FORECASTING OF

RENEWABLE ENERGY RESOURCES

Based on Microgrid and Market Access

ABOUT US

Who we are

We are a dedicated team of researchers and experts who recognize the urgent need for action in addressing climate resilience and energy transition in Pakistan. Our mission is to develop and implement effective policies for cleaner, renewable energy sources like solar and wind, aligning with Pakistan's 2030 goal of 30% renewable energy in its electricity mix. As a multidisciplinary team, we leverage expertise in three key disciplines of study—Energy Systems Engineering, Thermal Energy Engineering, and Electrical Power Engineering—to drive our mission forward. We are united by a shared vision of creating a sustainable and resilient future for Pakistan, where cleaner energy sources play a pivotal role in reducing the nation's vulnerability to climate-related challenges.

What we do

We conduct in-depth, evidence-based research to analyze and improve energy policies in Pakistan. Our focus is on advancing renewable energy solutions and engaging stakeholders to ensure effective policy implementation. Our methodology involves a critical examination of current energy policies to pinpoint areas of improvement and formulate strategies for the widespread adoption of renewable energy sources across various levels.

In line with our commitment to fostering sustainable practices, we have established a fellowship program as part of our broader initiatives that aims to facilitate evidence-based research for promoting energy transition in Pakistan. Through research studies, surveys, and forecasting, we plan to assess various aspects of energy transition, including the adoption of renewable energy technologies and their impact on climate change. Our approach involves active engagement with stakeholders to address their concerns and facilitate the effective implementation of policies, fostering the growth of renewable energy manufacturing and marketing facilities.

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Executive Summary

The Integrated Generation Capacity Expansion Plan (IGCEP) 2022-2031 outlines the aims and targets for expanding and diversifying Pakistan's generation capacity. It emphasizes renewable energy integration, remote area electrification, energy efficiency, and policy support as key goals to achieve a sustainable and reliable electricity supply. In microgrid deployment, the regulatory framework overseen by the National Electric Power Regulatory Authority (NEPRA) plays a vital role. NEPRA has implemented policies and regulations to facilitate the development and operation of microgrid systems. It has established guidelines for licensing, tariff regulations, net metering, and feed-in tariffs to encourage private investment, fair pricing, and the integration of renewable energy sources in microgrids. The aims and goals of the IGCEP are closely aligned with this work on the techno-economic analysis of microgrid deployment. This study contributes to renewable energy integration, remote area electrification, and energy efficiency objectives by evaluating the feasibility and benefits of widespread microgrid deployment. This analysis provides valuable insights and recommendations to support decision-making processes and guide the implementation of the IGCEP.

The importance of energy access for socioeconomic development is well recognized, and access to electricity has been shown to have a positive impact on productivity and economic growth. While progress has been made in increasing global electrification rates, recent years have seen a slowdown in electrification, particularly in remote areas, partly due to the impact of the COVID-19 pandemic. The study focuses on the electrification challenges in countries like Pakistan, India, Bangladesh, and Sub-Saharan Africa, where a significant population still lacks access to electricity. Despite having abundant renewable energy resources in Pakistan, the rural areas face major hurdles in terms of electricity access. The study aims to conduct a comprehensive techno-economic analysis of widespread microgrid deployment in Pakistan's electrical power sector. It seeks to address the technical, economic, and environmental aspects of deploying renewable energy-based microgrids and evaluate the social and economic implications of such deployment. The study also explores policy and regulatory frameworks and provides recommendations to promote the adoption and growth of microgrids in Pakistan.

Also overview of Existing Policies and Proposed Potential Business Models for Remote Area electrification are also proposed. It explores potential business models such as community-owned microgrids, pay-as-you-go systems, energy service companies, and hybrid models. The report recommends aligning policies, establishing financial mechanisms, investing in capacity building, and promoting technology adaptation. By implementing these recommendations, policymakers, investors, and stakeholders can accelerate sustainable electrification in remote areas, fostering economic development and improving quality of life.

Overall, this work and the IGCEP share a common objective of achieving sustainable and reliable electricity access in Pakistan.. everaging microgrid systems and aligning with the regulatory framework and policy goals, this study can contribute to the successful implementation of the IGCEP, promoting renewable energy, improving remote area electrification, and advancing the country's power sector towards a sustainable and resilient future.

Abstract

lHybrid renewable energy systems are often used for rural electrification as an economic-eco-friendly choice. This study analyzes techno-economic, environmental, energy, sensitivity, social, as well as breakeven analysis and investigates how these systems can be used to achieve SDG-7, 11 and 13. On the basis of load profile, geographical locations and climatic conditions, the system is modelled, simulated, and optimized. The optimal configuration and costs for the system components are obtained. The geospatial analysis approach is used for the identification of un-electrified remote areas. Pakistan has a large renewable potential across all its regions; Northern areas have great potential for Hydro, Punjab has potential for PV, and for Sindh and Balochistan, combined PV with wind is the most optimal solution for electrification. PV, hydro with battery is suitable for Gilgit Baltistan, with the least NPC and LCOE among all the regions.

In order to improve the overall efficiency of energy projects, customized business models are being proposed. In the proposed system, it is estimated that the deployment of RE-based MGs may reduce GHG emissions by up to 99%. The social impact assessment investigates how the deployment of energy projects will help the local economy and strengthen GDP. The breakeven analysis of the proposed energy system is also investigated in comparison to the cost of the grid extension scenario. Robust analysis is performed to ensure the technical reliability of the proposed system. Sensitivity analysis investigates uncertain parameter effects across NPC and LCOE. So, it is inferred from the study that the favourable way of rural electrification is the deployment of HRES-based microgrids. Before proposing massive transmission and distribution infrastructure investments for remote Pakistani areas, electricity planners must examine microgrids. Microgrid designs should be affordable in each geographical region to achieve a win-win situation for all stakeholders. Pakistan needs a robust policy and regulatory framework to scale up MG deployment. Finally, a statement is made about further research that will be done to develop this area of research.

1.Introduction

1.1 Access to electricity in the world

Energy is among the most essential criteria of a nation's socioeconomic development. It has been illustrated that access to electricity increases productivity and provides opportunities for economic development. The proportion of the world's population that possessed electricity (SDG-7) increased from 83 to 90.99 percent in 2010 between 2020. Although number of people who lacked access to electricity dropped from 1.20 billion in 2010 to 733 million in 2022, the rate of progress in electrification in recent years has been slow and inconsistent: from 2010 to 2018, an average of 130 million individuals acquired access to electricity each year, however from 2018 to 2020, that data dropped to 109 million. This slowdown of access to electricity in remote areas is affected due to COVID-19 pandemic[1]. From a total population of 773 million, 46.49, 42.8 and 27.88 million reside in the states of India, Pakistan, and Bangladesh, respectively. In Sub-Saharan Africa, there are approximately 576.72 million individuals who do not have access to electricity. Figure 1.1 illustrates the worldwide population having access to electricity (%).

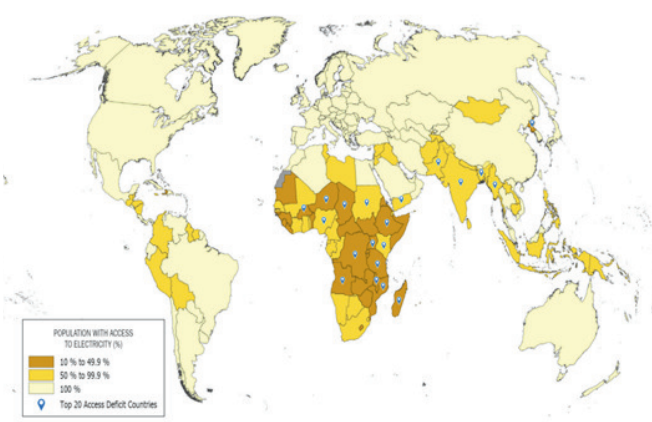

Figure 1.1. *Worldwide population having access to electricity [1]*

electrification challenges in countries like Pakistan, India, Bangladesh, and Sub-Saharan Africa, where a significant population still lacks access to electricity. Despite having abundant renewable energy resources in Pakistan, the rural areas face major hurdles in terms of electricity access. The study aims to conduct a comprehensive techno-economic analysis of widespread microgrid deployment in Pakistan's electrical power sector. It seeks to address the technical, economic, and environmental aspects of deploying renewable energy-based microgrids and evaluate the social and economic implications of such deployment. The study also explores policy and regulatory frameworks and provides recommendations to promote the adoption and growth of microgrids in Pakistan.

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Overall, this work and the IGCEP share a common objective of achieving sustainable and reliable electricity access in Pakistan.. everaging microgrid systems and aligning with the regulatory framework and policy goals, this study can contribute to the successful implementation of the IGCEP, promoting renewable energy, improving remote area electrification, and advancing the country's power sector towards a sustainable and resilient future.

1.2 Background

Already stated statistics indicate that the abovementioned regions lack significant power-producing capacity or energy infrastructure. To fulfil their development goals and sustain their expanding and emerging economies with rapid economic growth. Currently, developing countries confront significant challenges: (i) they are unable to satisfy the energy demand of remote areas individuals, (ii) they are producing electricity from conventional sources of energy due to which they are not contributing to making the world green, and (iii) they are unable to generate economical energy. Pakistan is on the edge of a transitional era, as the country's economic growth has increased, which increases electricity demand. Currently, the country's peak electricity demands 26,945 MW and is projected to reach 41,331 MW by 2031 [2]. In Pakistan, 58% of electrical energy is generated from fossil fuels, which are neither cost-effective nor eco-friendly. 25% of electricity is generated by hydropower and 13% by nuclear power. Currently, less than 4% of energy is generated by renewable energy sources, including 1.8% of wind energy, 0.50% of biogas, and 0.50% of solar energy. Total installed capacity by 2022 and projected power generation capacity are shown in Figure 1.2 Nonetheless, power generation remains between 18,000 and 20,000 MW, resulting in a 5,000–7,000 MW electricity shortfall [2]. By the end of 2031, Pakistan has planned to raise its renewable generation capacity by 30% [3].

The situation in rural areas of Pakistan, as described, is indeed challenging with regard to electricity access. Despite abundant renewable and non-renewable energy resources, many rural communities still lack access to electricity. One of the key reasons for the low electrification rate is the significant rural population, which accounts for approximately 62.5% of the total population [4].

