

Mini-Microgrids – Key to Rural Electrification



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It is a stark reflection of the modern era that a significant portion of rural populations globally still lacks access to adequate energy services to meet their basic needs. Despite being a core focus of Sustainable Development Goal 7 (SDG 7), reliable, affordable, and modern energy services remain out of reach for these underserved communities, perpetuating their state of energy poverty.

According to World Bank data (2023), 84% of people without access to electricity globally reside in rural areas. This lack of electricity significantly hinders access to essential services such as healthcare, education, and communication, thereby impeding the ability of rural communities to thrive.

In such isolated regions of developing countries, rural populations continue to rely on traditional energy sources like charcoal, firewood, and kerosene oil to meet their basic needs, such as lighting, cooking, and heating. However, these energy sources are environmentally harmful and pose significant health risks. The World Health Organization (WHO) reports that approximately 4 million deaths annually are linked to illnesses caused by indoor air pollution from cooking stoves using biomass, kerosene, and coal.

According to a report by the Economic and Social Commission for Asia and the Pacific (ESCAP, 2017), due to inadequate electricity access, Pakistani households spend approximately $2.3 billion annually on alternative lighting solutions such as kerosene lamps, gas lights, and battery-operated flashlights.

A major obstacle to electrifying rural regions is the remoteness of power grid networks, which are expensive and complex to expand due to various logistical, financial, technical, socioeconomic, and environmental barriers. Additionally, providing energy access to rural areas is challenging because of their lower electricity demand, which makes extending the central power grid to these areas financially unviable. Nevertheless, the last decade has witnessed substantial progress in global electricity access, which increased from 84% in 2010 to over 91% in 2021, with more than a billion people gaining access. However, this progress falls short of meeting Sustainable Development Goal 7 by 2030.

According to the International Energy Agency (IEA, 2023), as of 2021, about 675 million people remain without electricity, mostly in rural areas. In 2022, the number of people lacking access increased for the first time in 20 years, reaching 685 million. Furthermore, an additional 1.6 billion people live in weak-grid areas without reliable access to electricity. If current trends persist, 660 million people will still be living without Tier 1 electricity access by 2030. Moreover, challenges remain as people with very limited or unreliable electricity access are still considered electrified, with approximately 350 million individuals in Asia and the Pacific experiencing unreliable electricity supply.

Pakistan's energy landscape is equally concerning. As per the ESCAP 2024 report, approximately 23% of Pakistan's population, nearly 50 million individuals, lacks reliable electricity, while 8% have no electricity access at all. Additionally, almost half of the country's population lacks access to clean cooking fuels and technologies. These statistics highlight that the country is grappling with severe energy access challenges and is deeply mired in energy poverty.

A comprehensive Pakistan Energy Survey, titled "Insights into the True Energy Access Situation in Pakistan Based on the Multi-Tier Framework," was conducted in 2021-2022. Supported by the Energy Sector Management Assistance Program (ESMAP) and administered by the World Bank, the survey aimed to assess electricity access and clean cooking solutions using the Multi-Tier Framework (MTF).

Multi-Tier Framework (MTF)

The Multi-Tier Framework evaluates energy access across key dimensions such as capacity, reliability, affordability, and safety, categorizing households into six levels, ranging from Tier 0 (no access) to Tier 5 (full access), as illustrated in Figures 1 and 2.



Figure: 01 Multi-tier Framework
(Source: World Bank Energy Survey, 2024)

CAPACITY	TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
Power Capacity Ratings (minimum in W or daily Wh)		3 W 12 Wh	50 W 200 Wh	200 W 1.0 kWh	800 W 3.4 kWh	2,000 W 8.2 kWh
Supported Appliances		Very low-power appliances	Low-power appliances	Medium-power appliances	High-power appliances	Very high-power appliances
Typical Supply Technologies		Solar lantern	Rechargeable battery, SHS	Medium SHS, fossil fuel-based generator, mini-grid	Large SHS, fossil fuel-based generator, mini-grid, central grid	Large fossil fuel-based generator, central grid

Figure: 02 Tiers of Capacity of Electric Supply
(Source: ESMAP, 2016)

The findings indicate that 97.6% of the population has access to at least one form of electricity, with 89.2% connected to the national grid and 8.5% using off-grid technologies. However, 2.4% of the population remains without electricity access.

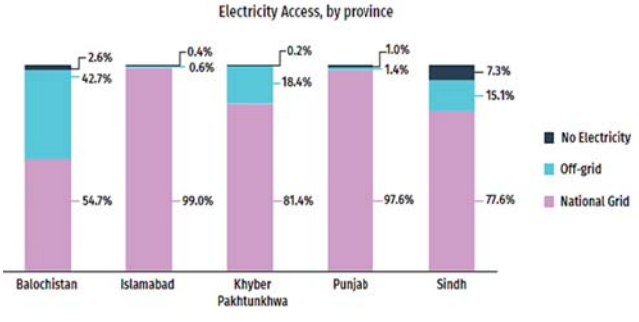


Figure: 03 Energy Access rate in different of Pakistan
(Source: World Bank Energy Survey, 2024)

Urban areas exhibit a higher grid connectivity rate (94.5%) compared to rural areas (86.9%), while off-grid solutions are more prevalent in rural regions (10.5%) than in urban areas (3.5%).

