with cost-reflective tariffs, streamline approvals through a single-window system with a 60-day limit, for hybrid and stand-alone microgrids while guaranteeing fair compensation.

Incentivizing renewable energy investments through tax benefits, subsidies, and low-interest financing is critical. Promoting Public-Private Partnerships (PPPs) can streamline processes and attract private capital, while community-centric models can foster local ownership and sustainability. Strengthening R&D for innovative technologies, enhancing workforce capacity, and establishing centralized monitoring systems can ensure continuous improvement. Lastly, fostering international collaboration through secure investments and transparent profit-sharing mechanisms will drive the long-term scalability and success of microgrid projects in Pakistan.

Chapter: 1

Introduction

Pakistan faces a critical energy demand-supply imbalance, having an installed power generation capacity of 46,035 MW, which significantly exceeds the peak demand of 22,000 MW.[2] This paradox highlights inefficiencies within the energy distribution system, leaving many rural areas without reliable electricity, even when demand and capacity exists. With approximately 61% of Pakistan's population residing in rural regions, energy access remains a significant challenge.[3]

According to the United Nations University (UNU), 96.6% of rural households experience severe energy shortfalls.[4] Extending the national grid to these underserved areas is economically unfeasible due to the high investment costs and logistical challenges associated with transmission infrastructure.

In light of these constraints, the question arises: how can we provide reliable and affordable electricity to Pakistan's remote and rural communities?

Pakistan has committed to ambitious climate and energy targets under international agreements, such as its Nationally Determined Contributions (NDCs), aiming to increase the share of renewable energy (RE) in its energy mix to 60% by 2030.[5] An estimated renewable energy potential of 2,900 GW from sources such as solar power alone, along with wind, hydro, and biomass, presents a significant opportunity to reduce reliance on fossil fuels for power/energy generation.[6] Renewable energy solutions, particularly decentralized systems like microgrids, present a viable alternative for rural electrification. These systems not only bypass the need for costly grid expansion, but also contribute to economic development by enhancing agricultural productivity, supporting small-scale industries, and improving social services in remote areas.

This report explores the role of microgrids in addressing Pakistan's rural energy access challenges and examines their potential to foster sustainable development, while aligning with the national climate and energy goals. Establishing microgrids is an important step forward in power distribution, providing a decentralized system that works alongside the traditional centralized grid model. Their ability to integrate local renewable resources, coupled with advanced control systems, makes them a viable solution for enhancing energy access, particularly in off-grid and remote areas. As national energy demand rises, with a significant percentage of the population residing in weak grid and off-grid areas, the need for sustainable off-grid electrification solutions and a framework to harness the untapped potential of Distributed Energy Resources (DERs) through microgrids has become quite apparent.[7]

According to the UK Department for International Development report, for lower middle income countries, a 1% increase in energy consumption increases GDP by 0.81%.[8] This underscores the potential of microgrids to contribute significantly to Pakistan's economic growth, particularly in rural and remote areas where energy access is currently limited. Microgrids not only enhance energy access but also strengthen the grid by reducing energy losses by 10-20% and improving energy efficiency by 20-30%, as noted by the institute of electrical and electronics engineers. 9 Furthermore, the International Renewable Energy Agency (IRENA) estimates that Pakistan's microgrid market could reach a value of 1.5 billion US dollars by 2025, driving local economic development and

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2 https://www.pc.gov.pk/uploads/report/IEP_Report_FINAL.pdf

3 https://tradingeconomics.com/pakistan/rural-population-percent-of-total-population-wb-data.html

4 https://ourworld.unu.edu/en/rural-pakistan-lends-insight-on-energy-poverty

5 https://unfccc.int/sites/default/files/NDC/2022-06/Pakistan%20Updated%20NDC%202021.pdf

6 https://tribune.com.pk/story/2436369/nothing-like-the-sun-can-solar-solve-pakistans-energy-woes

7 https://pakistan.un.org/en/206874-media-update-united-nations-pakistan-9-november-2022

8 https://www.eca-uk.com/wp-content/uploads/2016/10/EoD-HD116-Jan2014-Energy-Economic-Growth.pdf

9 https://ieeexplore.ieee.org/document/9453608 growth. [10]

The declining costs of key components, including photovoltaic (PV) modules, batteries, and smart meters, have significantly enhanced the financial viability of microgrids. For instance, the price of solar PV panels has dropped by nearly 90% over the last decade due to technological advancements and economies of scale. These upgrades have reduced the average electricity generation cost known as levelized cost of electricity (LCOE) to USD $0.20 per kWh, making microgrids a competitive solution in rural and remote areas. [11 12 13]

Due to the decreasing price of solar panels, urban areas in Pakistan are experiencing a PV boom. This shift is driven by rising electricity costs, which have reached up to PKR 50 per kWh, prompting many to install PV-based nano-grids, either grid-tied or stand-alone.While urban solar adoption offers cost savings, it impacts the national grid, posing major challenges like reduced utility revenues and grid stability issues[14 15]. In rural areas, affordable solar microgrids can bridge the gap, as these systems provide power at the lowest levelized cost of the solar PV technology, cheaper than extending the national grid.

In the future, if the national grid expands to unserved regions, these microgrids can be optimized using advanced strategies such as time-of-use tariff structures, where electricity pricing varies based on demand and supply. For instance, lower electricity rates during off-peak hours can incentivize consumers to shift energy-intensive activities, such as running appliances or charging EVs, to periods of low demand. Net metering can enable the export of surplus energy from microgrids to the national grid, leveraging time-sensitive pricing to maximize value, supporting the grid during peak demand, or storing surplus energy during low-demand periods. Also, demand response programs can adjust energy consumption patterns to match availability, enhancing efficiency. These microgrids can also provide ancillary services, such as frequency regulation and voltage control, to ensure grid stability for dense load centers. By integrating these strategies, microgrids can play a vital role in supporting a resilient and efficient energy ecosystem. [16 17]

Conclusively, microgrids hold immense potential in Pakistan, but also face significant financial and technical challenges. Chinese investments in Pakistan's power sector could be channeled towards the microgrid sector, which would accelerate progress in electrification and bridge the energy gap by providing capital, technological expertise, and strategic collaboration. Such partnerships could leverage the Belt and Road Initiative (BRI) framework to enhance Pakistan's energy infrastructure. By synthesizing insights from stakeholder interviews, simulations, and policy reviews, this report offers a roadmap for sustainable microgrid development in rural Pakistan, emphasizing the importance of targeted investments, revenue generation and enabling a strong regulatory environment.

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10 https://www.undp.org/pakistan/publications/energy-investments-powering-business-and-communities

11 https://openknowledge.worldbank.org/entities/publication/ee3960d4-0d83-5d7f-baca-a5f425a66c77/full

12 https://documents1.worldbank.org/curated/en/099122223180539643/pdf/P17515118ea44a020192941b81f7e8498e1.pdf

13 https://www.worldbank.org/en/news/press-release/2023/02/26/solar-mini-grids-could-sustainably-power-380-million-people-in-afe-africa-by-2030-if-action-is-taken-now

14 https://ieefa.org/articles/optimizing-solar-incentives-and-grid-infrastructure-pakistan-can-benefit-power

15 https://timesquaremarketing.com/the-solar-panel-price-crash-in-pakistan-a-transformative-shift/

16 https://www.energy.gov/femp/demand-response-and-time-variable-pricing-programs

17 https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Feb/IRENA_Innovation_ToU_tariffs_2019.pdf

Chapter: 2

Strategic importance of Chinese investments in Pakistan's Energy Sector

Chinese investments have played a key role in transforming Pakistan's energy sector, particularly under the China-Pakistan Economic Corridor (CPEC). Since 2013, CPEC has attracted approximately USD $25 billion in energy projects, enhancing Pakistan's generation capacity in coal, hydro, wind, and solar power. As of 2024, 14 energy projects with a total capacity of 8,020 MW have been completed under the first phase of CPEC, with an additional 1,184 MW under development. These projects have helped increase Pakistan's national grid capacity, improve power reliability, and reduce energy deficits.[18]

CPEC's shift to its second phase (CPEC 2.0), focuses on economic diversification, industrial cooperation, and clean energy. The phase is expected to see a rise in private Chinese investments, particularly in renewable energy projects such as solar and wind. This transition will help Pakistan in aligning with its Alternative and Renewable Energy (ARE) Policy 2019 goal to achieve at least 30% renewable energy in its power mix by 2030.

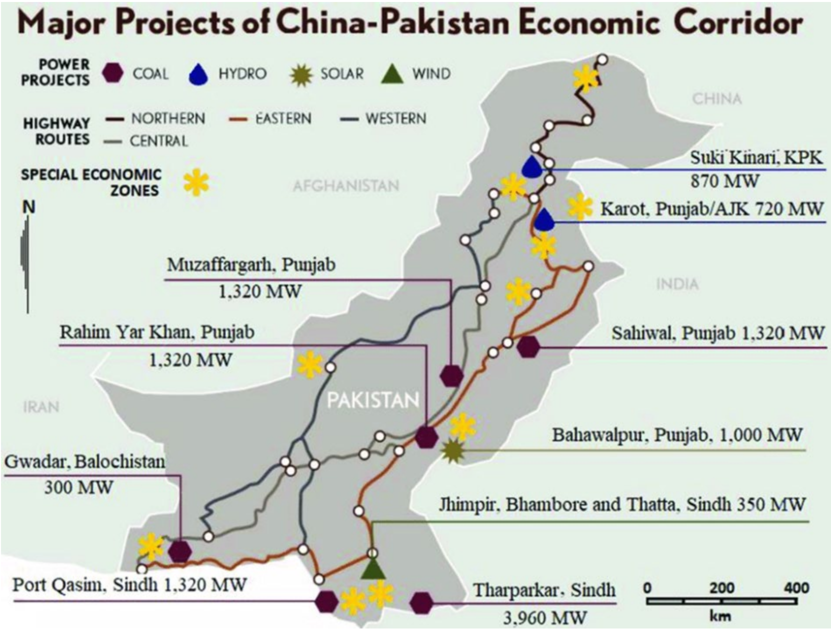

Figure 1. Map of Major Projects of China-Pakistan Economic Corridor

Figure 1 highlights the major power projects under the CPEC. These major energy projects include large-scale coal power plants like Port Qasim and Sahiwal (1,320 MW each) and Tharparkar (3,960 MW), alongside hydropower projects such as Suki Kinari (870 MW) and Karot (720 MW). Solar projects, including the Quaid-e-Azam Solar Park (1,000 MW), and wind farms like Jhimpir, Thatta, and Gharo (350 MW), also contribute significantly to the energy mix. These projects are complemented by infrastructural investments in roads and highways, enhancing connectivity for energy transmission and trade, facilitating the urban communities in Pakistan.

The strategic placement of energy projects near Special Economic Zones (SEZs) ensures a stable power supply for industrial operations. This will help in fostering Foreign Direct Investment (FDI) and economic growth in potential regions such as Muzaffargarh and Rahim Yar Khan, due to their proximity to infrastructure and resource hubs, can see overall economic development. Furthermore, projects like the Gwadar coal power plant (300 MW) support Gwadar's development as an energy and logistics hub, offering China a strategic maritime outlet to the Arabian Sea and diversifying its trade routes.

Despite these advancements, Pakistan still faces challenges due to inefficiencies, outdated infrastructure, and its reliance on imported fuels such as oil and RLNG, which make up 60% of the energy mix. While renewable sources like hydro, wind, and solar are cleaner and more cost-effective, they remain underutilized. The diversification of the energy mix through integration of more renewables will reduce dependence on imports, stimulate economic

18 https://www.cpicglobal.com/27-projects-worth-19b-completed-under-cpec-63-more-scheduled-for-completion-by-2030/

growth, and create a favorable environment for investors in renewable energy. [19]

The focus on green energy projects under CPEC 2.0 that aligns with global climate and energy transition goals, will provide both Pakistan and China with the opportunity to enhance energy security, reduce carbon footprint, and support sustainable economic growth. [20]

The most feasible and promising opportunity for Chinese investments is present in the form of renewable-based microgrids for rural unserved communities of Pakistan. The renewable-based microgrids, based on China's global success in deploying stand-alone, megawatt-level microgrids, will offer an innovative solution to Pakistan's energy crisis, electrifying areas where grid extension is not feasible. Chinese technological and financial contributions and support could alleviate initial capital barriers through the provision of innovative and affordable renewable energy infrastructure and machinery. Tax incentives and friendly trade policies with the neighbor would boost bilateral ties as well.