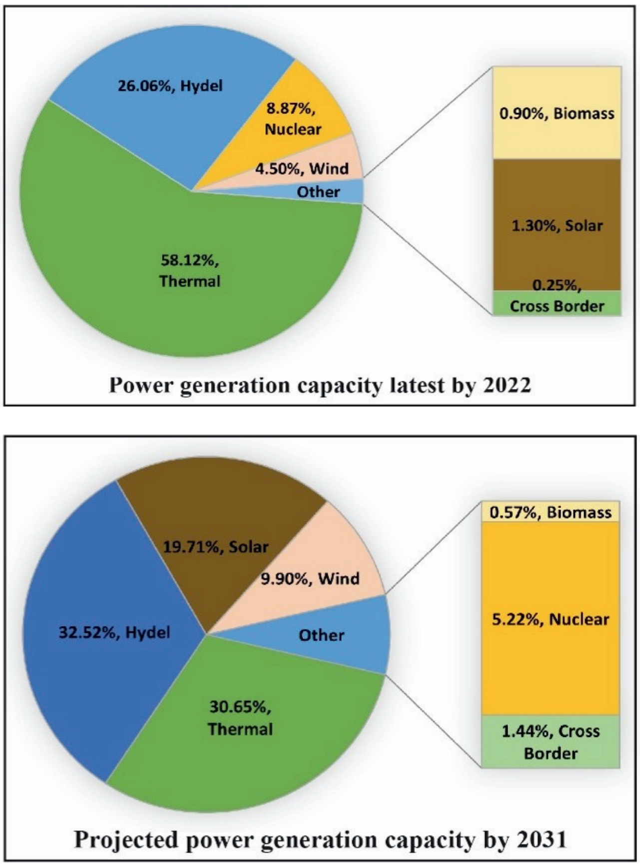

Figure 1.2. *Pakistan's current and projected generation capacity.*

Within these rural areas, about 14.05% of villages remain un-electrified, meaning they do not have access to grid-connected electricity. In the case of rural areas in Pakistan, addressing the electricity access gap is crucial for driving economic growth and improving the living conditions of rural communities. Implementing sustainable and cost-effective solutions, such as off-grid hybrid renewable energy systems, can help overcome the challenges posed by the remote locations and low energy demand in these areas. Figure 1.3 illustrates remote areas without electricity.

Village electrification in rural areas is challenging and expensive due to the low energy demand compared to metropolitan areas. Consequently, installing new transmission lines for these areas is difficult, and policymakers do not expect a transmission network to be established in the near future. Additionally, the absence of policies regarding techno-economic assessments and potential exploitation has contributed to this situation. According to the Asian Development Bank (ADB), electrifying rural parts of Pakistan using an off-grid energy infrastructure, specifically a Hybrid Renewable Energy System (HRES), is the most cost-effective solution. Implementing HRES-based electrification infrastructure offers various benefits, including financial benefits, emission reduction benefits, and energy resource savings. However, the extent of these financial perks can vary due to stochastic (random) nature and climatic or geographic conditions. Exact statistics of village electrification are illustrated in Figure 1.4. It

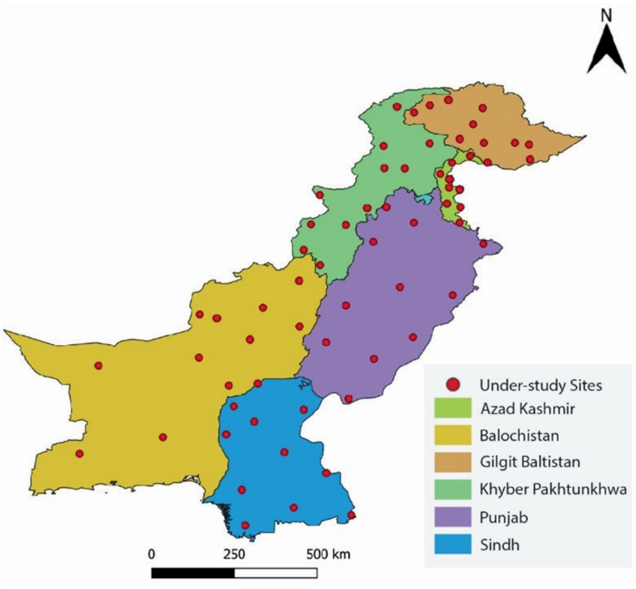

Figure 1.3. *Geographical illustration of the under-study area along selected sites.*

is important to conduct a location-based techno-economic evaluation when designing, planning, and optimizing hybrid systems for village electrification. This evaluation considers various indicators and assessment criteria to analyze the techno-economic impact of renewable energy systems[5]. Several evaluation indicators are commonly used in this analysis, such as NPC, CAPEX, LCOE, IRR, PBP, ROI, and GHG emissions. The social impacts on society, such as improved living conditions, enhanced education, and healthcare services, and increased economic opportunities, should be evaluated. Furthermore, a breakeven grid distance analysis is important, which assesses the distance from the existing grid at which it becomes more cost-effective to implement an off-grid hybrid system instead of extending the grid.

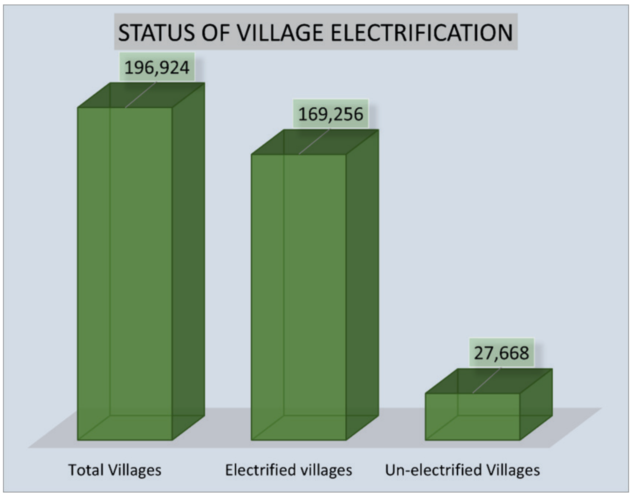

Figure 1.4. *Status of village electrification in Pakistan latest by "State of Industry Report*

1.3 Research questions

The following research questions have been formulated for this study:

1. Can microgrids (MGs) serve as a viable solution to address the challenges of electrification in underserved areas and high electricity rates?
2. What are the potential scenarios for the development of renewable energy-based microgrids in Pakistan?
3. How can the feasibility of microgrid deployment in specific areas in Pakistan be assessed?
4. How can the energy efficiency of microgrid projects be enhanced while considering financial modeling?
5. How can the policy and regulatory framework be effectively utilized to facilitate the widespread deployment of microgrids in Pakistan?
6. What recommendations can be provided to decision-makers to promote the adoption and growth of microgrids in Pakistan?

These research questions are important because they address the potential of MGs to address some of the challenges facing the electricity sector in Pakistan. Unelectrified areas and expensive electricity rates are two major problems that MGs could help to solve. MGs can also help to increase the energy efficiency of energy projects and promote the use of renewable energy.

1.4 The research's motivation

The National Electricity Policy, promulgated by the Government of Pakistan (GOP) in 2021, highlights the importance of sustainability in the country's electricity sector. Unlike some other developing nations, the policy direction in Pakistan is focused on passing electricity prices in full to end-consumers by withdrawing subsidies. This means that the government intends to eliminate or reduce the financial support provided to the electricity sector, leading to increased electricity prices for consumers. The decision to withdraw subsidies and pass the full cost of electricity to consumers has significant implications for the people of Pakistan. Currently, consumers in Pakistan already face high per-unit tariffs for electricity, and the removal of subsidies will likely further increase the financial burden on households and businesses. This policy direction reflects the government's efforts to promote sustainability in the electricity sector by ensuring that the costs of electricity generation, transmission, and distribution are borne by the end-consumers. While the move towards cost reflectivity and sustainability is crucial for the long-term viability of the electricity sector, it is important to consider the potential impact on the affordability and accessibility of electricity for the population. The government will need to implement measures to address the potential hardships faced by vulnerable and low-income households due to increased electricity prices. It is expected that the GOP will also focus on promoting energy efficiency measures and renewable energy sources to mitigate the impact of higher electricity costs and ensure a sustainable and affordable energy future for Pakistan.

Pakistan has indeed great potential for utilizing solar, hydropower, and wind energy resources. However, the utilization of these resources has been limited so far. The good news is that progress is being made in the development of solar energy infrastructure, as the government of Pakistan recognizes the significance of solar energy in the country's energy mix. To encourage investment in renewable energy, the government offers attractive incentives and tax credits. These measures aim to attract nvestors and facilitate the achievement of Pakistan's green energy target by 2030. Subsidies, zero duties on imported items related to renewable energy, and flexible investment plans contribute to making renewable energy an appealing option for Pakistan's energy portfolio. Various types of cutting-edge research are necessary to advance the adoption of renewable energy, particularly for the electrification of rural areas. Researchers have focused on optimizing standalone systems to enhance their efficiency and reliability for powering isolated communities. Additionally, there have been studies exploring integrated energy systems that combine solar, wind, and battery technologies. However, there is a shortage of information on combined renewable energy systems, indicating a need for further research in this area.

Conducting techno-economic feasibility analyses and advancing research on hybrid systems is indeed crucial for Pakistan to make significant progress in electrifying rural areas and tapping into its renewable energy potential. By assessing the technical and economic viability of different energy options and combining multiple renewable energy sources, such as solar, wind, and hydro, Pakistan can develop effective solutions tailored to its specific rural areas. In most of the previous studies researchers assumed constant electrical energy consumption for rural areas throughout the year when designing renewable energy systems (RES). It is important to consider the seasonal variations and specific energy demands of different rural areas to design efficient and reliable systems. Understanding the patterns of energy consumption and demand fluctuations can help optimize the sizing and configuration of renewable energy systems to ensure they meet the specific needs of each location.

Previous studies have mainly focused on areas with similar topography and climatic conditions, which may not accurately represent the heterogeneous nature of sites in a large geographical area like Pakistan. It is essential to conduct research that considers the diverse characteristics of different regions within the country. By examining a wide range of sites and considering their unique attributes, such as solar irradiation, wind speed, hydro potential, and local energy demand, a more comprehensive understanding can be gained, leading to more accurate and effective designs for rural electrification. Moreover, previous studies often employed random site selection and considered the same energy resources for each site. However, site selection should be based on careful analysis, taking into account the specific energy resources available at each location. For example, areas with abundant sunlight may benefit more from solar-based systems, while regions with high wind speeds can leverage wind energy. The overall system performance and economic viability can be optimized by tailoring the choice of energy resources to each site's characteristics.

Additionally, it is important to move beyond generic component selection for each site and consider site-specific factors when designing RES. Factors such as the availability of renewable resources, local energy demand, existing infrastructure, and economic considerations should be taken into account to achieve near-optimal results. Customizing the components and configurations of renewable energy systems based on the unique characteristics of each site can enhance system efficiency and maximize the utilization of renewable resources. Table 1.1 presents an extensive comparison of already carried-out studies and contributions of the proposed research.

So far, the climatic condition of each under-studied site impacts the storage technology's feasibility differently. It is also observed that in some areas of the world, temperature falls below the freezing point of water, which affects the generation of PV and hydel. It also affects the performance of battery storage systems. Thus, serving the load with a stochastic system at a certain period is impossible In majority of researches, default discount and inflation rates are considered, and systems losses are ignored. It's worth mentioning that most studies focused on techno-economic analysis. Not a single study has been conducted which help in the field of energy efficiency by setting allocation methods and using financial resources in the project.

Regarding the research gap and need for electrification in remote areas of Pakistan, the current study aims to conduct an in-depth techno-economic-environmental feasibility analysis of various combinations of stand-alone PV-wind-hydro-DG-battery-Fuel cell-based renewable energy systems. It would eventually result in an improvement in the standard of living of the locals, an uplift in the socioeconomic position of the rural areas, and long-term growth in Pakistan's gross domestic product (GDP).