Grid electricity access varies significantly across provinces: Punjab leads with 97.6% grid connectivity, followed by Khyber Pakhtunkhwa (81.4% grid, 18.4% off-grid), Sindh (77.6% grid, 15.1% off-grid), and Balochistan (54.7% grid, 42.7% off-grid). In Sindh, excluding Karachi, grid connectivity drops further to 67.7%, as illustrated in Figure 3.

Despite the expansion of the national power grid, approximately 80% of households still have Tier 2 or lower electricity access, reflecting persistent challenges in cost, capacity, and availability. Nationwide, only 3% of households enjoy Tier 4 or higher access, while 97% remain at Tier 3 or below. Particularly in rural areas, 7.3% of households are at Tier 0, experiencing minimal electricity access due to inadequate capacity or limited availability.

These findings underscore the pronounced electricity access challenges faced by rural and remote regions. Extending the grid to these areas often proves costly and economically unviable, especially in low-demand communities. Investment costs are difficult to justify given the low electricity tariffs. In areas where population density ranges between 26 to 50 individuals per square kilometer and locations are 20 kilometers or more from the nearest grid connection, Distribution Companies (DISCOs) consider grid extension financially impractical. This issue has remained unresolved for decades, presenting a complex and enduring challenge.

Given the scale and intricacy of these challenges, off-grid electrification emerges as the most viable solution for providing electricity to isolated and remote areas. This approach involves standalone power generation systems that leverage renewable energy sources to electrify underserved communities.

Rural electrification not only addresses energy access challenges but also drives significant socioeconomic development. It facilitates access to livelihoods, education, healthcare, sanitation, water supply, agriculture, and business opportunities. Moreover, it creates green jobs, fosters economic growth, promotes environmental conservation, enhances social equity, and improves overall quality of life.

Distributed Energy Resources (DERs)

In this context, Distributed Energy Resources (DERs) offer a practical and innovative solution. These small-scale power generation or storage technologies provide electricity close to the point of consumption. Examples include photovoltaic solar systems, wind turbines, mini-hydro plants, biomass generators, and energy storage systems like batteries.

Recently, small Solar Home Systems (SHS), have emerged as popular standalone off-grid option to electrify rural villages, owing to its low cost, ease of use, and being able to provide essential electricity services, such as lighting, energize a fan and phone charging. Although, it offers a basic viable approach and satisfy incremental improvement, it does not fully address energy poverty due to its limited capacity.

Therefore, the most practical and cost-effective option is to deploy renewable based mini/microgrid off-grid energy schemes using distributed renewable energy sources, to electrify underserved communities trapped in energy poverty. This can be the most viable option for communities with limited or no access to main central power grid because they independently produce and distribute electricity. These localized power grids serve communities, balancing scalability and reliability. They offer a steady power supply, making them ideal for rural electrification. However, they demand significant initial investment and effective management. In this context, harnessing the potential of distributed renewable energy sources in the form of mini-microgrids is an exciting prospect.

Research indicates that Distributed Renewable Energy (DRE) has been estimated to be able to supply electricity to about 500 million people by 2030. This technology not only serves as a clean alternative to dirty diesel generators but also enhances reliability and affordability for its users.

The International Energy Agency report, off-grid solutions will be the most cost-effective way to electrify about half of the world's unconnected population by 2030. Additionally, the groups such as the Asian Development Bank are promoting mini-hydro and solar power generation plants to provide electricity to remote rural regions via mini-grids.

Renewable energy mini-grids

As per the report of International Renewable Energy Agency (2018), renewable energy mini-grids are becoming popular to bridge the electricity access gap, with an estimated 60% of new connections by 2030 powered by renewables, and 40% of these through mini-grids. But to achieve this potential, current levels of deployment need to be scaled up.

From this perspective, the 2006 renewable energy policy mandated federal and provincial authorities to implement regulatory measures promoting off-grid renewable energy solutions, including mini-grids, but progress has been minimal.

It is important for the government and its development partners to support clean energy mini-microgrids, with the potential for future integration into the national grid. This requires establishing an ecosystem that fosters private sector involvement in industry. However, this energy transition journey focused on clean electricity access demands careful consideration. The deployment of renewable mini-grids for off-grid rural electrification encounters a multifaceted challenge, ranging from technical and financial hurdles to social and regulatory barriers.

Technical barriers include the intermittent nature of renewable energy, the need for advanced storage systems, and a lack of local expertise. High initial costs, limited affordable financing, and underdeveloped social engineering ecosystems present significant financial and socio-economic challenges. Regulatory hurdles, such as lack of supportive policies and bureaucratic red tape, further complicate the mini-grid deployment.