Microgrids face several challenges during the implementation phase, ranging from technical and financial hurdles to policy and community-related obstacles. These challenges are further explored in the section below, where a SWOT analysis of microgrid implementation in Pakistan highlights issues such as high initial investment costs, technical complexities in design and integration, unclear regulatory frameworks, difficulties in securing financing, and logistical challenges in deploying infrastructure to remote areas. [21]

Although the adoption of microgrids faces challenges in the implementation phase, they remain a viable and profitable investment for the local and foreign investors, and an affordable option for Pakistan's unserved electricity market.[22] Furthermore, Pakistan can also benefit from leveraging China's expertise to promote domestic manufacturing of renewable energy components in the future, ensuring long-term energy access, fostering rural development and economic growth. [23]

19 https://www.trade.gov/energy-resource-guide-pakistan-oil-and-gas
20 https://www.mdpi.com/2673-4591/75/1/31
21 https://wjarr.com/sites/default/files/WJARR-2024-3042.pdf
22 https://sun-connect.org/wpcont/uploads/sustainability-15-06366.pdf
23 https://www.globaltimes.cn/page/202407/1316498.shtml

Chapter: 3

Microgrids Implementation in Pakistan

Pakistan's energy infrastructure has been centralized since its inception, with limited emphasis on decentralized systems like microgrids. In July 2024, grid-connected areas of Pakistan faced an electricity shortfall of approximately 6,663 MW,[24] leading to extended power outages lasting up to 14 hours per day. The current electricity demand across Pakistan stands at 26,700 MW, while actual power generation lags far behind at 20,037 MW. This substantial deficit has resulted in widespread load shedding, with certain regions experiencing up to 10 hours of power cuts daily.[25] As of 2024, over 40 million people in Pakistan remain without access to electricity, and many more live in off-grid or underserved areas, with under four hours of electricity daily.[26]

Connecting these rural regions to the national grid requires substantive investments in the transmission sector including importing infrastructure equipment. Given these challenges, microgrids have emerged as a promising solution to address power deficits, particularly for rural and off-grid areas. Over the past decade, interest in solar-powered microgrids has significantly increased. These systems, with capacities ranging from 50 kW to 1 MW, are now deployed in energy-deficient regions, just like the 100 kW solar microgrid in Tharparkar electrifies 150 households, showcasing the potential for renewable energy to transform underserved communities.[27] [28] To support such initiatives, the National Electric Power Regulatory Authority (NEPRA) introduced the Microgrid Licensing Policy in 2022 to promote renewable energy (RE)-based microgrids in underserved regions. This regulatory framework has streamlined processes for net metering and power purchase agreements (PPAs), encouraging private sector investment and fostering the development of decentralized energy solutions. Such measures aim to bridge the energy access gap while supporting Pakistan's transition to cleaner energy. [29]

With the licensing framework in place, microgrids represent a significant opportunity for both foreign and local investors, particularly as the demand for reliable energy in underserved areas rises. As mentioned above, the UNU states that 96.6% of rural households experience severe energy shortfalls, making microgrids central to Pakistan's energy strategy for rural electrification[30]. According to the World Bank (2023), microgrids are projected to supply energy to 10 million people in rural areas by 2030. [31] Pakistan aims to generate 60% of its energy from renewable resources by 2030, with a significant portion expected from solar power.[32] Projections suggest that Pakistan can increase its solar power capacity to 10 GW by 2025 and 20 GW by 2030.[33]

With a spectacular decline in costs globally to around four US cents per kilowatt hour in 2023, the solar PV's global costs reduced to 56% as compared to fossil fuel and nuclear options. [34] Microgrids also present an

24 *https://tribune.com.pk/story/2468058/power-shortfall-rises-further-by-778mw-in-a-day*

25 *https://profit.pakistantoday.com.pk/2024/07/02/pakistan-grapples-with-extended-power-outages-as-electricity-shortfall-hits-6663-mw/*

26 *https://cleantechnica.com/2024/11/25/the-peril-promise-of-solar-power-in-pakistan/*

27 *https://rasta.pide.org.pk/cgp/techno-economic-analysis-of-widespread-microgrid-deployment-in-pakistans-electrical-power-sector/*

28 *https://link.springer.com/chapter/10.1007/978-3-7091-0109-4_15*

29 *https://www.ips.org.pk/wp-content/uploads/2023/07/21-Sustainable-Mini-grid-Solutions-for-Off-grid-Electrification-in-Pakistan.pdf*

30 *https://ourworld.unu.edu/en/rural-pakistan-lends-insight-on-energy-poverty*

31 *https://documents1.worldbank.org/curated/en/099071824081524723/pdf/P16931315c0d6403d18d3f1669067803800.pdf*

32 *https://www.trade.gov/country-commercial-guides/pakistan-renewable-energy*

33 *https://energycentral.com/news/rays-change-can-pakistan-harness-solar-power-shift*

34 *https://www.irena.org/News/pressreleases/2024/Sep/Record-Growth-Drives-Cost-Advantage-of-Renewable-Power*

opportunity for Pakistan to achieve its renewable energy targets as given in the ARE Policy 2019 to achieve at least 30% renewable energy by 2030. In alignment with this goal, the government has prioritized fostering international cooperation and attracting foreign investment in renewable energy. The CPEC 2.0 is expected to accelerate investments in green energy transition projects, including solar, wind, and hydroelectric initiatives. A significant focus of these efforts is on enhancing Pakistan's power transmission sector for better integration of renewable energy into the national grid. Such developments are projected to positively impact energy efficiency and economic growth in Pakistan.[35]

3.1. SWOT Analysis of Microgrid Implementation in Pakistan

A SWOT analysis, an evaluative framework used to assess Strengths, Weaknesses, Opportunities, and Threats, was conducted through structured interviews with Chinese stakeholders operating in Pakistan's power sector. These insights highlighted both the potential and the existing challenges of implementing microgrids in rural areas specifically in their deployment as emphasized by representatives leading renewable energy projects within these organizations.

Table 1. SWOT Analysis of Micro-grid Implementation in Pakistan

SWOT Analysis of Micro-grid Implementation in Pakistan			
STRENGTHS	**WEAKNESSES**	**OPPORTUNITIES**	**THREATS**
1. Abundant Renewable Energy Sources 2. Increased Policy Focus on Decentralized Systems 3. Adoption of Proven Renewable Technologies 4. Off-Grid Electrification for Remote Areas 5. Reduced Dependency on Fossil Fuels 6. Technological Advancements for Cost Efficiency 7. ARE Policy 2019 for Renewable Promotion 8. International Funding Opportunities	1. High UpfrontCosts 2. Technical and Skill Barriers 3. Dependence on Imported Equipment 4. Policy and Framework Gaps 5. Grid Integration Challenges 6. Maintenance and Operational Issues	1. Vast & Untapped Market 2. Opportunities in Renewable Energy Targets 3. Global Funding and Technical Assistance 4. Rising Energy Demand in Underserved Areas 5. Cost Reductions in RE Technology 6. Innovative Financing Models 7. Climate Resilience and Energy Security 8. Economic Development and Job Creation	1. Currency Depreciation Increasing Equipment Costs 2. Financial Challenges and Political Volatility 3. Security and Social Resistance 4. Risks in Conflict-Prone Regions 5. Equipment Theft and Vandalism 6. Energy Theft and Law Enforcement Issues 7. Competition with Fossil Fuels 8. Resistance from Fossil Fuel Industries 9. Grid Reliability and Microgrid Adoption Challenges

The interviews further emphasized that implementing microgrids through Chinese investment might face numerous challenges such as the lack of community awareness and acceptance regarding the benefits of new technology, often leading to resistance and hesitation in adoption. Security concerns, including risks to the lives of Chinese personnel working in Pakistan, further discourage investment and complicate operations. These concerns are exacerbated by political instability and risks in remote regions.

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35 *https://cpec.gov.pk/brain/public/uploads/documents/CPEC_2.0_Eng.pdf*

Supply chain issues also pose significant obstacles. Delays in importing equipment, compounded by corruption and demands for bribes, demotivate Chinese investors. Local shortages and unavailability of technological equipment further impede timely installation and maintenance efforts. Forecasting energy demand and environmental impact assessment in rural areas is another challenge, with inaccurate predictions leading to either underutilization or overloading of microgrid systems. Furthermore, uncertainty surrounding ownership and management models creates operational inefficiencies and conflicts among stakeholders.

High costs of storage technologies, such as batteries, limit their scalability, while the absence of policy incentives, such as subsidies or tax breaks for clean and renewable energy technologies, diminishes their appeal to investors. Other critical challenges include land acquisition disputes, energy and equipment theft, and unpredictable tariff structures. These issues will undermine the financial viability of microgrids. Additionally, a lack of coordination among government agencies, private investors, and local communities, particularly in the approval processes, will lead to fragmented efforts. Bureaucratic delays, corruption, and inconsistent oversight further complicate project development.

A lack of revenue from existing power projects, unprofitable investments, delayed returns, and an absence of clear profit-sharing mechanisms have made foreign investors hesitant and have hindered their trust. Financial and taxation barriers, lack of risk-sharing frameworks, absence of payment guarantees, outdated grid infrastructure, and insufficient technical and skilled labor will further hinder the progress of microgrid initiatives. Addressing these interconnected challenges is vital to creating a conducive environment for microgrid deployment and unlocking their transformative potential for rural electrification in Pakistan.

Chapter: 4

Overview of Regulatory Framework of Microgrids in Pakistan

NEPRA, the power sector regulator, introduced Microgrid Licensing Regulations, 2022, marking a significant step towards promoting renewable energy (RE)-based microgrids to serve underserved and off-grid regions. Established under Section 47 of the Regulation of Generation, Transmission, and Distribution of Electric Power Act, 1997, these regulations provide a legal framework for the licensing, construction, ownership, and operation of microgrids. They enable market participants to harness economic and environmental benefits, presenting substantial opportunities for Chinese investors to leverage their technological expertise and expand their market presence.

4.1. Policy and Regulatory Overview of NEPRA Microgrid Licensing Framework

The "National Electric Power Regulatory Authority Licensing (Microgrid) Regulations, 2022" came into effect immediately upon issuance, deriving legal authority from the Regulation of Generation, Transmission, and Distribution of Electric Power Act, 1997 (Act No. XL of 1997). The document explains key terms like "microgrid" (a small-scale power grid that can operate independently), "microgrid license" (authorization to build and run such grids), and "unserved market" (areas without access to electricity from the main grid). It also sets technical limits, with microgrids typically operating at a voltage of up to 33 kV and serving loads of up to 5 MW.

A "microgrid license" permits the holder to construct, own, and operate a microgrid for the generation, distribution, and supply of electricity. An "unserved market" refers to areas not currently served by the host distribution licensee, located beyond 5 kilometers from existing distribution facilities, and excluded from the licensee's approved investment plans.

The application process accommodates electronic, email, or courier submissions, with a 60-day processing timeline. Licenses are granted for a 10-year term, with provisions for extensions, stakeholder consultations, and public hearings. Compliance with technical standards is mandatory to ensure safe and efficient microgrid operations. For example, IEEE 1547 focuses on the integration of distributed energy resources, while IEC TS 62898 provides guidelines for planning, operating, and maintaining microgrid systems, including energy storage, protection, and power quality.

The framework ensures fair tariffs for both consumers and licensees, with NEPRA retaining the authority to reassess unjustified tariffs. It also allows for microgrid integration or acquisition during network expansions, ensuring fair compensation and infrastructure compatibility.

It mandates exclusive Standard Operating Procedures (SOPs) for billing, connection/disconnection policies for microgrids, and consumer complaint resolution. Accurate financial records, regular audits, and submission of financial and tariff-related documents to NEPRA are mandatory to ensure transparency and accountability. Certain regulatory exemptions are provided, and NEPRA reserves the right to issue additional guidelines as necessary.