1.5. Objectives

The comprehensive analysis conducted in this study focuses on the widespread deployment of Microgrids (MG) in Pakistan. The study contributes to the field of energy systems by introducing innovative methods and addressing various aspects related to techno-economic analysis, social impact, environmental analysis, break-even grid distance, sensitivity analysis, and comparative evaluations. Here's a breakdown of the contributions outlined in the study.

1. This study introduced a novel method for analyzing energy systems using geospatial information and simulated data. Moreover, the study focuses on techno-economic analysis, which contributes to the field of energy efficiency by establishing techniques for allocating and utilizing financial resources in the project.
2. This study presents a social analysis of the HRES program to evaluate human development and social acceptance. The rural unemployment problem has been tackled through employment creation and the development of local transportation infrastructure. Further environmental analysis and reduction in carbon emissions are analyzed using RETScreen Expert.
3. The circular break-even grid distance is investigated to determine MG's feasibility and effectiveness.
4. Improved sensitivity analysis is analyzed independently using the HRES model to provide customers, investors, and researchers with the optimal solution. The optimized system's seasonal energy balance and HRES power output are analyzed.
5. Performed comparative comparisons between proposed MG's based on LCOE and NEPRA-set tariffs.

This study provides policy implications for the nationwide implementation of hybrid renewable energy systems. It will also assist existing energy policies, such as the IGCEP and ARE Policy 2019, to increase the proportion of renewable energy in the current energy mix through 2030 and 2047.

1.6. Literature review

In the literature, various authors have proposed RE-based MGs as a substitute for fossil-fuel-based systems for off-grid applications or rural electrification, where RE sources are available. As a result of the stochastic nature of RE sources, storage devices for energy are crucial for renewable energy systems. This scenario emphasizes a battery storage system[6].

To assure cost-effectiveness and stability under sustainable energy indexes, Zhang et al. [7] suggest optimization of hybrid diesel-solar-battery energy system for smart building electrification using a thorough optimization model based on efficient EMS and a new meta-heuristic search approach. Han et al. [8] proposed a PV/battery combination framework according to load demand and roof area for domestic consumers in Switzerland. The PV/battery combination has a larger NPC value than the standalone PV. For office buildings in China's solar resource zone, Zou et al. [9] proposed an optimized design of a hybrid solar/battery system taking three uncertain factors into account.

Chauhan et al. [10] explored the techno-economic viability investigation on implementing an integrative PV/wind/biomass/hydro system with a battery as backup for the un-electrified rural area of India situated in Chamoli to support cooking and electrical energy demand. In his investigation, the author also emphasizes social factors, such as the number of jobs created annually and the breakeven grid distances. Based on site-specific attributes, supply of resources, and in the context of cheap and clean green energy (SDG-7), Kumar et al. [11], Chatterjee et al. [12], and Krishan et al. [13], [14] Investigated hybrid model having PV/wind/DG/hydro/battery storage systems for rural areas in India based on NPC, LCOE, GHG emissions, and highest renewable fraction. Bertheau et al. [15] employ geospatial analysis and energy system modeling to reduce the lack of data scarcity and uncertainty about the number and locations of islands that don't have electricity and their potential for renewable energy. This methodology helps in identification of un-electrified islands, model energy, and simulate 100% RE systems. Key information for energy planning can be derived using the presented tool, such as electrification type (stand-alone, grid-connection, mini-grid), distribution system network design, increased upstream generating needs, power production costs, and dispatch strategies of off-grid systems [16].

An article by Tsurkan et al. [17] systematizes insights on potential business mechanisms for integrating projects in boosting the energy efficiency of the regional economy, as well as examining the challenges associated with their applications. The authors investigated numerous financial and organizational frameworks for energy-efficient initiatives, including public-private partnerships, municipal-private partnerships, and the Local Initiatives Support Program.

1.6.1 From Perspectives of Pakistan

Pakistan possesses a plethora of different renewable resources. The North and Western areas of the nation have great potential for PV, hydroelectric, and wind energy. Similarly, the Southwestern region has a good solar profile, resulting in a perfect location for constructing residential and commercial-scale solar systems. Some significant studies on techno-economic assessment to recoup power deficiency issues have been reported in the literature. For example, considering many objectives, Habib et al. [18] optimized the stand-alone hybrid wind/DG/battery systems design using a model predictive control (MPC) approach. To fulfil the load demand of a community in the D.I Khan district, Fahad et al. [19] investigated the scalability of a system and its techno-economic viability. The electrical and agricultural loads of a village in the Punjab were recently evaluated by a techno-economic evaluation performed by Shahzad et al. [20]. Similarly, the techno-economic feasibility studies of various PV/wind/hydro/battery-based hybrid system configurations for different sites across GB is conducted by Mazhar [21]. In addition, the study examined GHG forest absorption analysis.

Tahir et al. [4] conducted a study in Balochistan, Pakistan, suggesting using an off-grid energy system that combines PV and hydrogen technologies to provide electricity to rural households. This proposed energy system was found to be viable both economically and technically. The researcher also performed a break-even study to compare the system's cost to that of a grid extension scenario and a robustness analysis to confirm the system's reliability. Hence, fuel cells can be viable for a RE-based system. The fuel cell generates power from hydrogen when RE sources are insufficient. Fuel cells are good energy storage devices due to their efficiency, low maintenance, and low GHG emissions [22]. Ceran et al. [23] evaluated the cost-benefit analysis of solar, wind and fuel cell-based system for three different type of loads, which proved cost-effective. It is also investigated whether FC has the potential to serve load when the generator is down for a long period.

Nawaz et al. [24] present an integrated decision-making paradigm for techno-economic-environmental sustainability and optimum size of renewable-dominated hybrid independent MG's in KPK to minimize LCOE and NPC. In addition, a comparative analysis of LCOE, dispatch techniques, and Fuel-cell based systems is conducted. In addition, environmental assessment, including quantitative analyses of carbon absorption and sensitivity analyses for several uncertain variables, are also investigated. Iqbal et al. [25] aims to develop a hybrid (PV/Battery/Grid) system for University in Muzaffarabad, AJK. Since both systems serve the same load, the results for the proposed and existing systems are compared. Solar energy reduces the on-grid hybrid system's LCOE to Rs.0.251/kWh.

Ref.	Yr.	CT	Tool	Analysis type					Load	OGD	Technologies						Objective function			Explicitly considered parameters					Robustness		SA	BED	FM
				GS	T	E	E	S			PV	W	H	DG	FC	BSS	NPC	CAPEX	LCOE	IRR	ROI	PBP	EE	RF	CSF	UML			
[10]	2015	IND	HOMER		✓	✓		✓	CMT, CML	No	✓	✓	✓			✓	✓		✓								Yes		
[26]	2019	CND	HOMER		✓	✓			RSD	No	✓	✓			✓	✓	✓		✓						✓		No		
[24]	2019	IND	HOMER		✓	✓	✓		RSD	No	✓	✓		✓		✓	✓	✓	✓	✓	✓	✓		✓			No	✓	
[27]	2020	PAK	HOMER		✓	✓			RSD	Yes	✓			✓		✓	✓	✓	✓						✓		Yes		
[28]	2020	MLY	iHOGA, Simulink		✓	✓	✓		CMT	No		✓		✓		✓	✓	✓	✓				✓				No		
[15]	2020	PHP	HOMER		✓	✓			CMT	Yes	✓	✓				✓	✓	✓	✓				✓	✓			No		
[29]	2021	MCO	ESCEA, SAM		✓	✓			RSD	No	✓	✓				✓	✓		✓						✓		No		
[30]	2021	IND	GOA, PSO		✓	✓	✓		RSD, CMT	Yes	✓		✓			✓	✓		✓						✓	✓	No		
[21]	2021	PAK	HOMER		✓	✓	✓		CMT	Yes	✓	✓	✓	✓		✓	✓		✓				✓	✓			No		
[31]	2021	AUS	HOMER		✓	✓			CMT	No	✓			✓		✓	✓		✓				✓	✓	✓	✓	Yes	✓	
[32]	2022	TRK	HOMER		✓	✓			RSD	No	✓	✓		✓		✓	✓	✓	✓	✓	✓						Yes	✓	
[24]	2022	PAK	HOMER, RetScreen		✓	✓	✓		RSD	Yes	✓	✓	✓	✓		✓	✓		✓	✓		✓			✓	✓	Yes		
[4]	2022	PAK	HOMER		✓	✓			RSD	No	✓	✓			✓		✓	✓	✓				✓	✓	✓	✓	Yes	✓	
[33]	2022	IND	HOMER		✓	✓	✓		CMT	No	✓	✓		✓		✓	✓	✓	✓					✓	✓	✓	Yes		
[25]	2022	AJK, PAK	HOMER		✓	✓	✓		INL	Yes	✓			✓		✓	✓	✓	✓								Yes		
[PS]		PAK	HOMER, Retscreen	✓	✓	✓	✓	✓	RSD	Yes	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Yes	✓	✓

Table 1.1. *Summary of major studies carried out and contribution of this research.*

Note: CT: Country, CND: Canada, IND: India, MCO: Morocco, MLY: Malaysia, TRK: Turkey, AUS: Austria, PHP: Philippines, PAK: Pakistan, T: Technical, E: Economical, E: Environmental, S: Social, RSD: Residential, CMT: Community, INL: Industrial, CML: Commercial, PV: Photovoltaic, W: Wind, H: Hydro, DG: Diesel generator, FC: Fuel cell, BSS: Battery storage system, NPC: Net Present Cost, CAPEX: Capital Expense, LCOE: Levelized Cost of Energy, IRR: Internal Rate of Return, ROI: Return on Investment, PBP: Payback Period, EE: Excess Energy, RF: Renewable Fraction, CSF: Capacity Shortage Fraction, UML: Unmet Load, SA: Sensitivity Analysis, BED: Break-even Grid Distance, FM: Financial Mechanisms, PS: Present Study.

2. Methodology

The study was conducted sequentially, employing different research methodologies to answer each research question. The study conducted a literature review and textual/content analysis to examine the significant impact of microgrids (MG) in the regions of South Asia and Africa. The focus was on understanding the technical and economic interactions of MG deployment in Pakistan and prospective customers of MG's. The research employed qualitative analyses to develop two possible scenarios and collected data to simulate and evaluate the feasibility of MG development. To validate the collected data, multiple sources were used. The research team employed various methods for data collection, including survey questionnaires, interviews, and site visits. These approaches aimed to gather comprehensive and reliable information to support the analysis and evaluation of different scenarios.

To determine the feasibility and business viability of MGs in specific scenarios, a techno-economic analysis was conducted using HOMER-Pro. It is a dedicated optimization tool for analyzing microgrids. It allows for the assessment of technical and economic factors to understand the performance and potential profitability of MG deployment. Overall, the study utilized a combination of qualitative analyses, data collection methods, and techno-economic analysis to gain insights into the impact, feasibility, and business viability of microgrids in the context of South Asia and Africa, with a specific focus on Pakistan.