Overcoming Barriers to Mini-Grid Adoption

Therefore, in order to address the above challenges and enhance project viability, there is a dire need to leverage technological advancements to reduce costs, explore innovative financing, strengthen social engagement, and advocate for a supportive regulatory framework. These efforts aim to upscale the widespread adoption of mini-grids to accelerate the energy access process, thereby empowering marginalized communities and fostering sustainable development. There is light at the end of the tunnel—the future of mini-microgrids in rural communities is promising due to ongoing technological development, such as improved energy storage, efficient solar panels, and hybrid renewable energy solutions.

DC-based solutions for Rural Electrification

DC technology, once limited, is gaining ground, and DC products are becoming more accessible and efficient. This progress, supported by ongoing research and development, positions DC-based solutions as a novel emerging technology for rural electrification. For instance, DC micro/nano grids offer a viable alternative to small Solar Home Systems (SHS), providing better energy access for electricity and clean cooking facilities efficiently. Additionally, falling solar panel and battery storage prices are enhancing the affordability and viability of off-grid energy schemes like mini-microgrids for rural electrification.

Community energy, where local stakeholders own and manage projects, can play a vital role in this regard. The engagement of the local community helps to understand their needs and concerns and enables their participation in the ownership of local decentralized renewable energy-based projects. These systems provide affordable, reliable power and promote local economic growth, job creation, and energy equity. However, regulatory barriers, high upfront costs, and limited technical capacity hinder adoption.

In this regard, national policies need to prioritize community ownership, streamline regulations, and incorporate risk-sharing mechanisms. Innovative financing like micro-loans and public-private partnerships is also essential to upscale and accelerate the widespread adoption of off-grid energy schemes to address energy access disparities.



Technology transfer and indigenous development are essential for marginalized groups' participation in the energy transition. In this regard, international cooperation is vital for knowledge sharing, capacity building, and resource mobilization. A holistic approach addressing these challenges and leveraging technological innovation and indigenous development, along with global partnerships, is needed to develop sustainable energy solutions for underserved communities.

NEPRA's mini-grid tariff strategy

NEPRA's mini-grid tariff strategy in Pakistan allows bilateral agreements between developers and consumers, offering flexibility but potentially leading to disparities. The model must balance financial sustainability and affordability, considering regional and socioeconomic differences. Policymakers should attract investment while ensuring project viability through innovative financing, targeted subsidies, and stable regulations, such as tax breaks, grants, fair pricing, and market access to off-grid renewable energy projects. This includes mechanisms like feed-in-tariff or net metering programs. The tariff structure should foster local economic growth using tiered pricing or cross-subsidization to ensure mini-grid sustainability and affordability, promoting reliable electricity access and socioeconomic progress in underserved areas.

Conclusion

Based on qualitative analysis of stakeholder consultations and secondary data analysis, it can be concluded that to upscale widespread adoption of mini-microgrid adoption, supportive regulatory frameworks aligned with ARE Policy 2019 are vital for advancing renewable energy microgrids and meeting national energy access targets (SDG 7.1) by 2030. In this regard, the key recommendations include identifying suitable locations with extensive site surveys, industry-academia collaboration to drive innovation and indigenous development, financial viability through targeted funding schemes, and encouraging CSR activities to boost private sector involvement, engaging local communities in decision-making, drive social development, and introducing monitoring and assessment mechanism for impact evaluation to identify policy strengths and weaknesses etc. All these steps can enhance scalability, affordability, and sustainability of mini/microgrids for rural electrification.

Though some initiatives have been taken in this regard, universal access to reliable, affordable and modern energy services (SDG 7) leaves much to be desired. Thus, by addressing energy access challenges comprehensively and adopting sustainability and inclusive policies holistically, the country can pave the way for just energy transition to alleviate energy poverty, promote energy equity and achieve climate resilient energy access for sustainable development.

End Notes

- *Fostering a Green, Affordable and Inclusive Energy Transition in the Impoverished Regions of Pakistan, (UN, ESCAP, 2024)*
- *Policies and Regulations for Renewable Energy Mini-grids, (IRENA, 2018)*
- *Off-Grid Solar Market Trends Report, World Bank/ESMAP, October 2024*
- *Pakistan Energy Survey, Insights into the true energy access situation in Pakistan based on the Multi-Tier Framework (ESMAP, World Bank, 2024)*
- *Renewable Energy for Remote Communities: A Guidebook for Off-Grid Projects*
- *Community Energy Benefits: Powering Universal Wellbeing (IRENA, 2024)*
- *Minigrids and Access to Electricity in SAARC- 2021*
- *Sustainable Mini-grids Solutions for Off-Grid Electrification, Policy Brief, Institute of Polices Studies, Islamabad*
- *ESMAP, Beyond-Connections, Energy Access, Redefined, 2016*
- *IEA, Access to Electricity, SDG-7, Data and Projections – Analysis*
- *UN Environment Programme (GOAL,7)*
- *Others include IEA Yearly Reports, World Bank Statistics, ADB, World Energy Council, ADB SEforALL (website and reports)*

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