Most of the operational and planned microgrids in Pakistan leverage solar or small-scale hydropower, offering cost-effective and sustainable solutions for rural electrification. NEPRA's regulations allow for grid interconnection where feasible, emphasizing clear technical standards and mutually agreeable terms. This initiative holds particular importance in rural, remote, and underdeveloped regions such as Baluchistan, KPK, and Sindh, where access to the national grid remains limited or non-existent.

4.2. Challenges in NEPRA's Microgrid Regulations for Attracting Chinese Investment

The NEPRA regulatory framework 2022 presents some limitations for microgrid implementation in unserved areas of Pakistan, particularly in attracting Chinese investment. These challenges include a short-term license tenure, lack of financing incentives, capacity limit, tariff uncertainty, and unclear standards for grid interconnection as shown in table 2.

Table 2. Challenges in NEPRA's Microgrid Regulations for Attracting Chinese Investment

No.	Challenge	Solution
1	**Capacity Cap (5 MW Limit)** The current cap restricts the size and scalability of microgrid projects, limiting their expansion and technical viability.	Increase capacity cap to 10–15 MW, especially for hybrid and stand-alone microgrids.
2	**Grid Arrival Clause** The regulation allows host distribution licensees to take over microgrid assets upon grid expansion, creating long-term ownership uncertainty.	Guarantee fair compensation and allow microgrid operators to integrate as Independent Power Producers (IPPs) or Distribution Service Providers (DSPs).
3	**Licensing Tenure (10-Year Cap)** A short licensing period of 10 years of a 25 year project discourages long-term investments and strategic planning.	Extend licensing tenure to 20–25 years and/or introduce clear renewal criteria.
4	**Tariff Uncertainty** NEPRA retains the authority to reassess tariffs at any time, leading to unpredictable revenue streams.	Implement tariff stability agreements for at least 5–7 years and allow cost-reflective tariffs.
5	**Regulatory Complexity and Bureaucracy** The application process is slow and involves multiple regulatory layers, increasing delays and administrative costs.	Establish a single-window clearance system and enforce the 60-day approval period strictly
6	**Financing and Incentives for RE-Microgrids** The absence of financial incentives, such as tax breaks or risk mitigation funds, reduces RE project attractiveness for investors.	Offer tax holidays during a few initial years of the RE-based microgrid projects, risk mitigation funds, and low-interest financing options.
7	**Technical Compliance with IEEE& IEC Standards only** Strict adherence to IEEE and IEC standards increases costs and may not align with Chinese technology preferences.	Allow phased compliance timelines for IEEE & IEC and recognize Chinese technical standards where appropriate.

No.	Challenge	Solution
8	**Political and Policy Instability** Frequent regulatory and policy changes create uncertainty for long-term investments and operational security.	Ensure parliamentary approval for major regulatory changes and introduce policy continuity guarantees.
9	**Local Partnerships and Knowledge Transfer** Limited technical and managerial expertise among local partners can slow project execution and reduce efficiency.	Facilitate joint ventures with local entities and offer capacity-building initiatives.
10	**Risk Sharing Mechanisms** Investors face disproportionate risks related to political instability, currency fluctuations, and regulatory changes.	Introduce public-private risk-sharing frameworks, including government-backed guarantees, insurance schemes, and currency hedging mechanisms.

4.3. Case Study: QASPPL Microgrid Licensing Model to Facilitate Chinese Investments in Rural Pakistan

The successful licensing of microgrid projects for Quaid-e-Azam Solar Power (Private) Limited (QASPPL) by NEPRA highlights a regulatory model that supports decentralized renewable energy initiatives. Under licenses MGL/01/2023 and MGL/02/2023, NEPRA enabled the development of solar microgrids with a combined capacity of over 1.3 MW in rural Punjab.

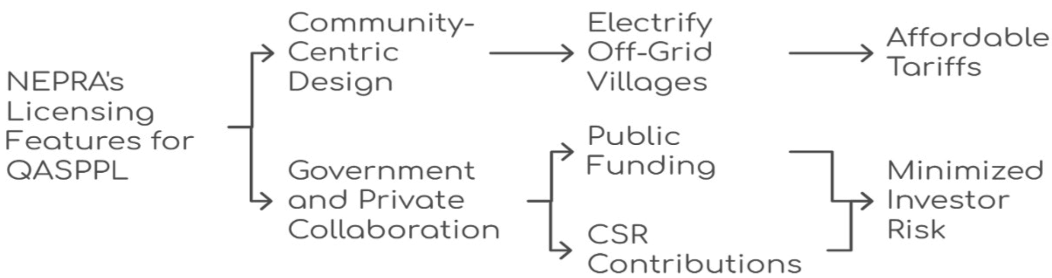


Figure 2. QASPPL Microgrid Licensing Features

The framework illustrated in Figure 2, emphasizes streamlined licensing processes, technical compliance requirements, and community-focused designs, ensuring benefits for both investors and local populations. The QASPPL microgrid project serves as a model for future Chinese investors by showcasing a scalable, government-supported approach to renewable energy development. Backed by the Government of Punjab and regulated under the NEPRA Licensing (Microgrid) Regulations, 2022, for a 10-year term, it offers a transparent framework that minimizes risks and builds investor confidence. The use of advanced solar technologies, such as high-efficiency panels and lithium-based batteries, underscores the project's technical feasibility.

This initiative taken by the government balances community goodwill with financial sustainability through a phased tariff system, transitioning from free energy to nominal charges. In this way, the regulations offer a replicable revenue model for emerging RE-based microgrid markets. Moreover, the project aligns with China's BRI, focusing on sustainable infrastructure and rural development. By addressing energy poverty in unserved areas, it demonstrates socio-economic benefits, including improved living standards, education, and employment opportunities. The funding structure of QASPPL, combined public resources with Corporate Social Responsibility (CSR) initiatives, highlighting the potential of Public-Private Partnerships to attract foreign investment while ensuring financial viability.

While challenges such as infrastructure gaps and financial sustainability remain, solutions like co-financing arrangements and consistent policy support can enhance long-term viability. Overall, the QASPPL microgrid model provides a compelling blueprint for Chinese investors, offering both economic returns and developmental impact in similar markets.

Chapter: 5

Feasibility Analysis of Microgrids in Rural Areas of Pakistan using HOMER Software: A Case Study

5.1. Introduction to Feasibility Assessment

The objective of this feasibility assessment is to evaluate the technical, financial, and operational viability of implementing renewable energy-based microgrid systems in selected rural areas of Pakistan. HOMER Pro software has been employed for this analysis due to its robust capabilities in optimizing hybrid energy systems, assessing resource availability, and conducting sensitivity analysis.

5.2. Selected Areas for HOMER Pro Simulations for Our Case Study

The selected sites for this feasibility study include Jam Nawaz Ali (Sindh), Girote (Punjab), Sakhra (KPK), and Wadh (Balochistan). These regions represent diverse geographic, demographic, and energy demand profiles. Each site was chosen based on its significant potential for renewable energy resources, limited access to grid electricity, and opportunities for socio-economic uplift through improved energy access.

The load demand of each site varies with agricultural seasons and can be effectively managed through solar-powered combination energy systems, ensuring a stable electricity supply even during peak demand periods. These sites also provide an opportunity for Chinese investment under CPEC 2.0 to scale up electrification through microgrids, potentially leveraging their expertise. The map below in figure 3, shows the site selected for the feasibility study of microgrids in Pakistan.

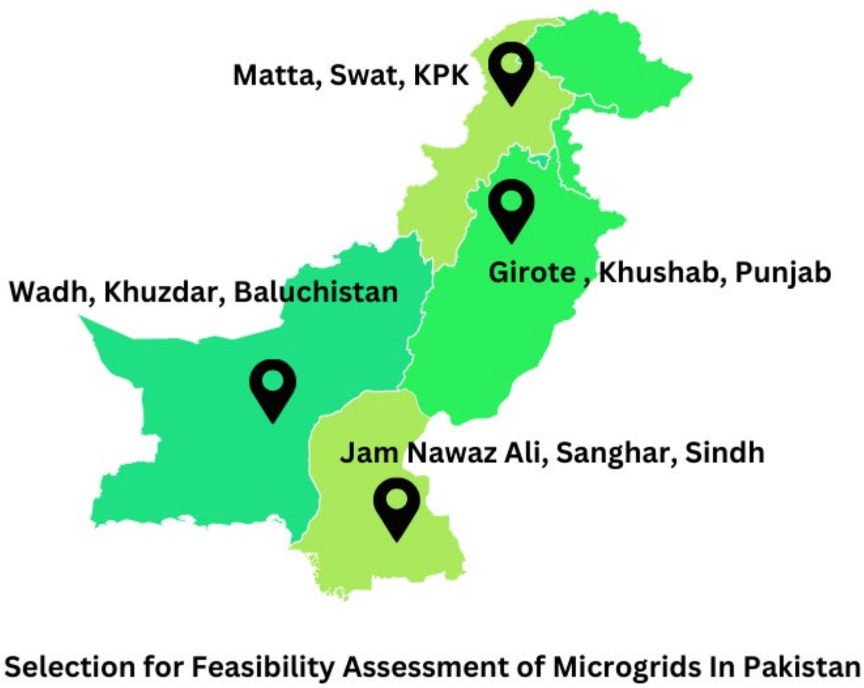


Figure 3. Site Selection for Feasibility Assessment of Pakistan

1. Jam Nawaz Ali, Sanghar, Sindh

Jam Nawaz Ali is a sub-district in Sanghar district in Sindh, facing a significant challenge due to a negative population growth rate. This may be attributed to factors such as migration to urban areas in search of better employment, education, and healthcare opportunities, limited economic development, and inadequate infrastructure. The region benefits from high solar energy potential, a predominantly agricultural economy, whereas it has limited access to a reliable grid, making it highly suitable for decentralized energy solutions.

2. Girote, Khhushab, Punjab

Girote is an unserved rural community located near the Thal Desert and the agricultural plains of Khushab District in South Punjab. The region's proximity to the desert ensures high solar power potential, making it an ideal site for solar-powered microgrids. Limited access to reliable grid infrastructure and a strong reliance on agriculture, particularly irrigation, makes Girote an ideal site for our study as it can provide stable power, harness its solar energy potential, enhance agricultural productivity, and improve essential services for the community.

3. Sakhra, Swat, KPK

Sakhra, located in Swat District, KPK, is a promising area for the development of microgrids as it is rich in renewable energy potential, particularly solar and hydropower, due to its hilly terrain and sunny climate. These factors make Sakhra an ideal candidate for decentralized energy solutions, especially microgrids, which can effectively address the area's unreliable electricity access.

4. Wadh, Khuzdar, Balochistan

Wadh, in Balochistan's Khuzdar District, shown in is ideal for microgrid deployment due to its rugged terrain and scattered settlements, which hinder traditional grid expansion. The region's arid climate and abundant sunlight make solar energy highly viable, complemented by wind energy potential. Microgrids with battery storage can meet rising energy demand during peak periods like irrigation and harvesting, ensuring reliable power. This improved energy access can stimulate agriculture, business activities, and small enterprises, supporting the region's development.

5.3. Resource Availability

For renewable energy generation, ensuring an abundant and sustainable supply of resources is crucial, particularly for standalone microgrids. This guarantees a stable energy supply. Since all the microgrids in this study are hybrid systems powered by solar energy in combination with other sources, we have evaluated the solar potential for all selected sites alongside assessments of biomass, wind, and hydro resources.

Solar and wind energy potentials were readily available in HOMER Pro, sourced from NASA's database. Biomass resources were calculated using data from the World Bank's Biomass Study, while hydro resources were evaluated based on area-specific dynamics and streamflow assumptions. The resource data is discussed below.

5.3.1. Solar Energy Resource

The software HOMER Pro analyzes the solar resource data for each site from NASA's database. The software analyzes the solar radiations and clearness of the sky, all the figures below show the site specific solar Global Horizontal Irradiation (GHI), i.e. (Average daily radiations (kWh/m²/day) with a clearness index ranging (0-1). The site specific solar energy resource assessment is discussed below.