The research processes, tools and techniques used during the study are briefly described

- **Data Collection**

In addition to conducting a qualitative analysis, the study also collected numeric data for the techno-economic analysis. The nature and necessity of the data determined the selection of various sources for data collection. These sources included relevant international and national publications, journals, and reports. Numeric data was crucial for the techno-economic analysis as it provides quantitative information that can be used to assess the technical and economic feasibility of microgrid deployment. This data could include parameters such as electricity consumption patterns, generation costs, equipment costs, load profiles, and financial indicators. Qualitative data, on the other hand, was also collected and reported in the document.

Qualitative data provides descriptive information, opinions, and insights that help contextualize the findings of the study. This data could be gathered through interviews, observations, and analysis of documents such as project proposals, case studies, or expert opinions. By combining both qualitative and quantitative data, the study aimed to provide a comprehensive understanding of the impact, feasibility, and business viability of microgrids in South Asia and Africa, specifically focusing on Pakistan.

- **Literature Review**

In order to conduct the techno-economic analysis, the study referred to a range of research papers covering topics such as techno-economic analysis, energy modeling, renewable energy resources, grid resiliency, system stability, and protection issues. These research papers provided valuable insights and methodologies for evaluating the technical and economic aspects of microgrid deployment. In addition to research papers, the study also examined important policy documents that are relevant to microgrid development. These policy documents included the ARE Policy 2019, National Electricity Policy 2021, IGCEP 2021, and NEPRA (Microgrid) Regulations 2021. These policy documents outlined the regulatory framework and guidelines pertaining to microgrids in the respective regions.

Furthermore, the study followed a scientific approach by studying and conducting various research articles. This scientific methodology involved a systematic and rigorous analysis of existing literature, data collection, and interpretation to ensure the validity and reliability of the study's findings. By considering a wide range of research papers, policy documents, and conducting the study scientifically, the research aimed to ensure a comprehensive and evidence-based analysis of the techno-economic aspects of microgrid deployment in South Asia and Africa, with a focus on Pakistan.

- **Survey**

In the study, data collection was conducted through a survey using a questionnaire. The questionnaire was designed to gather information from students and officials relevant to the research objectives. To distribute the questionnaire, a Google Forms link was shared with the target participants. Using Google Forms as a platform for the questionnaire allowed for convenient and efficient data collection. Participants could access the questionnaire through the provided link and provide their responses electronically. The questionnaire itself can be found in Annexure-I of the report, providing readers with a reference to the specific questions asked.

- **Interviews**

In addition to the survey questionnaire, the study also conducted one-to-one correspondence with concerned persons and experts in relevant offices such as PDO (Pakistan Development Organization), PEDO (Pakistan Energy Development Organization), AJKED (Azad Jammu and Kashmir Energy Department), IESCO (Islamabad Electric Supply Company), and NEPRA (National Electric Power Regulatory Authority), among others. This one-to-one correspondence involved direct communication and interviews with individuals who hold expertise or have direct involvement in the field of microgrid deployment and related activities. By engaging with these experts, the study aimed to gather in-depth insights, opinions, and firsthand information on various aspects of microgrid development, including technical, economic, regulatory, and policy-related factors.

The input obtained through one-to-one correspondence with concerned persons and experts played a crucial role in enriching the qualitative analysis and enhancing the overall understanding of microgrid deployment in South Asia and Africa, specifically in Pakistan. By combining the survey questionnaire data with insights from experts and officials, the study aimed to provide a comprehensive and well-rounded analysis of the feasibility, business viability, and impact of microgrids in the target regions

- **Textual Analysis**

The research methodology followed during the study can be summarized as per Figure 2.1. The flowchart illustrates the step-by-step process that was undertaken to conduct the research. The methodology framework for techno-economic planning and sustainability assessment of renewable hybrid standalone microgrid infrastructure in Pakistan is designed to address the country's energy crisis and leverage its potential for solar power installations. Pakistan is experiencing an energy crisis, as per the literature, the most practical countries for installing solar power plants.

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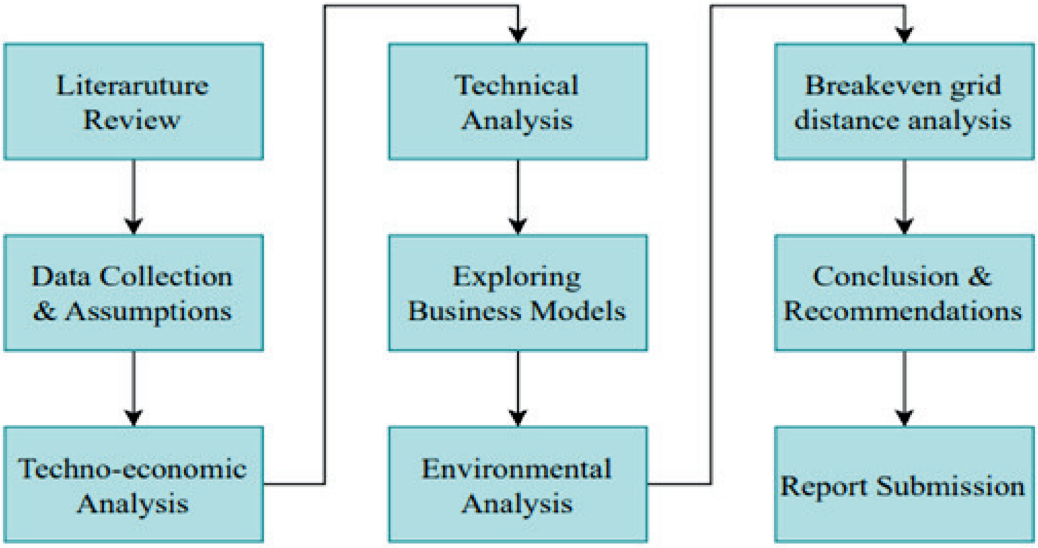


Figure 2.1. *Summary of major studies carried out and contribution of this research..*

2.1 Resources data

2.1.1 Solar radiation and temperature data

To accurately model hybrid systems, real-time solar radiation data is crucial, particularly for solar energy modules. In Pakistan, although ground-based solar measurement stations funded by the World Bank are available, they may not cover all the sites under study. In such cases, researchers have utilized built-in hourly profile datasets from NASA databases to simulate different hybrid systems [34]. The satellite-based data provided by NASA is considered acceptable in the absence of on-ground data, and it has been widely used by researchers in their studies [35]–[38]. It is worth mentioning that when utilizing satellite-based data, it is essential to validate and calibrate the results against any available ground-based measurements or other reliable sources. This helps ensure the accuracy and reliability of the simulated data and the subsequent analysis and design of hybrid systems.

The average monthly solar radiation and monthly average ambient temperature of different regions of Pakistan are shown in Figure 2.2 as well as tabulated in Table A1. In the country, just northern areas experienced low solar radiation in winter season, whereas all other areas experienced good solar radiation in summers and winter seasons. Intense Solar radiation is produced due to the high clearness index resulting from a particle-free and clear atmosphere. Furthermore, solar cells are effective at low temperatures. Furthermore, at low temperatures, solar cells operate efficiently. Therefore, it can be inferred that implementing a photovoltaic-based hybrid system would yield an effective energy supply to all areas of Pakistan.

2.1.2 Wind speed data

Wind resource mapping conducted by NREL and USAID reveals the presence of numerous small and large wind resource patches in various regions of Pakistan, particularly in Sindh and Balochistan [40]. The global wind atlas also indicates the presence of isolated wind corridors with high wind potential in these

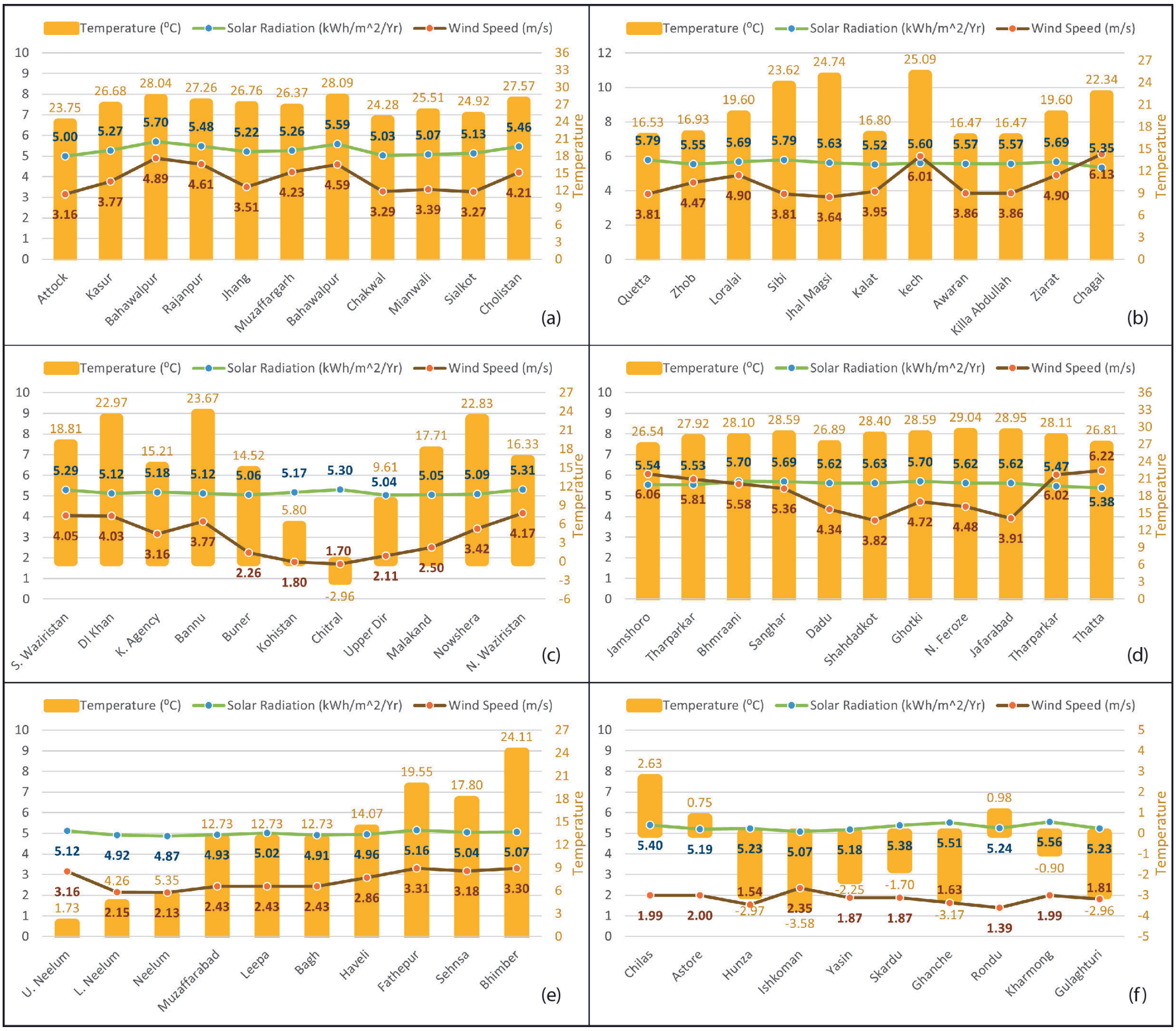


Figure 2.2. *Average temperature, solar radiation, and wind speed of under-studied sites (a) Punjab, (b) Balochistan, (c) KPK, (d) Sindh, (e) AJK, and (f) GB.*

regions compared to others. While wind resources are available in the northern areas of the country, they are less steady and vary frequently.

Additionally, the transportation of wind power plant components to high altitudes is challenging due to reduced wind speeds at lower altitudes caused by mountainous terrain. To overcome the lack of ground-based data, online datasets are directly integrated into the HOMER software for wind resource analysis. Baseline wind speed data is acquired at a height of 50 meters, and HOMER adjusts the raw data to a specified scale. The hub height for wind turbine designs in this study ranges from 20 to 30 meters, considering the topography and surrounding areas of each site. The study identifies the highest wind speeds observed at different locations in Pakistan. For example, in Chagai, Balochistan, the highest wind speed of 7.77 m/s was observed in July. In Cholisan, Punjab, the highest wind speed of 6.93 m/s was recorded in June. Similarly, in Waziristan, KPK, the highest wind speed of 4.73 m/s was observed in May, while in Tharparkar, Sindh, the highest wind speed of 8.23 m/s was recorded in June. Additionally, Bhimber, AJK, experienced a maximum wind speed of 4.09 m/s in April, and Inshkoman, GB, had the highest wind speed of 2.52 m/s in May. Figure 2.2 and Table A1 in the study present the average wind speed data for selected sites. Based on the wind speed data from the selected sites. It is evident that Balochistan and Sindh have good wind resources, while other regions exhibit relatively lower wind speeds. This highlights the favorable conditions for harnessing wind energy in Balochistan and Sindh, making these areas particularly suitable for the implementation of wind power projects in Pakistan.

2.1.3 Hydro flow data

The northern areas of Pakistan are known for their significant hydro resource potential, and many hydropower plants are already operational in these regions, generating energy at low tariffs. The availability of water resources in these areas varies throughout the year due to seasonal factors. During the summer, the melting glaciers and abundant water from rainfall contribute to high hydropower flow. Conversely, in the winter season, lower hydropower flow is observed, necessitating the need for diversified energy sources. To meet the energy requirements and address this seasonality, many micro-scale hydropower plants have been installed to cater to the needs of suburban and countryside areas. These hydropower plants are favored due to their low operating costs and suitability for local energy generation. Figure 2.3 in the study illustrates the monthly average water flow rates for the selected sites.

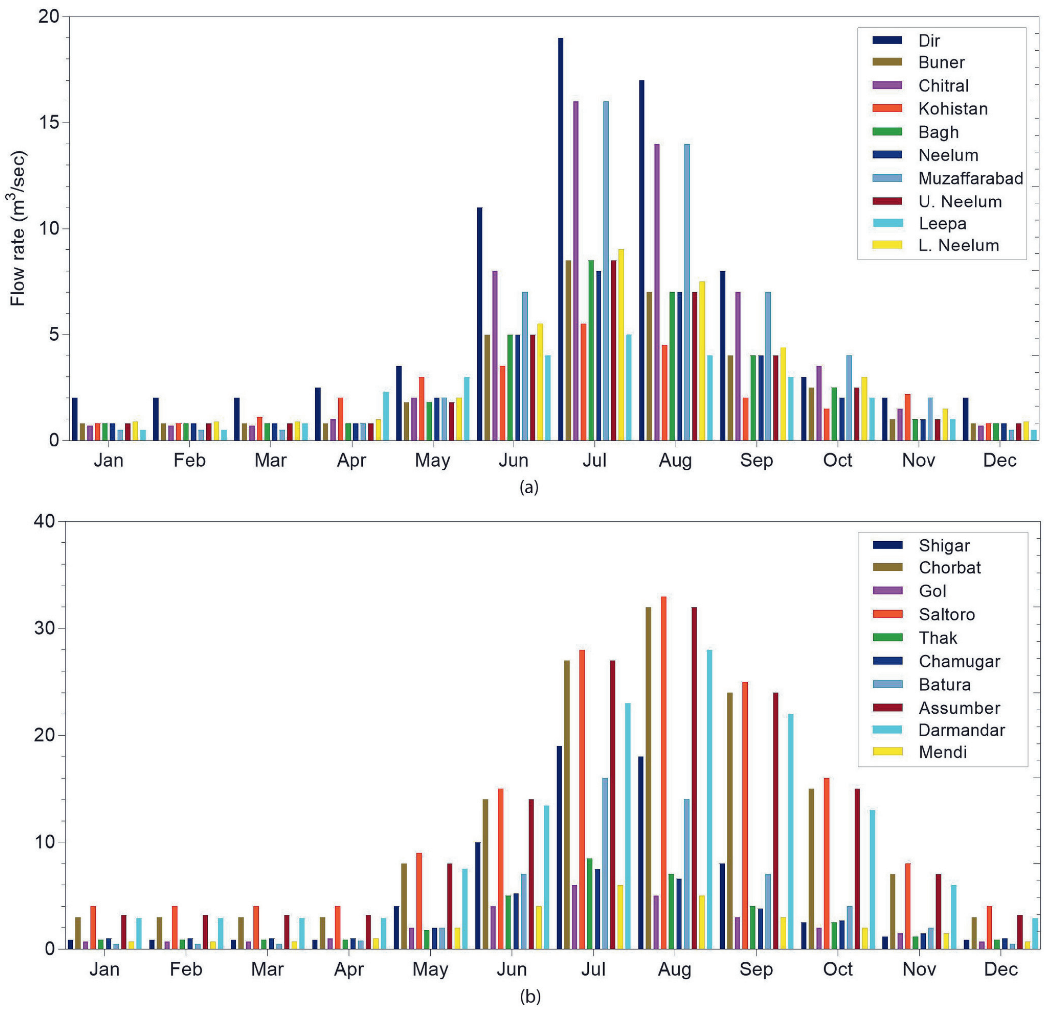


Figure 2.3. *Average monthly hydro streamline flow rate (m3/s) for selected areas.*

In this study, the hydropower resources and technical data are determined by analyzing the data from various installed hydropower plants managed by organizations such as PDO, PEDO, GBW&P, and WAPDA in the northern region. The summarized data can be found in Table A2. The data indicates a wide range of flow rates, with the highest recorded at 15.871 m3/s and the lowest at 1.690 m3/s. From November to March, most of the study sites exhibit an average flow rate of 0.50 m3/s. However, during the summer and monsoon seasons, the flow rate significantly increases, surpassing the winter flow rates by more than tenfold in many cases. These variations in water flow highlight the seasonal nature of hydropower resources in the northern areas of Pakistan. While the availability of water is abundant during the summer and monsoon seasons, it decreases during the winter season. Therefore, a diversified energy mix is necessary to ensure a reliable and consistent power supply throughout the year. Hydropower, alongside other renewable energy sources, can play a crucial role in meeting the energy demands of these regions and reducing dependence on fossil fuels.

2.2 Geospatial analysis

This study is focused on the electrification of remote areas. The research methodology incorporates two main approaches. Firstly, a geospatial analysis approach is employed to identify remote areas that lack access to electricity. This approach utilizes spatial data and analysis techniques to map and identify un-electrified regions. Geospatial analysis has been utilized in previous studies [41]–[44] for electrification planning and is considered a valuable tool in identifying areas with limited or no electricity access. It involves analyzing data on power system transmission grids, statistics on isolated areas, and other relevant spatial information. In this study, a similar approach is adopted, leveraging geospatial analysis techniques and open-source software such as QGIS [45]. Secondly, open-source energy system modeling is used to assess the potential for achieving a 100% renewable energy (RE) system in the case study area. This approach involves utilizing energy system modeling tools to simulate and evaluate the feasibility of transitioning to a fully RE-system. By analyzing various parameters such as energy demand, resource availability, and system configurations, the modeling enables an assessment of the potential for achieving a sustainable and self-sufficient energy system in the remote areas. To model power demand in geospatial analysis, a spatial interpolation approach is utilized. This technique, commonly used in different studies, enables the estimation and modeling of power demand in areas where data may be limited or unavailable. By interpolating data based on available information and spatial characteristics, a more comprehensive understanding of power demand in remote areas can be obtained.

2.3 Identification of un-electrified areas

The data on un-electrified areas in this study were collected from various electric supply companies, authorities, and previous studies referenced as [4], [20], [46]–[50]. In the initial stage of the study, different areas from various climatic and geographical zones were selected for analysis. However, it was observed that the climatic conditions of nearby areas were quite similar. Based on this observation, a clustering approach was adopted, grouping together un-electrified areas that shared similar available renewable energy (RE) resources. This clustering approach allowed for the selection of representative areas within each cluster, providing a comprehensive representation of un-electrified regions across a larger geographical area, namely Pakistan. in the study presents the names and geographical coordinates of the selected areas that were chosen to represent each cluster. These areas were identified based on their proximity and similarity in terms of available renewable energy resources. By selecting representative areas, Table 2.1 the study aims to capture the characteristics and energy needs of un-electrified regions within the different clusters across Pakistan. It is important to note that the selection of these representative areas is crucial in ensuring that the study captures the diversity and variability of un-electrified regions across the country. By considering areas with similar geographical conditions, the study can provide insights and recommendations that are applicable to a wider range of un-electrified areas in Pakistan.