1.

Jam Nawaz Ali: The average daily solar radiation of 5.85 kWh/m²/day. Figure 4 highlights the strong solar energy potential of Jam Nawaz Ali, Sindh, with daily solar radiation ranging from 4.5 to 6.5 kWh/m²/day and an annual average of 5.85 kWh/m²/day. Minimal seasonal variation and moderate atmospheric clarity make the site ideal for solar microgrids, supporting reliable energy generation and sustainable development.

Figure 4. Solar GHI Resource for Jam Nawaz Ali, Sanghar, Sindh

2.

Girote: The solar radiation peaks at over 6 kWh/m²/day. Figure 5 illustrates Girote's strong solar energy potential, with daily solar radiation ranging from 4 kWh/m²/day in December to over 6 kWh/m²/day in May and June. The clearness index indicates stable atmospheric conditions, making the region well-suited for efficient solar PV performance, particularly during the high-radiation summer months.

Figure 5. Solar GHI Resource for Girote, Khushab, Punjab

3.

Sakhra: The maximum solar radiation of 7 kWh/m²/day. Figure 6 highlights Sakhra's strong solar energy potential, with daily solar radiation peaking at around 7 kWh/m²/day in June. The clearness index remains steady between 0.5 and 0.8 throughout the year, indicating favorable conditions for solar PV systems. These metrics confirm the region's suitability for efficient and consistent solar energy generation, particularly during the summer months.

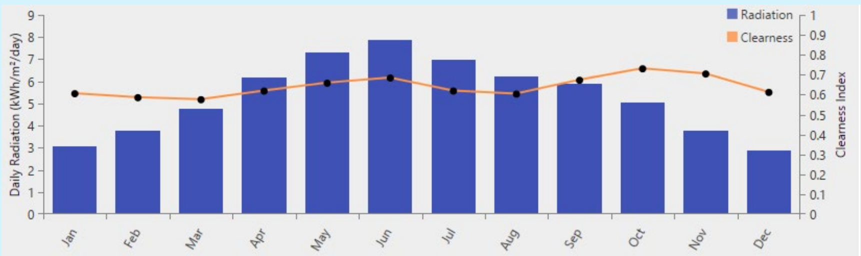


Figure 6. Solar GHI Resource for Sakhra, Swat, KPK

4.

<u>Wadh:</u> This region experiences consistent solar radiation above 5.5 kWh/m²/day. Figure 7 demonstrates Wadh's strong solar potential, with daily radiation exceeding 5.5 kWh/m²/day from March to September and peaking at nearly 7 kWh/m²/day in May and June. Even in winter, radiation remains around 4.5 kWh/m²/day. A consistent clearness index of 0.5 to 0.7 ensures favorable conditions for solar energy, making solar PV systems a reliable primary energy source for microgrids.

Figure 7. Solar GHI Resource for Wadh Khuzdar

5.3.2. Biomass Availability

Biomass resource potential was evaluated using data from the World Bank's report on "Biomass Resource Mapping in Pakistan," focusing on large-scale dairy farms and standard biogas conversion parameters.

Biomass availability in Khushab shows seasonal variation. While livestock manure and municipal solid waste (MSW) remain stable year-round, crop residues (e.g., wheat straw, rice husk, maize stalks) peak post-harvest in late autumn (Kharif crops) and late spring (Rabi crops). However, with manure and different crop residues available year-round, an average of at least 100 tonnes/day of biomass will consistently be available with biogas yield per tonne of manure ranging from 25–30 m³. Based on the energy content of biogas (21 MJ/m³) and the electrical efficiency of biogas engines (30–40%), the estimated gross power generation capacity is 0.36 MW.

5.3.3. Wind Energy

The software HOMER Pro analyzes wind resource data from NASA's database. The wind profile of Wadh, Khuzdar, Balochistan as seen in figure 8, shows average wind speeds of 4 to 5.5 m/s year-round, with higher speeds from March to May and slightly lower values during summer (July–September). While wind speeds are moderate, they are adequate to support small-scale wind turbines as a complementary energy source. Wind energy can supplement solar generation during winter and nighttime, improving the overall reliability of the microgrid.

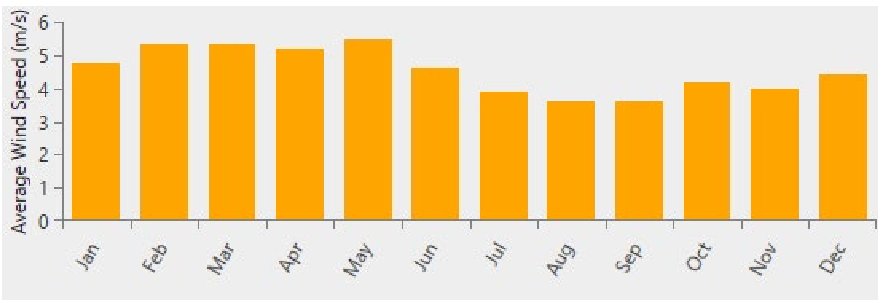


Figure 8. Wind Resource for Wadh Khuzdar

5.3.4. Hydro Resource

The hydro resource for this study was estimated based on the area specific parameters and the stream flow of water. The seasonal streamflow at Sakhra, Swat, KPK, has been estimated at 2,000 L/s during the peak summer months. The figure 9 is based on general flow patterns in the Swat Basin, considering factors like higher elevation, smaller catchment area, and increased runoff, which result in reduced flow near Sakhra. The peak streamflow in July, driven by glacial melt and rainfall, is suitable for a small hydropower plant. Hydrological models, such as SWAT, suggest that this estimate aligns with observed seasonal trends. The hydro resource at Sakhra (shown in Figure 9) exhibits strong seasonal variation, with average streamflow increasing significantly in summer and peaking at 2000 L/s, while winter flow drops below 500 L/s. This seasonal variability indicates that hydropower could complement solar PV generation in a hybrid energy system, optimizing energy production during peak summer months.

Figure 9. Hydro Resource for Sakhra, Swat, KPK

5.4. Load Profile Evaluation & Price Assumptions

The evaluation of energy consumption and seasonal profiles for each location is based on census data provided by the Pakistan Bureau of Statistics[36]. Each household is assumed to consist of six people, with an average energy use per person estimated at 693.5 kWh/year. This results in a total energy consumption of 4,161 kWh/year per household. The calculation incorporates the average daily energy consumption of a household in rural areas, estimated at 0.78 kW/day, along with the nominal energy usage for street and commercial needs in rural communities, which amounts to 4.98 kW/day. Data for these estimates was collected from rural communities in Balochistan and Sindh.

The total energy consumption per household is derived by multiplying per-person usage by the average household size of six, as indicated by census data. For each area, the total annual energy demand is calculated by multiplying the per-household consumption by the number of households. Seasonal energy profiles reveal peak demand during summer months, primarily due to cooling requirements, while demand decreases in winter. This emphasizes the importance of energy storage systems or complementary solutions to address these fluctuations. The profiles, as illustrated in Table 3, underscore the necessity for a microgrid or hybrid energy system to accommodate seasonal variations and ensure a reliable year-round energy supply.

36 https://www.citypopulation.de/en/search/

Table 3. Load Profile and Energy Consumption

Location	Population (2023)	Peak (kW)	Scaled Annual Average (kWh/ day)	Seasonal Energy Profile
Jam Nawaz Ali	~6,311	1000 kW	8000 kWh/day	Peaks in June-July due to cooling demand or renewable energy generation, lower in Jan-Dec. Needs storage or complementing sources for year-round reliability.
Girote	~24,875	1600 kW	10,000 kWh/day	Peaks in summer months (June-August) due to cooling, with lower energy demand in Nov-Jan. Requires flexible energy systems for seasonal fluctuations.
Sakhra	~25,000	1200 kW	11000 kWh/day	Peaks in May-July due to higher cooling demand, lower in Jan-Feb. A consistent energy system needed to meet yearly variations.
Wadh	~27000	1716 kW	14,500 kWh/day	Moderate peaks in May-July, lower variability in the cooler months. A stable energy system suits predictable demand patterns.

The price assumptions for the HOMER Pro inputs are based on a range of components tailored for off-grid energy systems. The prices are derived from various suppliers and reflect the competitive market in Pakistan and international sourcing. These prices are sourced from reputable Chinese suppliers including JBMS.pk, Made-in-China, Alibaba, and Pulita Energy. These price assumptions are given below:

Table 4. Price Assumptions for off-grid energy systems

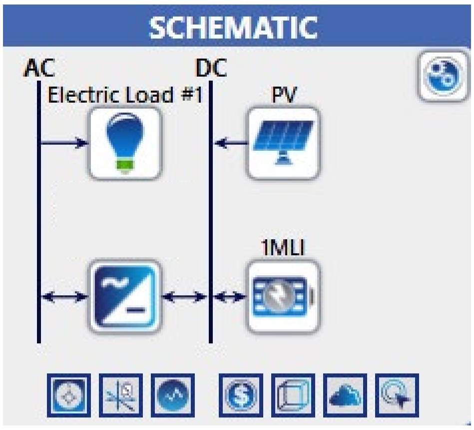
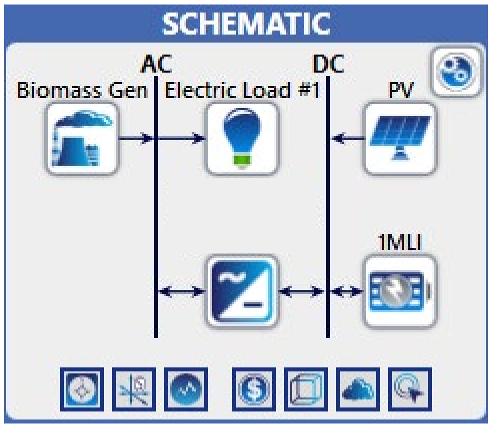
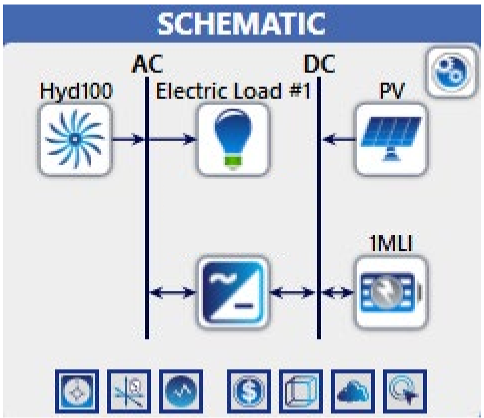
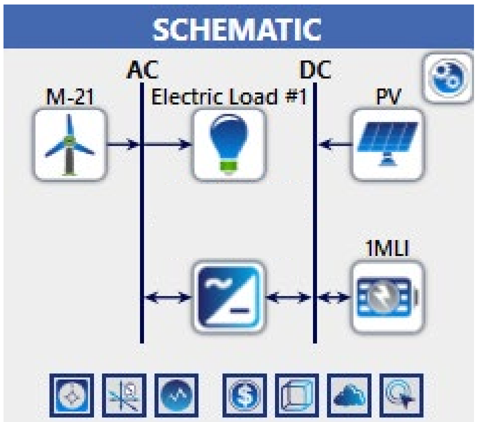
Component	Capacity/Features	Approx. Price (USD)	Description	Source
Solar PV plates	Solar Panels - Competitive pricing, multiple models.	30 rupees per watt	Solar panel options for small to large-scale installations in Pakistan.	JBMS.pk
Li-ion Battery	1MW – BESS with Container, Based on a modular design	$12,000.00-$60,000	Large-scale lithium-ion solar energy storage for industrial use	Made-in-China
Off-Grid Inverter	1MW off Grid 576V 600V 1250kVA Pure Sine Wave Hybrid Inverter	$106,000.00-$120,000.00	Pure sine wave hybrid inverter for off-grid energy systems.	Made-in-China
Biomass Generator	10kW-500kW, 1500/1800 RPM, 50/60Hz	$5,000 - $200,000	Biomass gasification power plant with water-cooled engine, DC 24V electric start	Pulita Energy

Hydropower Generator	Hydro Power Plant (100kW) - High efficiency, low maintenance.	$50,000.00	Compact Francis turbine system for small-scale hydroelectric projects.	Alibaba
Wind Generator	Wind Turbine Kit (500 kW - 2 MW)/ Durable, energy-efficient, range of capacities	$10,000.00-$20,000	Permanent magnet wind turbine system with variable pitch for efficient energy generation.	Made-in-China

5.5. System Design and Configuration

The microgrid configurations are designed based on the resource availability at the selected research sites. As illustrated in Table 4, all microgrids are solar-powered and equipped with battery energy storage systems. Site-specific resources further define the configurations: biomass integration in Punjab, wind energy utilization in Balochistan, and hydro energy deployment in Swat, aligning with the respective resource abundance of each location.

Table 4. Schematic Diagram of the Microgrid Configurations

Schematic Diagram For Jam Nawaz Ali, Sanghar Sindh	Schematic Diagram For Girote, Khushab, Punjab
	
The schematic illustrates an off-grid renewable energy microgrid system for Jam Nawaz Ali, consisting of a Solar PV array for energy generation, an off-grid inverter to convert DC to AC power, and a Li-ion Battery Energy Storage system	The schematic shows an off-grid renewable energy microgrid for Girote, Khushab, and Punjab, combining a Solar PV array, off-grid inverter, Li-ion Battery Storage, and biomass generator.
Schematic Diagram For Mattta, Swat, KPK	**Schematic Diagram For Wadh, Khuzdar Balochistan**
	
The schematic shows an off-grid RE-based microgrid system for Sakhra, Swat, featuring a Solar PV array, Li-ion Battery Energy Storage, Hydro Generation, and an off-grid inverter.	The schematic illustrates an off-grid renewable energy-based microgrid system for Wadh, Khuzdar, Balochistan, combining Solar PV, Wind Energy Generation, Li-ion Battery Storage, and an off-grid inverter.

5.6. Technical Performance of the Microgrid Configurations

The technical performance of the microgrid configurations, as shown in Table 5, highlights the efficiency and sustainability of renewable energy (RE)-based systems. The data indicates that the microgrids primarily rely on solar PV energy for power generation. Table 5 shows that annual energy consumption is approximately one-fourth of the annual energy production. This surplus is attributed to the integration of battery energy storage systems in each microgrid configuration, enabling efficient energy management. Furthermore, the table reflects significant excess energy generation, which accounts for the derating factors applied to each component of the hybrid energy system over the project's 25-year lifespan. This ensures system reliability and accommodates potential performance degradation over time.

Table 5. The Technical Performance of the Equipment in Microgrids

Location	Annual Energy Production (kWh/yr)	Annual Energy Consumption (kWh/yr)	Excess Energy (kWh/yr)	% Renewable Energy Production	Breakdown of Energy Sources
Jam Nawaz Ali, Sindh	18,044,725 kWh/yr	4,378,639 kWh/yr	13,301,667 kWh/yr	100%	100% PV
Sakhra, Swat, KPK	15,173,692 kWh/yr	3,648,11 kWh/yr	11,316,287 kWh/yr	100%	93.2% PV (14,137,486 kWh), 6.83% Small Hydro (1,036,206 kWh)
Wadh, Balochistan	25,474,181 kWh/yr	5,280,567 kWh/yr	19,998,281 kWh/yr	100%	61.6% PV (15,684,707 kWh), 38.4% Wind (9,789,474 kWh)
Girote, Khushab, Punjab	16,259,538 kWh/yr	5,283,740 kWh/yr	10,496,225 kWh/yr	96.7% Renewable & 3.3% Biomass	98.9% PV (16,082,613 kWh), 1.07% Biomass Generator (176,925 kWh),

The key observation from the table is that energy generation from the microgrids is entirely renewable, except for the Girote microgrid, where 1.07% of the energy comes from biomass and 98.9% from solar energy. While biomass is not strictly renewable, it is considered a clean energy source. The breakdown of energy sources further highlights the dominance of PV energy generation across all microgrid configurations.

Hydropower contributes only 6.83% to energy production, as it relies on run-of-river systems and is abundant primarily during the peak summer season. Similarly, biomass generators account for 1.07% of energy production due to their dependence on seasonal crops (e.g., Kharif and Rabi crops) and, in some cases, manure. On the other hand, wind energy, which is sufficiently available and variable, demonstrates strong potential in Balochistan, contributing 38.4% to the system's energy production.

The energy surplus generated by the microgrids presents numerous opportunities for profitability, including grid exports, ancillary services, and energy wheeling mechanisms through the trade of excess energy. These microgrids ensure clean and reliable power, effectively addressing issues such as grid instability, transmission constraints, and frequent load shedding. Surplus energy can be stored for future use, exported to nearby communities, or sold to the main grid, creating additional revenue streams. This not only enhances the financial viability of the microgrids but also ensures energy availability for rural consumers during peak demand periods or emergencies.

5.7. Capacity and Cost of Equipment

The feasibility assessment of the equipment for the microgrid systems across different sites is shown in table 6, presenting a compelling opportunity. As the equipment's installed capacity, capital cost, and replacement costs offer a balanced approach to a reliable, cost-effective, and profitable scenario , making it an attractive investment while ensuring energy access for underserved communities.

Table 6. Capacity and Cost of Equipment

Equipment	Location	Installed Capacity	Capital Cost[37] ($)	Replacement Cost ($)
Solar PV System	Jam Nawaz Ali, Sindh	9 MW	0.95M	-
	Sakhra, Swat, KPK	11 MW	1.2M	-
	Wadh, Balochistan	8.9 MW	0.9M	-
	Girote, Khushab, Punjab	9.6 MW	1M	-
Li-Ion Battery	Jam Nawaz Ali, Sindh	10 MWh	1.5 M	2.1M (Year 10 & Year 20)
	Sakhra, Swat, KPK	7 MWh	1.1 M	$883,437.63 (Year 10 & Year 20)
	Wadh, Balochistan	10 MWh	1.5M	2.1M (Year 10 & Year 20)
	Girote, Khushab, Punjab	10 MWh	1.5M	2.1M (Year 10 & Year 20)
Small Hydro Power Plant	Sakhra, Swat, KPK	98 kW	50,000	-
Wind Turbine	Wadh, Balochistan	4.5 MW	48,000	16,000 (If required)
Biomass Generator	Girote, Khushab, Punjab	2.1 MW	1.05M	-
Off-Grid Inverter	Jam Nawaz Ali, Sindh	1.5 MW	106,005	33,314 (Year 15)
	Sakhra, Swat, KPK	1.6MW	139,230	55,379 (Year 15)
	Wadh, Balochistan	1.8 MW	178,019	71,253 (Year 15)
	Girote, Khushab, Punjab	2.3 MW	202,907	197,794 (Year 15)

Solar PV systems are ideal for Pakistan's geographic conditions, given the high solar GHI. The capital costs range from $0.95M for the 9 MW system in Jam Nawaz Ali, Sindh to $1.2M for the 11 MW system in Sakhra, Swat, KPK, demonstrating scalability. Systems in Wadh, Balochistan (8.9 MW for $0.9M) and Girote, Khushab, Punjab (9.6 MW for $1M) further emphasize the cost-effective and widespread adoption of solar energy. The no replacement costs for the entire project life reduce long-term financial burdens and enhance returns for investors.

Li-Ion batteries are crucial for ensuring reliability by storing surplus energy for periods of low generation. The replacement costs, ranging from $0.8 to $2.1M in years 10 and 20, are factored into the financial planning, ensuring long-term functionality. This technology ensures consistent power delivery, even during cloudy days or nighttime, addressing the intermittency of renewable energy sources. For rural consumers, this guarantees uninterrupted

37 *The capital cost refers to the cost of the equipment's installed capacity.*

power, supporting daily activities and economic growth.

The **small hydro power** in Sakhra, KPK adds energy diversity and reliability, providing continuous generation during seasonal high water availability, while wind turbines in Wadh, Balochistan offer supplementary energy where wind resources are abundant. Both systems are cost-effective, with the wind turbine having a $16,000 replacement cost, making them long-term attractive investments.

The **biomass generator** in Girote, Khushab, Punjab, utilizing agricultural waste, supports the local economy and contributes to a circular economy by providing steady power.

Off-grid inverters, essential for converting DC power to usable AC power, are relatively inexpensive in case of community based microgrids. The off-grid inverter installations include a 1.5 MW system in Jam Nawaz Ali, Sindh ($106,005), a 1.6 MW system in Sakhra, Swat, KPK ($139,230), a 1.8 MW system in Wadh, Balochistan ($178,019), and a 2.3 MW system in Girote, Khushab, Punjab ($202,907), with replacement costs expected after 15 years. These systems are cost-effective and contribute to system profitability by allowing for the export of surplus energy.

The combination of solar PV, wind, small hydro, biomass, and battery storage in these microgrids provides a diversified, sustainable energy solution for rural Pakistan. For investors, this mix offers a path to long-term profitability, with less replacement costs as the price of the equipment depreciates with time, and the potential to export surplus energy to the grid or local communities. For rural consumers, these microgrids offer reliable, cost-effective, and environmentally friendly electricity, reducing reliance on fossil fuels. The integration of energy storage ensures continuous power, even during fluctuations in renewable generation, minimizing the risk of energy shortages.

5.8. Financial Metrics

The financial metrics of RE-based microgrid systems in Pakistan, including microgrid configurations simulated for Jam Nawaz Ali, Sakhra, Wadh, and Girote, provide a comprehensive overview of the potential economic performance and investment appeal of each system. Key indicators like Levelized Cost of Energy (LCOE), Return on Investment (ROI), Internal Rate of Return (IRR), Payback Period, Net Present Cost (NPC), and Operations & Maintenance (O&M) costs illustrate the financial feasibility and attractiveness of these projects in table 7. These metrics are provided by the software as outputs to evaluate the feasibility of the microgrids within the region as shown in figure 7 offer a clear understanding of the financial dynamics of microgrid investments in Pakistan, providing a well-rounded view of their profitability, sustainability, and appeal for investment.

Table 7. Financial Metrics

Location	Annual Worth ($/yr)	LCOE ($/kWh)	ROI (%)	IRR (%)	Pay-back Period (yrs)	NPC ($)	O&M Cost ($/yr)	CAPEX ($)
Jam Nawaz Ali, Sanghar, Sindh	111,600	0.07433	38.12	6.15	13	2.79M	60,000	2.5M
Sakhra, Swat, KPK	156,000	0.1183	23.57	19	2.59	4.68M	66,000	5.68M
Wadh, Khuzdar, Balochistan	160,000	0.1733	40	12.98	7.7	4M	313,602	5.19M
Girote, Khushab, Punjab	193,200	0.0707	28.47	33	2.4	4.83M	82,575	3.76M

Capital Expenditure, (CAPEX) is the initial investment required for a microgrid. HOMER calculates it as the sum of the unit costs multiplied by the respective quantities, plus installation costs and other additional expenses. CAPEX varies significantly across locations, from $2.5M at Jam Nawaz Ali to $5.68M at Sakhra. This wide range reflects the scale of each project and the associated infrastructure needs. High CAPEX projects, such as Sakhra, promise substantial energy production but come with higher financial commitments, making them suitable for investors seeking long-term, large-scale opportunities. In contrast, lower CAPEX systems, like those in Girote, offer less financial risk and quicker capital recovery, appealing to investors looking for moderate-scale, faster returns.

IRR and ROI provide insight into the profitability of each system. HOMER calculates Internal rate of return (IRR) is the discount rate at which the base case and current system have the same net present cost. HOMER calculates the IRR by determining the discount rate that makes the present value of the difference of the two cash flow sequences equal to zero. Similarly, Return on investment (ROI) is calculated by subtracting the cumulative nominal cash flow in year zero from the cumulative nominal cash flow in the final year. Divide that number by the lifetime and then again by the cumulative nominal cash flow in year zero. The cumulative nominal cash flow in year zero is equivalent to the base case capital cost minus the current system capital cost.