MG	Area	Region	Climate	Coordinates
Punjab				
MG-01-P	Jhand	Attock	1B	33° 02' 25.45" N 71° 43' 48.83" E
MG-02-P	Kitan Kalan	Kasur	0B	30° 52' 15.96" N 73° 56' 11.74" E
MG-03-P	Kakiwala	Bahawalpur	0B	27° 54' 50.25" N 71° 14' 39.68" E
MG-04-P	Basti Lashari	Rajanpur	0B	29° 29' 37.99" N 70° 15' 12.28" E
MG-05-P	Roranwali	Jhang	0B	31° 06' 17.54" N 72° 24' 21.92" E
MG-06-P	Ramsar	Muzaffargarh	0B	30° 34' 07.95" N 70° 49' 53.61" E
MG-07-P	Derawar	Bahawalnagar	0B	28° 46' 02.25" N 71° 20' 09.64" E
MG-08-P	Saghar	Chakwal	1B	32° 55' 04.56" N 72° 10' 07.42" E
MG-09-P	Muzaffarpur	Mianwali	1B	32° 25' 11.51" N 71 37' 36.64" E
MG-10-P	Balaggan	Sialkot	1B	32° 21' 32.68" N 74° 49' 43.90" E
MG-11-P	T.S Khan	Cholistan	0B	29° 30' 49.45" N 72° 13' 56.95" E
Khyber Pakhtunkhwa				
MG-01-K	Tatai	S.Waziristan	3B	32° 11' 11.45" N 69° 36' 06.12" E
MG-02-K	Kulachi	DI Khan	3B	31° 44' 41.91" N 70° 05' 02.97" E
MG-03-K	Katkai	K. Agency	2B	33° 47' 06.69" N 70° 04' 22.30" E
MG-04-K	A. Waziran	Bannu	1B	32° 54' 54.79" N 70° 49' 37.66" E
MG-05-K	Gokand	Buner	5A	34° 33' 32.45" N 72° 32' 22.86" E
MG-06-K	Bar Jalkot	Kohistan	5A	35° 17' 07.82" N 73° 16' 09.02" E
MG-07-K	Terich	Chitral	5A	36° 21' 31.71" N 72° 19' 08.25" E
MG-08-K	Chakianan	Upper Dir	5A	35° 12' 56.02" N 71° 55' 31.27" E
MG-09-K	Dheriulgram	Malakand	2B	34° 34' 05.80" N 71° 56' 46.83" E
MG-10-K	Mandori	Nowshera	2B	33° 24' 18.01" N 71° 27' 01.28" E
MG-11-K	Datakhel	N. Waziristan	4B	32° 55' 54.87" N 69° 49' 03.47" E
Azad Jammu & Kashmir				
MG-01-A	Kamri	U. Neelum	4A	34° 43' 44.93" N 74° 57' 00.12" E
MG-02-A	Kel	L. Neelum	4A	34° 55' 40.74" N 74° 26' 32.47" E
MG-03-A	Lawat bala	Neelum	4A	34° 43' 18.07" N 73° 55' 10.56" E
MG-04-A	Pir Simar	Muzaffarabad	3A	34° 24' 00.26" N 73° 34' 46.55" E
MG-05-A	Reshian	Leepa	4A	34° 14' 49.03" N 73° 49' 54.82" E
MG-06-A	Chitrora	Bagh	4A	34° 00' 21.47" N 73° 49' 56.53" E
MG-07-A	M.S Dhook	Haveli	4B	33° 56' 45.97" N 74° 08' 12.40" E
MG-08-A	Datote	Fatehpur	1B	33° 26' 01.24" N 74° 10' 02.84" E
MG-09-A	Gagnara	Sehnsa	1B	33° 31' 53.41" N 73° 46' 21.47" E
MG-10-A	K.Chanatar	Bhimber	1B	32° 58' 34.41" N 74° 08' 16.52" E

Table 2.1. *Name, area and region of geographical regions, climatic zones, and coordinates of selected unelectrified areas.*

MG	Area	Region	Climate	Coordinates
Baluchistan				
MG-01-B	Haji Ghaibi	Quetta	3B	30° 11' 56.06" N 67° 04' 40.24" E
MG-02-B	Hassan zai	Zhob	3B	31° 17' 20.76" N 69° 28' 21.99" E
MG-03-B	Poonga	Loralai	2B	30° 19' 11.95" N 68° 44' 16.64" E
MG-04-B	Talli	Sibi	2B	29° 34' 38.07" N 68° 02' 39.19" E
MG-05-B	Hathare	Jhal Magsi	0B	28° 14' 21.54" N 67° 25' 38.50" E
MG-06-B	Iskaloo	Kalat	3B	29° 03' 13.27" N 66° 33' 34.75" E
MG-07-B	Alandoor	Kech	0B	26° 15' 05.57" N 63° 05' 12.07" E
MG-08-B	Korak	Awaran	1B	26° 51' 09.81" N 65° 44' 21.48" E
MG-09-B	Darozagi	K. Abdullah	3B	30° 18' 30.43" N 66° 34' 58.06" E
MG-10-B	Sanjawi	Ziarat	2B	30° 15' 39.40" N 68° 32' 56.24" E
MG-11-B	M. Chah	Chagai	2B	29° 00' 29.48" N 62° 27' 04.48" E
Sindh				
MG-01-S	Nooriabad	Jamshoro	0B	25° 12' 06.05" N 67° 48' 17.27" E
MG-02-S	N.U.K Palia	Tharparkar	0B	24° 28' 13.99" N 70° 59' 17.81" E
MG-03-S	Pirano Jobar	Bhmraani	0B	25° 41' 17.98" N 70° 15' 48.31" E
MG-04-S	S. Sikandar	Sanghar	0B	26° 17' 39.13" N 69° 02' 23.46" E
MG-05-S	Johi	Dadu	0B	26° 48' 52.50" N 67° 20' 56.98" E
MG-06-S	Gaibidero	Shahdadkot	0B	27° 38' 06.79" N 67° 34' 09.64" E
MG-07-S	Pir Kamal	Ghotki	0B	27° 32' 04.19" N 69° 36' 15.99" E
MG-08-S	Kamaldero	N. Feroze	0B	27° 11' 06.27" N 68° 09' 45.07" E
MG-09-S	K.K. Jamali	Jafarabad	0B	28° 17' 43.71" N 68° 15' 58.72" E
MG-10-S	Mehrand	Tharparkar	0B	24° 41' 06.20" N 69° 18' 44.33" E
MG-11-S	Shah Bander	Thatta	0B	24° 10' 01.94" N 67° 54' 12.62" E
Gilgit Baltistan				
MG-01-G	Chilas	Chilas	7	35° 24' 52.62" N 74° 08' 41.11" E
MG-02-G	Gorikot	Astore	7	35° 18' 06.38" N 74° 50' 32.67" E
MG-03-G	Attabad	Hunza	7	36° 18' 56.92" N 74° 48' 32.01" E
MG-04-G	Ghizar	Ishkoman	8	36° 33' 09.20" N 73° 48' 44.63" E
MG-05-G	Yasin	Yasin	8	36° 23' 53.35" N 73° 16' 34.46" E
MG-06-G	Thorgu	Skardu	8	35° 18' 10.32" N 75° 44' 31.67" E
MG-07-G	Daghoni	Ghanche	7	35° 15' 12.06" N 76° 09' 34.93" E
MG-08-G	Chhamugarh	Rondu	7	35° 50' 39.57" N 74° 31' 49.11" E
MG-09-G	Tarkati	Kharmong	7	34° 49' 11.56" N 76° 11' 25.90" E
MG-10-G	Gultari	Gulaghturi	8	36° 11' 04.10" N 72° 48' 50.96" E

Table 2.1. *Cont.*

Note: 3A: Ward-Humid, 4A: Mixed-Humid, 5A: Cool-Humid, 0B: Extremely Hot-Dry, 1B: Very Hot-Dry, 2B: Hot-Dry, 3B: Warm-Dry, 4B: Mixed-Dry, 7: Very Cold, 8: Subarctic.

2.4 Load Modelling

Individuals in rural houses of Pakistan uses electricity to operate basic home appliances, e.g. LED light, fan, television, mobile phone charger, refrigerator, iron, water pump, etc. the operating hours of electrical appliances are calculated based on the probabilistic approach used in a similar type of studies [4], [51], [52]. The schedule of different appliance usage is considered while constructing the load profile. Different load profiles are considered for accurate scheduling of load profiles for summer, monsoon, and winter seasons.

A probabilistic approach is used in this study to create an electrical profile for rural households. The usage patterns of various electrical appliances are considered, and the load profile is calculated by distributing the energy usage throughout a single day. HOMER software incorporates load fluctuations to provide a realistic representation of the load profile. Electrical load profile is calculated by distributing the total amount of energy used over a single day. Table A3 and Figure 2.4 in the study provide detailed calculations and represent the scaled seasonal daily average load profile. The peak demand for warm and cold areas is observed to be highest during summer and winter, respectively. HOMER software incorporates day-to-day load changes of 2% and hour-to-hour load fluctuations of 10% to generate a realistic load profile. The load factor, which represents the ratio of average load to peak load, is calculated s 0.3 for warm areas and 0.35 for cold areas. This indicates that, on average, the electrical load is around 30% to 35% of the peak load in warm and cold areas, respectively.

In this study, the load profile of a community is modelled, considering that the community consists of 50 houses. The average peak demand per household is determined to be 8.11 kWh/day for cold areas and 6.65 kWh/day for warm areas. As the focus of the study is on residential community-type load, these values are used to estimate the overall energy demand for the community. For warm areas, the average peak demand for the community is calculated as 332.5 kWh/day (8.11 kWh/day*50 houses), while the average annual energy demand is estimated to be 119,059 kWh/year. Similarly, for cold areas, the average peak demand for the community is calculated as 405.5 kWh/day (6.65 kWh/day*50 houses), and the average annual energy demand is estimated to be 155,342 kWh/year. Figure 2.5 represents the average annual energy demand for the modelled community. This visualization provides a clear representation of the overall energy demand trends throughout the year, highlighting the variations and seasonality in energy consumption.