A high IRR of 33% at Girote, Khushab, Punjab suggests an attractive return relative to the initial investment, while a more moderate IRR of 19% at Sakhra still offers stable returns, albeit with lower risk. Similarly, ROI at 38% for Jam Nawaz Ali and 33% at Girote signals strong returns relative to the capital invested, making them highly lucrative, particularly for investors interested in profitable, stable opportunities.

Payback is the number of years at which the cumulative cash flow of the difference between the current system and base case system switches from negative to positive. The payback is an indication of how long it would take to recover the difference in investment costs between the current system and the base case system. The Simple payback is where the nominal cash flow difference line crosses zero. The Payback Period is crucial for assessing the speed at which an investment recoups its costs. With shorter payback periods like 2.4 years at Girote and 2.59 years at Sakhra, investors can quickly recover their initial outlay, reducing exposure to risk. In contrast, longer payback periods, such as 13 years at Jam Nawaz Ali, may be acceptable for those focusing on long-term gains, though they require careful consideration of sustained profitability.

The net present cost (or life-cycle cost) of a Component is the present value of all the costs of installing and operating the Component over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime. HOMER calculates the net present cost of each Component in the system, and of the system as a whole. Net Present Cost further highlights the relative costs of each project. Lower NPC values, such as $2.79M at Jam Nawaz Ali, indicate cost-effective investments with higher potential returns as it involves Solar Power and Battery Storage only, and not any other renewable technology in combination. On the other hand, the higher NPC at Sakhra reflects a larger-scale system, but with a greater potential for long-term revenue generation.

In HOMER, the Annual Worth is a financial metric that represents the annualized value of a project's cash flows over its lifetime. Annual Worth is calculated by HOMER dividing the Total Net Present Value by the Analysis Period. The Annual Worth provides an indication of the overall and recurring financial benefits of each system. For example, Jam Nawaz Ali's present annual worth of $111,600 suggests steady, moderate returns, while Sakhra's $156,000 annual worth signals a larger, sustained financial flow. The O&M costs vary by system complexity, with Wadh's $313,602 per year reflecting its diversified energy mix, and Jam Nawaz Ali's more modest $60,000 per year. These ongoing expenses must be carefully considered for long-term sustainability based on the renewable energy configured with the combination.

The graphs below provide a comparison of the financial metrics for microgrid configurations across four sites, as detailed in Table 7.

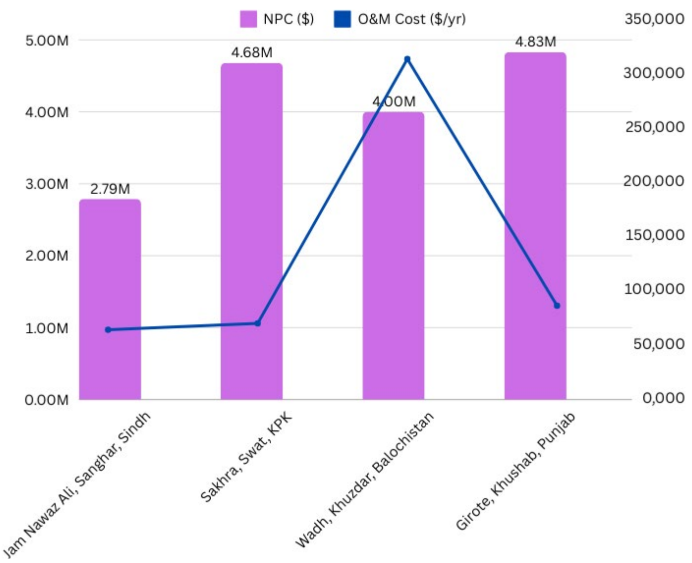


Figure 10. Net Present Cost ($) Vs. O&M Cost ($/yr)

Figure 10, shows a graph comparing the net present cost (NPC) that represents the total financial commitment over the lifetime of the energy project, while the operational and maintenance (O&M) costs indicate recurring yearly expenses. Jam Nawaz Ali again emerges as the most economical microgrid solution with the lowest NPC ($2.79M) and O&M costs ($60,000/year), minimizing both upfront and ongoing expenses. Sakhra has the highest NPC at $4.68M as it has small hydropower in combination with solar and battery, coupled with moderate O&M costs of $66,000/year. Wadh, while having a moderate NPC ($4M), suffers from extremely high O&M costs of $313,602/year, due to the operations and maintenance required for wind energy generation, as a high capacity of 4.5MW is installed along with Solar PV and Battery which significantly impacts its profitability. Girote has a moderate NPC ($4.83M) as biomass is affordable in Pakistan and reasonable O&M costs ($82,575/year), making it more efficient than Wadh but less economical than Jam Nawaz Ali.

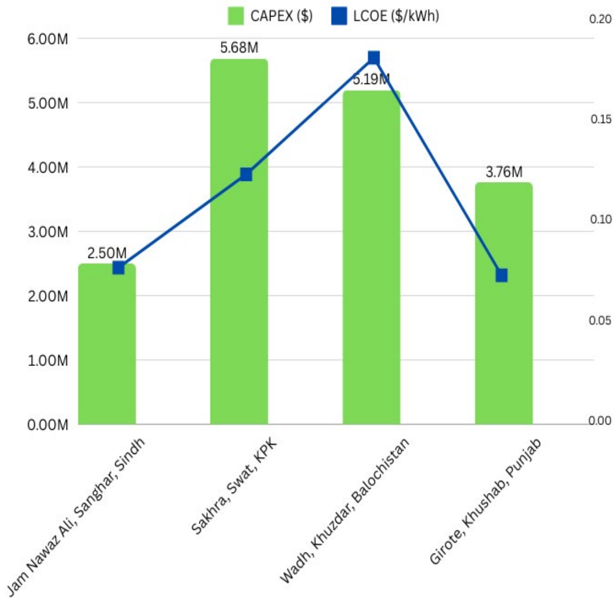


Figure 11. CAPEX ($M) Vs LCOE ($)

Figure 11, shows a graph comparing Capital Expenditure (CAPEX) and the Levelized Cost of Energy (LCOE) across four regions, highlighting key financial indicators for microgrids. Jam Nawaz Ali has the lowest CAPEX at $2.5M, making it the most cost-efficient project in terms of initial investment as it has Solar PV and Li-ion microgrid configuration only. Its LCOE of $0.074/kWh ensures affordable energy production. Sakhra, on the other hand, has the highest CAPEX ($5.68M) and a moderate LCOE of $0.118/kWh, due to the small hydropower in microgrid configuration which increases its overall cost. Wadh is the least cost-effective with a CAPEX of $5.19M and the highest LCOE at $0.173/kWh due to expensive wind energy technology in the microgrid configuration. Girote stands out with the lowest LCOE ($0.071/kWh), indicating superior cost-effectiveness due to energy production from biomass as a renewable resource in microgrid configuration, despite its moderate CAPEX of $3.76M.

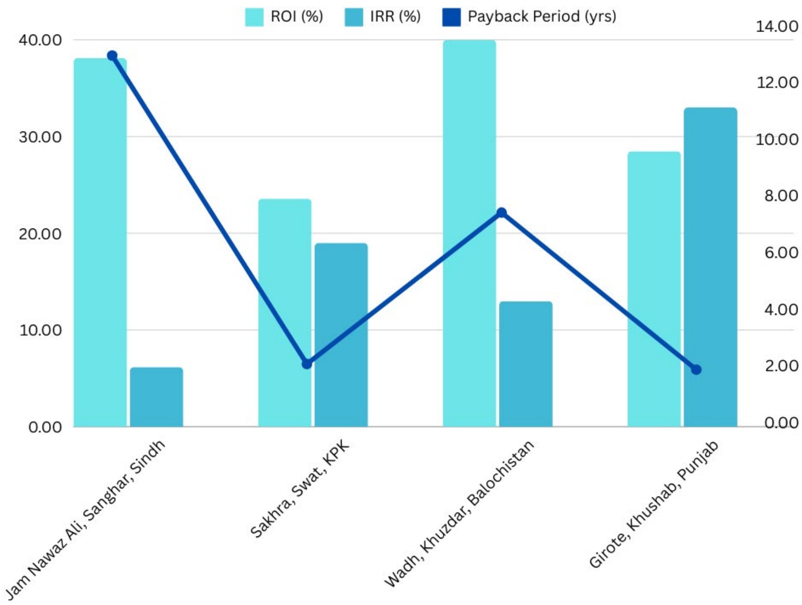


Figure 12. ROI (%) and IRR (%) Vs. Payback Period (Yrs)

Similarly, figure 12 illustrates key profitability indicators for microgrid configurations across the four sites ROI and IRR serve as essential measures of investment profitability, while the payback period reflects the time required to recover initial costs. Among the four microgrid configurations, Jam Nawaz Ali outperforms the others with the highest ROI (40%), a strong IRR (33%), and a short payback period of 2.6 years. This indicates an excellent return on investment and quick recovery of initial costs. Sakhra follows with an ROI of 35%, but its IRR is significantly lower at 12%, and its payback period extends to 3 years. Wadh shows the lowest ROI (5.5%) and IRR (8.5%), reflecting poor profitability despite a short payback period of 2 years. Girote matches Sakhra in ROI (35%) but has a slightly shorter payback period (2.4 years), demonstrating better capital recovery efficiency.

These findings underline the critical importance of optimizing CAPEX, ROI, and O&M costs to ensure the financial viability and sustainability of microgrid projects in different regions.

To build on these insights, the next section explores proposed business models and billing mechanisms that can maximize the profitability of microgrid investments, particularly for Chinese investors.

Chapter: 6

Proposed Business Models and Billing Mechanisms for Chinese Investment in Microgrids

For Chinese investors exploring profitable opportunities in Pakistan's microgrid sector, Private Company-Owned Microgrids and Public-Private Partnerships (PPPs) are recommended as the most viable business models. The choice of an appropriate billing mechanism is pivotal to ensuring the financial sustainability of these projects while maintaining consumer satisfaction. The selection of a billing mechanism should align with the project's operational goals, target demographics, and local regulatory frameworks.

6.1. Private Company-Owned Microgrids

Private company-owned microgrids offer an attractive business model for investors, particularly Chinese companies, by providing full ownership and control over operations and billing mechanisms. [31]

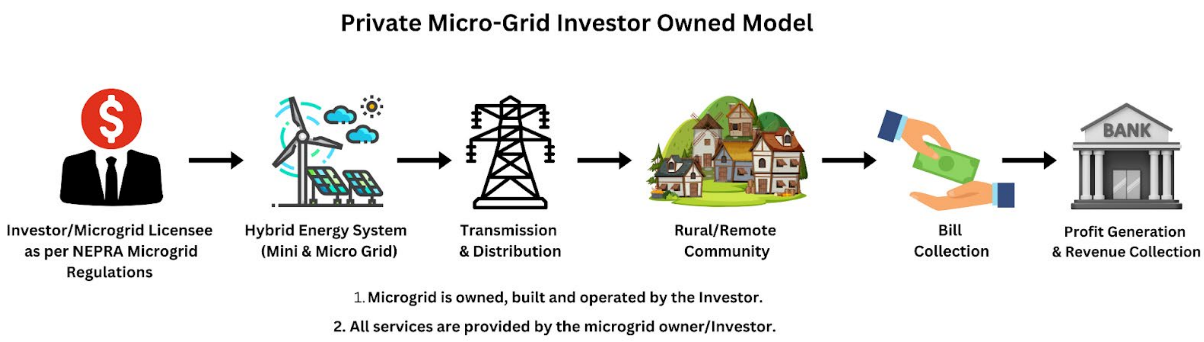


Figure 13. Private Company-Owned Microgrids Investor Model

The model shown in Figure 13 demonstrates that the investor first gets a license from NEPRA for a renewable energy based microgrid, and gets approval for installation. After the successful installation and deployment of the microgrid, according to its highest feasibility, it will arrange the consumer distribution lines of electricity for energy access to unserved communities.Then the billing mechanism is developed (which is discussed in detail below). After the billing collection through different methods, the process of profit generation and revenue collection is completed and the investor starts recovering his initial capital in the first few years.In this way, microgrids are owned, built and operated by the investor, with service provision limited to the private investor and owner.

6.1.1. Billing Mechanism for Private Company-Owned Microgrids

Private company-owned microgrids are highly profitable due to their flexibility in setting competitive tariffs and streamlined decision-making without government oversight. Features like real-time metering, dynamic tariffs, flexible payment options, and effective revenue management further enhance profitability, making them a promising solution for remote and underserved markets. The following sections provide a detailed explanation of the billing mechanisms and the associated processes.

a. Electricity Metering, Data Transmission & Data Processing

The first step is deployment of smart meters at consumer premises to monitor real-time electricity usage, for accurate and up-to-date energy consumption data through wireless data transmission. This data will be transmitted to and collected via an online data cloud platform with a dedicated communication network. As soon as the data is received and collected, it is then stored and processed with precise energy consumption tracking to facilitate efficient and accurate billing processes.

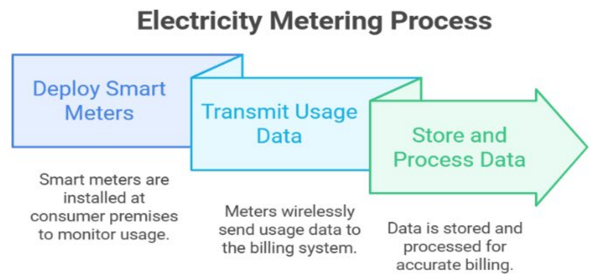


Figure 14. Electricity Metering and Billing Data Collection

b. Tariff Calculation & Consumer Segmentation

The next step is tariff calculation for the various consumer groups in the rural community such as residential, small-scale businesses and agricultural activities. Tariff adjustment should be based after analyzing the operational costs, market demand, and fuel prices For an effective cost recovery, justified and affordable tariff based on the average wages should also be considered. In this way, tariff adjustments will balance profitability with affordability to meet the needs of rural communities effectively.

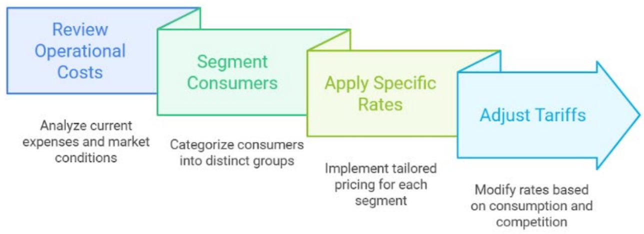


Figure 15. Tariff Calculation and Adjustment

c. Billing Setup and Payment Collection

Prepaid and postpaid billing systems should be implemented to streamline payment collection and ensure efficient energy usage tracking and balance management. Prepaid billing enables upfront payments, facilitating effective cost recovery, while postpaid systems generate monthly invoices based on accurate consumption data, delivered through SMS, email, or physical copies. To enhance accessibility and convenience for rural consumers, multiple payment options should be offered, ensuring flexibility and ease of use.

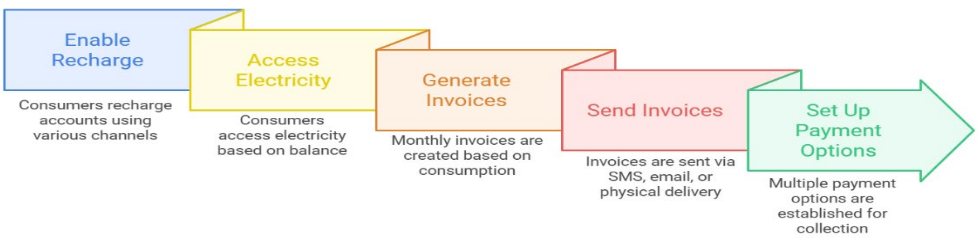


Figure 16. Billing Setup and Payment Collection

d. Revenue Management

Payments collected from consumers will primarily fund the ongoing operations and maintenance of the microgrid. Advanced analytics will monitor payment behaviors, optimize collection strategies, and minimize default risks, ensuring efficient cost recovery. In the initial years, revenues will focus on repaying the capital investment. After the payback period, subsequent revenues will serve as profits for Chinese investors, accounting for replacement costs and supporting the long-term sustainability and scalability of the microgrid to meet growing energy demands.

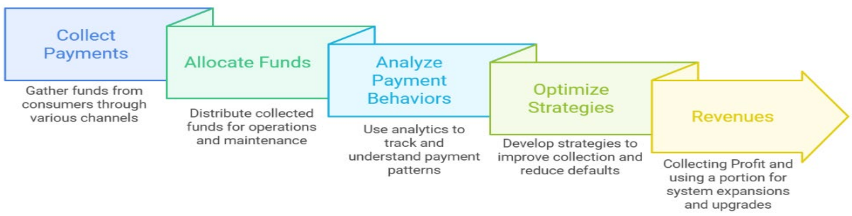


Figure 17. Revenue Management

While private company-owned microgrids offer full ownership and operational control to investors, the next section based on Public-Private Partnerships (PPPs) presents an alternative approach that leverages collaboration between government entities and private stakeholders to share risks and resources for microgrid deployment.

6.2. Public-Private Partnerships (PPPs)

Public-Private Partnerships (PPPs) are a collaborative model that combines the resources and expertise of public entities, such as government agencies, with private investors and energy companies.

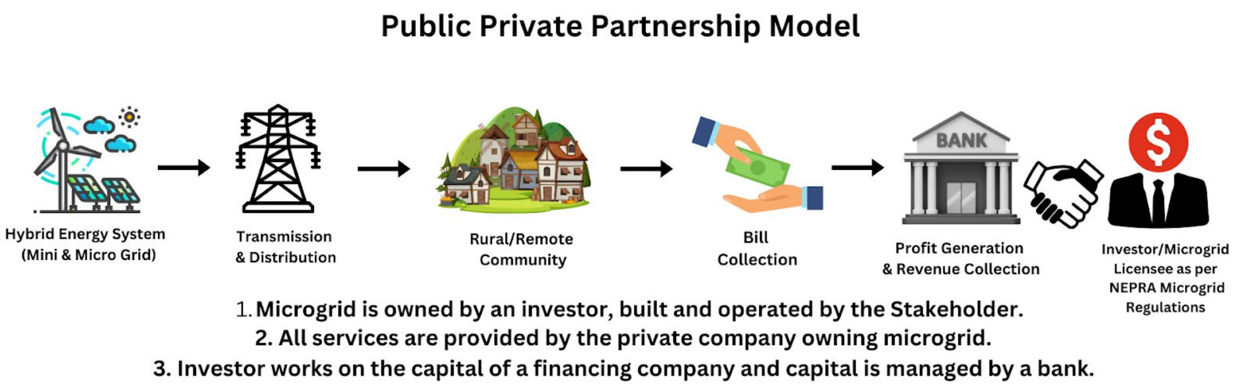


Figure 18. Public Private Partnerships Investor Model

PPPs create an efficient framework in maintaining public oversight and accountability. This is because of the risk sharing aspect. [32] The investor is not vulnerable to the challenges associated with the installation and investment for a microgrid that he plans for a specific site or community. As shown in Figure 18, the microgrid is owned, built and operated by a private company being a stakeholder in the project. The private company will get the microgrid license from NEPRA for deployment and operation of the microgrid. After deployment of microgrids, the company will develop the distribution network for streamlining energy access to the consumer. After the development of the whole infrastructure, the unserved community will get access to electricity. Each month the bill will be collected via postpaid or prepaid method. The financing company being the investor will get their revenue and capital will be managed by the bank, and the private company will either get paid their service and operations cost or will be paid according to their share in the microgrid.

6.2.1. Billing Mechanism for Public-Private Partnership (PPP) Microgrids

This practical process leverages collaborative governance to enable accurate metering, subsidized tariff structures, integrated billing systems, and transparent revenue sharing. By combining public oversight with private sector efficiency, it ensures affordability for rural consumers, sustainable operations, and alignment with national energy goals while fostering long-term profitability and growth.

a. Electricity Metering

For installing meters, public and private stakeholders should collaborate to co-finance the installation to finance (AMI/AMR) advanced metering system at consumer end to enable accurate and real-time tracking of electricity usage while distributing the financial burden between both sectors. Regular government audits of meter readings will be conducted to verify data accuracy, minimize billing errors, and enhance transparency. This approach will foster consumer trust and ensure compliance with regulatory standards, ensure data accuracy and reduce billing errors, ensuring transparency, and hence, contributing to the overall effectiveness and reliability of the microgrid system.

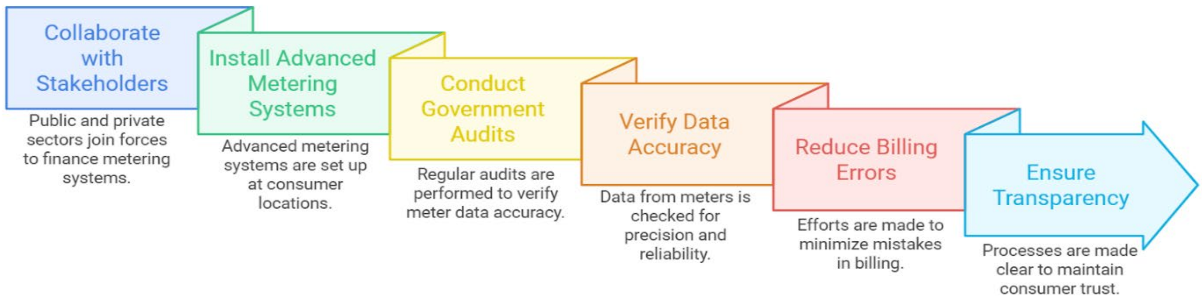


Figure 19. Electricity Metering & Billing Data Transparency

b. Tariff Application

For tariff structuring, subsidized tariffs will be applied for vulnerable populations, with the government covering the difference between the actual cost of electricity and the subsidized rate. This ensures affordability and promotes social equity by making energy accessible to low-income households for effective cost recovery. A hybrid tariff system will be implemented, where basic energy consumption will be priced at a subsidized rate for all users, while usage beyond a specified threshold will be billed at higher rates. This dual approach not only supports equitable access to electricity but also encourages energy conservation and helps balance operational costs, ensuring the financial sustainability of the microgrid.

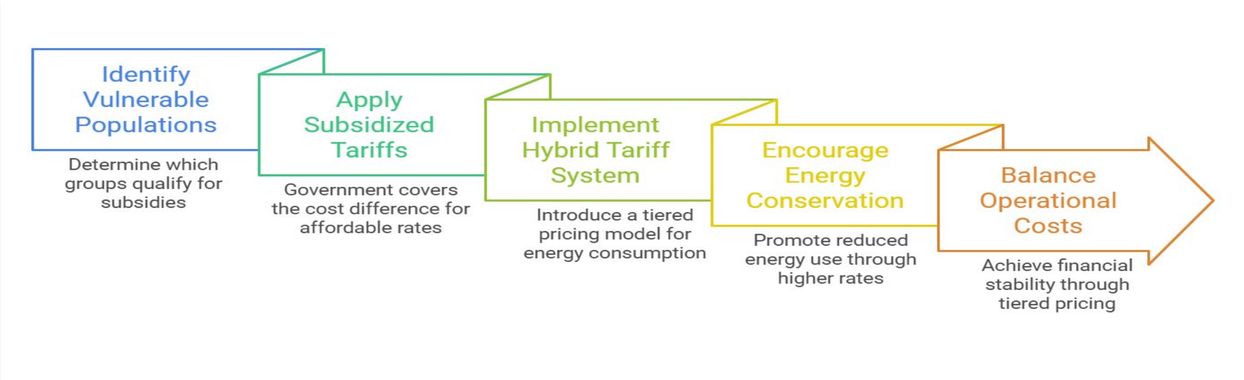


Figure 20. Tariff Adjustment & Application

c. Billing and Payment Collection

An integrated, centralized billing platform will be established to connect private operators and local government agencies, streamlining invoicing, payment collection, and reporting. This system will reduce administrative costs, enhance accuracy, and improve coordination between stakeholders. For payment collection, a cross-subsidization model will be implemented, where higher tariffs charged to commercial users offset the subsidies provided to residential consumers. This approach will ensure the financial sustainability of the microgrid while maintaining affordability for low-income households, balancing profitability with social equity.