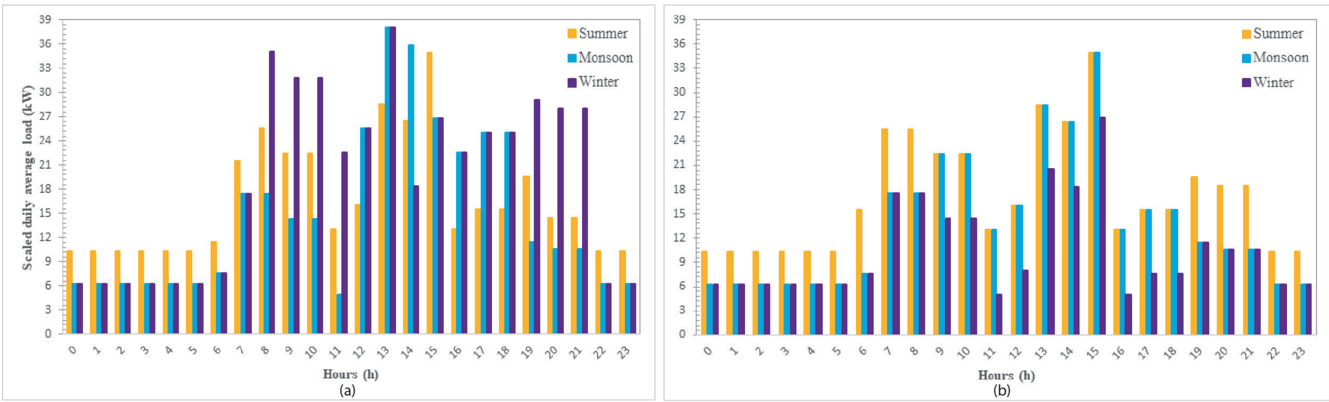


Figure 2.4. *Seasonal load profile of (a) cold (b) warm areas.*

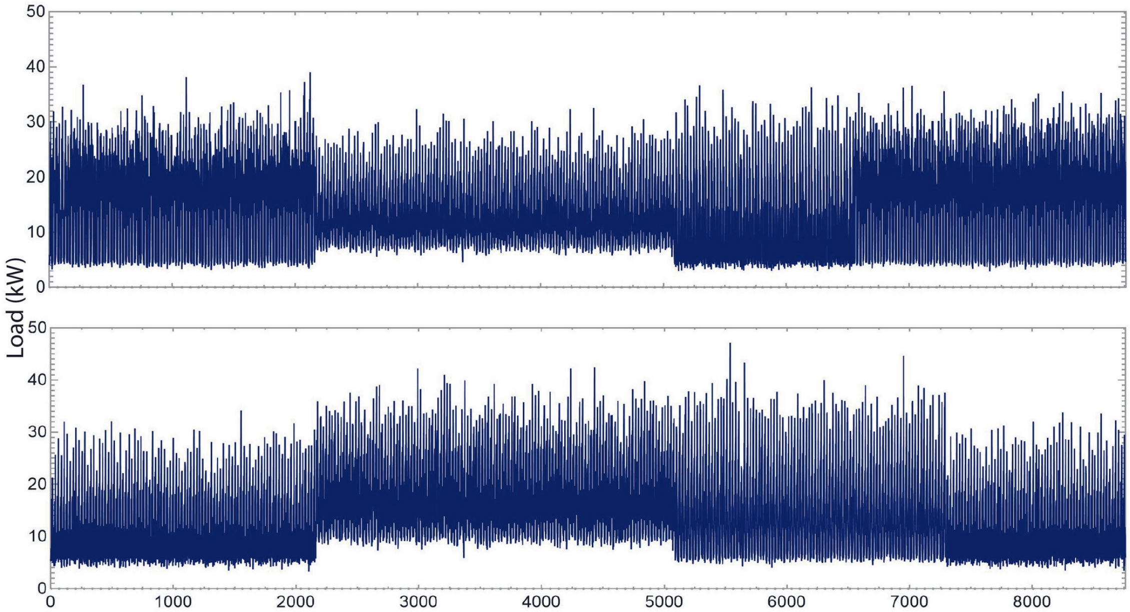


Figure 2.5. *Adopted residential load profiles of cold (top) and warm (bottom).*

3. System Modelling and Analysis

This section describes system architecture, theoretical framework, economic modelling, and performance indicators. Economic and performance parameters, i.e., NPC, PBP, IRR and ROI. Furthermore, mathematical modelling of each component associated with microgrid design, i.e., photovoltaic system, wind turbine, hydel system, fuel cell system, battery storage system, and power converters. System modelling and analysis are conducted in three major layers. The first layer is the theoretical framework, in which the different microgrid components are modelled. The second layer is economics modelling, which is related to different financial decision variables on which any system's feasibility depends. The third layer corresponds to performance parameters mostly related to capacity factor (CF), annual energy production, and system efficiency.

3.1 System architecture

Institute of Electrical and Electronics Engineers (IEEE) characterized a microgrid as [53] system which generates, distributes, and manages its electricity. It can use solar panels, wind turbines, generators, or energy storage devices. Microgrids can boost renewable energy utilization and offer backup power during outages. In short, locally generated power from available renewable resources energy storage systems meet the load demand of an area for which it is designed.

To electrify remote areas across a large geographical area, different MG's are proposed, which include PV, Wind turbine, hydro turbine, battery, fuel cell, diesel generator, converter, electrolyzer and hydrogen tank, as shown in Figure 3.1. PV generates DC power, which is then converted into AC power using a converter. The access power is stored in battery or electrolyzer. The electrolyzer converts the DC power into hydrogen, which is stored in a hydrogen tank. During autonomous hours, FC utilizes the stored hydrogen and generates electricity to fulfil the load demand. Wind and hydro turbines are directly connected to the load bus bar. If the designed system cannot supply power to load, DG is a backup to meet the electrical load demand.

3.2 Evaluation and analysis modelling

Preliminary assessments of the selected areas are crucial to ensure the desired outcomes and meet the energy demands of the communities. It has been observed in the literature that energy schemes in developing nations have often failed due to a lack of understanding of the community's specific energy load [54]. To address this concern, a comprehensive evaluation of resources and load demands is conducted for the selected sites in order to model hybrid renewable energy systems. Thorough resource evaluation involves assessing the renewable energy potential of each site, such as solar radiation, wind speed, and hydro resources. This evaluation provides insights into the availability and variability of renewable resources, enabling the design of optimized energy systems that can effectively harness these resources. HOMER is used for modelling, optimization, and analysis of hybrid systems. Two different dispatch strategies are implemented: load following and cycle charging. The load following strategy activates the storage system when RES is insufficient to meet the load demand, ensuring the load requirements are fulfilled.

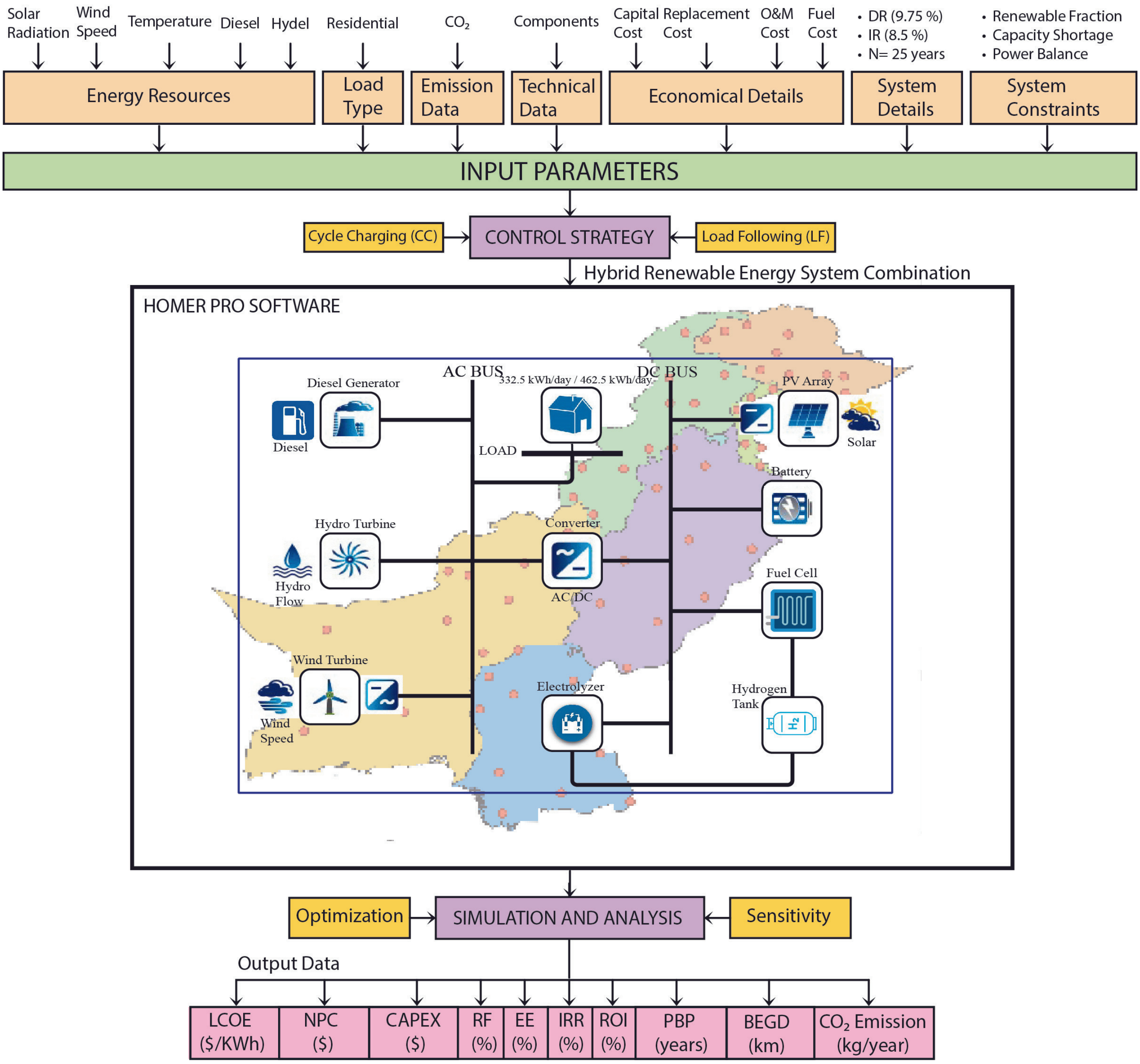


Figure 3.1. *Overview of the HRES modelling using HOMER pro.*

On the other hand, the cycle charge strategy triggers the diesel generator when the RE system cannot satisfy the load demand. To ensure reliable operation and avoid excessive load shedding, the study limits the maximum capacity shortages to 0.1%. This upper maximum load-shedding limit defines the threshold at which load shedding may occur if a high peak in demand persists for an extended period. Additionally, the study sets 10% of the total load as the minimum operating reserve. This reserve represents the minimum fraction of operating capacity that the system should be able to provide in the event of an increase in demand or scarcity of available renewable energy. The project's lifetime is determined to be 25 years, representing the duration for which the system's performance and economic viability are assessed. The flowchart shown in Figure 3.2 describes the Approach Used research in this research for Techno-Economic Analysis during the study.

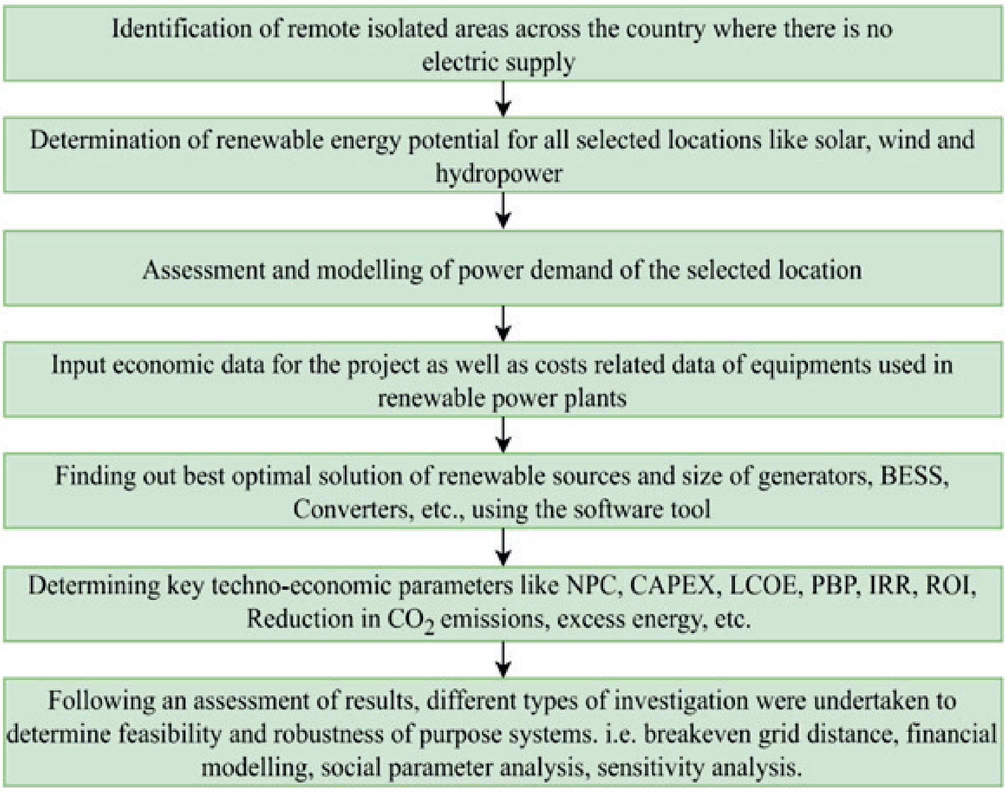


Figure 3.2. *Approach used for Techno-Economic Analysis.*

3.2.1 Techno-economic analysis

NREL develops HOMER for techno-economic investigation and optimal sizing of HRES. Various studies have been conducted in the literature in which researchers prefer using HOMER (Table 1.1). HOMER follows three steps to achieve optimized results: system modelling, simulation and optimization, and sensitivity analysis. In the first step, the RES is designed based on the load demand and system specification, which include technical and economic parameters. In addition, it also needs the average hourly load profile, solar irradiance, wind speed, and hydro resources. In the second step, HOMER simulates multiple RES system configurations and ranks each optimized configuration based on NPC as an economic criterion. In the final step, HOMER performs the optimization procedure for the individual input value of the sensitive parameters to a value that determines how the results are influenced.