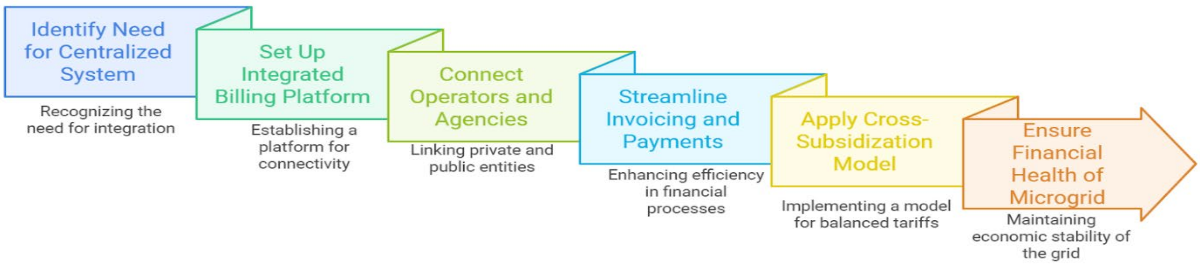


Figure 21. Centralized Billing and Payment Collection

d. Revenue Distribution

Clear revenue-sharing agreements will be established between public and private partners, initially outlined in the PPP contract, ensuring that revenues from electricity sales are distributed according to pre-agreed terms. This arrangement provides financial benefits to both stakeholders and fosters mutual accountability. The government oversees the transparent allocation of subsidies, ensuring they reach intended beneficiaries, while private operators manage funds for ongoing operations, system maintenance, and future investments. This division of responsibilities will promote operational efficiency and ensure that subsidies are effectively applied to support the microgrid's sustainability and growth.

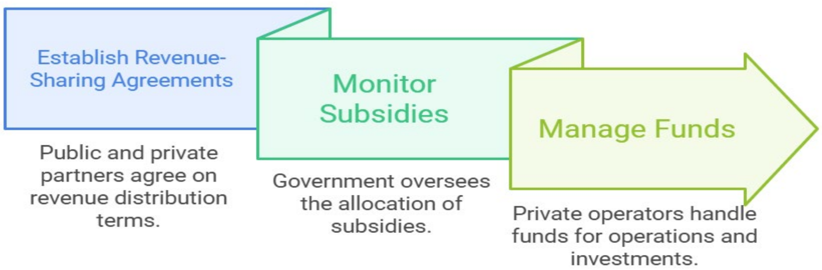


Figure 22. Tariff Distribution

Table 6. Comparison of Functionality of Proposed Billing Mechanism

Comparison of Functionality of Proposed Billing Mechanism		
Aspect	Private Company-Owned	Public-Private Partnerships (PPPs)
Metering	Fully managed by the private company.	Shared metering systems with government oversight.
Tariff Setting	Market-driven tariffs for flexibility and profitability.	Subsidized tariffs co-designed with the government.
Payment Collection	PAYG (Pay-as-you-Go) and postpaid systems directly managed by the company.	Payment platforms co-managed by public and private entities.
Revenue Management	Entirely reinvested by the private company.	Revenue shared between private investors and government.
Risk	Full risk borne by the private company.	Risks shared between public and private stakeholders.
Consumer Benefits	Flexible payment options for underserved regions.	Affordable rates and subsidy-backed access.

Chapter: 7

Leveraging China's Global Microgrid Expertise: Opportunities and Lessons for Pakistan

China's global investments in microgrids highlight its leadership in renewable energy technologies and innovative financing mechanisms. Case studies from Africa, Southeast Asia, and the Pacific Islands showcase strategies that Pakistan can adapt to address its rural electrification challenges. Key lessons include:

1. Public-Private Partnerships (PPPs)

China's success in Ethiopia's Green Energy Microgrid Project shows the value of PPPs. [33] By collaborating with private firms and using concessional loans, this model can attract investment easily while reducing financial risks. The collaboration between the Ethiopian government, Huawei, and the Export-Import Bank of China illustrated how tailored funding and technological partnerships can address rural energy needs.

2. Localized Capacity Building

In Laos, Chinese investment included training programs to enhance local capacity, ensuring sustainability and reducing operational dependencies. [34] This model can be adopted to apply similar strategies to train local engineers and technicians in microgrid operations, reducing the reliance on foreign expertise over time.

3. Community-Centric Models

Myanmar's community-owned microgrid projects underline the importance of engaging local communities. [35] This approach empowered locals with economic opportunities and ensured energy access in conflict-prone areas. Similarly, in Pakistan's remote or volatile regions, it can foster community ownership that will improve project acceptance and security. This is already in practice in unserved areas of Pakistan, like areas in FATA and Tharparkar.

4. Hybrid and Climate-Resilient Systems

The solar-wind hybrid systems deployed in Fiji demonstrate the importance of designing microgrids to withstand climatic challenges. [36] With many areas in Pakistan vulnerable to extreme weather, hybrid microgrids that integrate diverse renewable sources can ensure reliability and disaster resilience. In Sindh, locals consider installing nano-scale wind and solar to receive the benefits of energy independence from the grid.

5. Strategic Financing and Aid Integration

China's integration of financial tools, such as concessional loans and support from international funds like the Green Climate Fund, enabled projects in underdeveloped regions. Pakistan can explore partnerships with international development banks and secure foreign aid to offset high initial costs for microgrid projects, especially for areas that have been affected by floods, droughts and extreme climate conditions due to global warming.

6. Targeted Use Cases

Chinese projects like Fiji's microgrids for disaster relief and healthcare facilities highlight the strategic targeting of critical sectors. Pakistan can prioritize microgrid deployment for schools, hospitals, and agriculture in rural areas, aligning with national development priorities while ensuring project viability. Also, communities who have been displaced or face issues of outmigration due to natural calamities, could acquire energy access in the form of microgrids.

By adopting strategies focused on tailored financing, community engagement, capacity building, and climate resilience, Pakistan can effectively deploy microgrids while providing Chinese investors with lucrative opportunities in its energy sector. China's leadership in renewable energy technologies, producing 70% of global solar panels and 80% of batteries, positions it as an essential partner for Pakistan, where 50 million people remain off-grid. Investment models like Build-Operate-Transfer (BOT) and Independent Power Producer (IPP) arrangements offer Chinese investors cost recovery through energy sales, supported by incentives such as carbon credits and tax benefits under CPEC. These investments would not only help address Pakistan's energy deficit but also strengthen bilateral economic ties, with capacity-building initiatives and localized production enhancing project execution while bolstering China's geopolitical influence and renewable energy leadership.

Chapter: 8

Policy Recommendations for Advancing Microgrid and Minigrid Development in Pakistan

To overcome barriers and challenges facing stand-alone micro-grids' implementation in the rural and remote areas of Pakistan and to attract Chinese Investments in this sector, this section presents targeted and data-driven policy recommendations. These recommendations are designed to overcome regulatory, financial, social, and technical challenges and accelerate the deployment of sustainable mini- and microgrids.

1. Reforming Regulatory Frameworks

The 5 MW capacity cap and 10-year license term for stand-alone microgrids having a 25 year project life set by NEPRA needs to be reviewed, and adoption of IEEE 1547.4 guidelines to standardize design, interconnection, and planning processes needs to be carried out. The government must prioritize transmission upgrades to ensure compatibility with renewable-based microgrids and establish stringent cybersecurity standards like ISO/IEC 27001. Similarly, Environmental Impact Assessments (EIAs) should follow a streamlined and standardized process, modelled on Bangladesh's rural electrification framework, to expedite project approvals.

2. Attracting Investments through Incentives

Introduce tax exemptions for renewable energy equipment imports and offer low-interest loans specifically for microgrid developers. Redirect fossil fuel subsidies toward financing hybrid renewable energy systems. Utilize geospatial analysis tools to identify priority regions for microgrid deployment and ensure that investment decisions are guided by evidence-based energy access data.

3. Driving Adoption of Renewable-Based Microgrids

Provide direct financial incentives, such as subsidies and risk-sharing guarantees, for renewable microgrid deployment. Revise competitive bidding processes to ensure transparency and fairness, prioritizing bids that demonstrate clear community benefits. Invest in research to optimize break-even distances and identify the most cost-effective microgrid configurations for rural areas.

4. Enhancing Billing Systems and Consumer Confidence

Implement tiered tariff structures to ensure affordability for low-income users while maintaining financial sustainability for operators. Deploy advanced metering infrastructure (AMI) and Pay-As-You-Go (PAYG) systems to improve billing accuracy and revenue collection. Strengthen consumer protection regulations to prevent overcharging and build trust between consumers and microgrid operators.

5. Strengthening Public-Private Partnerships (PPPs)

Develop a streamlined approval process for PPP microgrid projects, reducing bureaucratic delays and ensuring performance accountability through clear benchmarks and government oversight. Include mandatory provisions in PPP agreements for community benefit-sharing and transparent revenue reporting. Incentivize private sector participation by offering performance-based financial rewards.

6. Empowering Communities for Long-Term Sustainability

Establish local cooperatives to manage microgrid billing systems and ensure community ownership. Launch targeted awareness campaigns to educate communities about the benefits of microgrids and their role in energy planning. Implement deferred payment options for economically vulnerable households to ensure inclusive energy access.

7. Promoting Innovation and Capacity Building

Fund R&D projects focusing on cost-effective microgrid technologies, including dynamic pricing models and digital billing platforms. Support vocational training programs for microgrid installation, operation, and maintenance, particularly in rural areas, and introduce retention policies to reduce brain drain from the energy sector. Pilot innovative microgrid projects with government subsidies to test scalable solutions.

8. Monitoring, Evaluating, and Refining Policies

Establish a centralized monitoring system to track the performance of microgrid projects against set benchmarks. Conduct regular billing audits and stakeholder feedback reviews to refine regulatory frameworks. Publish completion reports with detailed evaluations and disseminate lessons learned to improve future microgrid deployments.

9. Simplifying Governance and Reducing Bureaucracy

Streamline microgrid project approvals by limiting the number of required departmental clearances to a single window. Standardize application fees across jurisdictions and ensure transparency in all regulatory processes. Create an energy review group within the Planning and Development (P&D) department to oversee microgrid project approvals and performance.

10. Encouraging International Collaboration and Security

Establish partnerships with multilateral donors and green investment funds to secure technical and financial support for microgrid projects. Enhance security protocols for foreign workers, especially in high-risk areas, by deploying specialized law enforcement units. Introduce transparent profit-sharing frameworks and policy guarantees to attract and retain foreign investors under CPEC 2.0.

Conclusion

Microgrids offer reliable, cost-effective, and sustainable energy solutions for off-grid and underserved communities by utilizing region-specific resources. The NEPRA Microgrid Licensing Framework (2022) provides a foundation for investment and innovation, yet challenges such as regulatory barriers, high upfront costs, and social acceptance persist. The financial assessment indicates that all sites analyzed are feasible for microgrid implementation, with each exhibiting varying levels of positive returns. Among the four projects, Jam Nawaz Ali stands out as the best case due to its overall financial and operational efficiency having battery and Solar PV in the microgrid configurations. Among the natural resource-based microgrid configurations, Girote, Khushab, Punjab, which incorporates biomass in its setup, emerges as the most favorable site. This is attributed to its low capital expenditure (CAPEX) and levelized cost of energy (LCOE), combined with a short payback period and a high financial return.

To maximize the profitability of microgrid investments, for ensuring long-term sustainability, flexible billing mechanisms, such as private ownership models for operational autonomy and public-private partnerships for revenue stability, are proposed to enhance cost recovery and efficiency. The development of microgrids, supported by China's expertise, presents a transformative opportunity to address Pakistan's off-grid energy challenges. This approach aligns with the objectives of CPEC 2.0, which emphasizes sustainable and inclusive economic growth through renewable energy investments. By leveraging renewable energy technologies, Pakistan can improve energy access while fostering economic and social development in underserved regions. Community engagement, capacity-building initiatives, and blended financing models can further enhance inclusivity. With the right mix of policies, financing, and community involvement, microgrids can become a cornerstone of Pakistan's clean energy transition.

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