3.2.2. The financial mechanism for energy efficient projects

The financial mechanism for implementing energy projects in this study focuses on increasing energy efficiency by utilizing different allocation methods and leveraging financial resources to reduce the initial capital expenses for investors. Various mechanisms are considered for the projects, including financial leasing, debt financing, tariff regulation, and public-private and municipal-private partnerships. However, it is observed that using banking loans with alternative mechanisms is more feasible and accessible. Consequently, debt financing through the allocation of loans is identified as the primary mechanism for the energy efficiency projects in this study. This approach allows for the efficient allocation and utilization of financial resources to support the implementation of energy efficiency measures and optimize the overall financial sustainability of the projects.

3.2.3 Environmental aspects

In this study, the environmental aspects of the energy systems are analyzed using RETScreen Expert, a software tool commonly used for assessing renewable energy and energy efficiency projects. To ensure an uninterrupted power supply throughout the year, a combination of renewable energy sources (RES) and diesel generators (DG) is utilized in various areas. To evaluate the environmental impact, the proportional share of the diesel generator's annual generation is used to determine the carbon emissions. By comparing the carbon emissions before and after integrating renewable energy resources, the reduction in greenhouse gas emissions can be determined. The study utilizes greenhouse gas emission factors for CO2, CH4, and N2O. These emission factors represent the amount of greenhouse gas emissions associated with oeach unit of electricity generation. The proposed emission factors used in this study are 442 g/kWh for CO2, 0.0241 g/kWh for CH4, and 0.0136 g/kWh for N2O [55]. By incorporating these emission factors into the analysis, the study quantifies the carbon emissions reduction achieved by integrating renewable energy resources into the energy system. This provides valuable insights into the environmental benefits and potential mitigation of greenhouse gas emissions through the adoption of renewable energy technologies.

3.2.4 Social aspect assessment criteria

During the installation of energy projects, a significant number of people are employed throughout the entire lifecycle, including construction, operation, and decommissioning phases. Recognizing the social aspect of these projects, an assessment criterion has been incorporated to quantify the employment opportunities generated by the energy project. Table A4: Employment potential of hybrid renewable energy supply systems.in the study provides information on the employment potential of various renewable energy supply systems. This table outlines the estimated number of jobs that can be created across different renewable energy technologies. The employment potential varies depending on the specific technology and project scale. By considering the social aspect and employment generation, the study aims to highlight the positive impact of renewable energy projects on the local economy and job creation. This information can be crucial in assessing the socioeconomic benefits and promoting the adoption of renewable energy technologies as a means to not only address energy needs but also stimulate economic growth and employment opportunities.

3.2.5 Break-even distance (BED) for grid extension

In rural areas, accessibility to electricity is facilitated through two main approaches: off-grid power systems and grid extension. The choice of infrastructure for remote areas, located far from the existing grid, is determined by conducting BED. Grid extension, as an option, needs to be assessed based on various factors including health, economy, environmental impact, landscape, contribution to the community, and technical aspects [56]. To determine the most economical approach, a comparison is made between the costs of grid extension and off-grid hybrid renewable energy systems (HRES). The BED analysis helps illustrate which strategy, grid extension or off-grid HRES, is more cost-effective for a given scenario. The cost of grid extension can vary depending on factors such as load requirements, the capacity of conductors, tower size, and voltage levels. These factors influence the decision-making process when choosing between a hybrid power system and grid extension. The specific costs associated with grid extension, such as the costs of HV transmission lines, substations, distribution transformers, consultancy services, civil works, contingency costs, etc., can vary depending on the geography, voltage level, and line thermal limits. In this study, the grid extension costs are obtained through direct engagement with relevant authorities such as NTDC, AJKED , and IESCO as detailed cost information is not publicly available. It is worth noting that the costs of grid extension provided in this study range from 8,000 to 20,000 dollars per kilometer (8K-20K $/km), reflecting the various cost components associated with infrastructure development. For example, the cost of a 1-kilometer transmission line is estimated at $301,625, while a distribution line costs $15,255. These cost estimates and data serve as important inputs for the BED analysis, ,enabling a comparison of the economic feasibility of grid extension versus off-grid HRES solutions in rural areas. The BED is calculated by using (A1)[57].

3.2.6 Sensitivity analysis

The sensitivity analysis conducted in this study focuses on examining how various parameters impact the NPC and LCOE of hybrid energy systems. Several important variables are considered, including the nominal discount rate, inflation rate, project life, solar irradiance, wind speed, and load demand. The sensitivity analysis aims to understand how changes in these parameters affect the economic viability and competitiveness of the hybrid energy systems in Pakistan. Among these variables, the inflation rate is identified as particularly significant due to its high impact in the context of emerging economies like Pakistan. Inflation rates can greatly influence pricing, including the cost of imported goods, which can have a significant bearing on the economic outlook of the country [58]. By analyzing the sensitivity of these parameters, the study provides insights into the potential risks and uncertainties associated with the financial and economic aspects of renewable energy initiatives in Pakistan. It allows for a better understanding of the research outcomes from an investor's perspective and informs decision-making processes related to renewable energy investments. Considering the sensitivity of discount and inflation rates, along with other variables, helps in assessing the robustness and viability of renewable energy projects in Pakistan. It allows policymakers, investors, and stakeholders to consider the potential impacts of different scenarios and make informed decisions regarding the deployment of renewable energy technologies in the country.

3.2.7 Robust analysis

In this study, the reliability of the hybrid renewable energy system is thoroughly examined. The objective is to ensure that the system can meet the load demand of the proposed area in a reliable and consistent manner. The analysis considers the techno-economic feasibility of the project, which is crucial for the successful implementation of renewable energy projects. One of the key considerations in the study is to make the energy system affordable for customers while also ensuring a reliable and secure electricity supply. The robustness of the HRES is thoroughly analyzed and verified to assess its reliability in meeting the energy demands of the proposed sites. Power generation profiles are examined for all seasons of the year, including months with the maximum and minimum energy demand. In warm areas, the peak energy demand is typically observed in July, while in cold areas, it occurs in January. By analyzing the power generation profiles for these critical months, the study evaluates the HRES's ability to meet the peak load demand and ensure a reliable power supply.

3.3 Theoretical framework

3.3.1 PV Panel

In this study, a monocrystalline module with fixed azimuth angle is used, named as "LONGi Solar LR6-72PE", has a rating capacity of 370W. This module has excellent efficiency, easily available in the local market, cost competitive, and suitable for space-constrained sites. The 72-cell module makes it perfect for commercial and large-scale projects. The economic and technical specifications for the selected module are given in Table A5. The electrical power () is generated by the Module in presence of sunlight is calculated by using (A2)[32]. To encounter the degradation effect of solar panels, the temperature effect of PV panels is considered.

3.3.2 Wind turbine

The output power of a wind turbine depends on the cut-in, cut-out and rated wind speed, and power output of individual turbines as expressed in Eq. (A4)[59]. The wind speed data used in this study is recorded at the altitude of 24 m, and the steady wind speed needed to convert.

3.3.3 Hydro turbine

Hydroelectric power is generated in areas where water is abundant and has a significant flow rate to run the turbine, which produces electrical output. For this purpose, Natel FreeJet FJ-7A, with a rated capacity of 49kW, is selected based on net head availability and design flow rate; the efficiency of this turbine is 59.52% [24]. Assuming a 25-years lifespan for the turbine, pipe head losses are taken as 15%. Cost details and available head for HPPs for different sites of the hydro system are set to be different (see Table A2). While designing the layout of the hydro turbine, the optimal head is an important parameter. HOMER utilizes the available net head to calculate the effective net head, using (A8).

3.3.4 Battery

Energy storage technologies are used to satisfy the load demand during low output of REs. Li-ion and lead-acid batteries are commonly used in stationary applications, including LF, management, and regulation. This study chooses a generic Li-ion battery due to its best operation. The temperature effect is considered to model the degradation losses. The operating voltage of a battery is 12V, and the operating voltage of a 40V PV module [60]. So, the string size is kept at 4 to ensure 40V DC. Cost and technical parameters are summarized in Table A7[61]. The storage capacity is computed by (A10).

3.3.5 Electrolyzer

An electrolyzer is an electrochemical device that uses electrolysis to split water into hydrogen and oxygen. It operates by utilizing electrical power as an input. Different types of electrolyzers exist, including PEM, solid oxide, phosphoric acid, methanol, and alkaline electrolyzers, each suited for specific applications. This study focuses on the PEM electrolyzer, commonly used in rural applications. The theoretical efficiency of the PEM electrolyzer can reach up to 94%, although practical efficiency is typically around 85% [62]. To determine the electrical energy requirements and hydrogen production rate, the study employs equations (A15) and (A16) [63]. Considering the efficiency and operational characteristics of the PEM electrolyzer, the study aims to accurately estimate energy requirements and hydrogen production capabilities. This information is vital for optimizing the design and operation of hybrid energy systems that incorporate electrolyzers for hydrogen production. Cost and technical parameters are summarized in Table A8.

3.3.6 Hydrogen tank

Hydrogen produced from the electrolyzer can be stored in a tank with the help of a compressor. The power required for compression is shown in Eq. (A17)[38]. The tank's internal pressure is estimated at (A18)[63]. Cost and technical parameters are summarized in Table A9. HOMER evaluates the autonomy of the hydrogen tank using (A19), referred to as the ratio of the energy capacity of the hydrogen tank to an average electrical load.

3.3.7 Diesel generator

A hybrid system that combines a diesel generator with wind, hydro and solar energy resources offers an alternative solution. The rapid ON-OFF property makes it ease to use DG with RERs. DGs are also used as backup supplies in grid-connected areas in case of power outages. In the absence of renewable energy, DG will be utilized to meet energy demand; annual fuel consumption value (FAC) is obtained by (A20). DGs power many suburban districts of Great Britain, and the government supplies fuel to all locations, making it easy and reasonable to transport fuel to the site [64]. However, O&M costs are significantly greater than others because of the high cost of diesel fuel. CAPEX of DG is reasonable and equivalent to the cost of components of RERs. In this study, Auto-size Genset is used. Table A10 Provides the technical specifications and cost per kW, DG's used in different hybrid systems.

3.3.8 Fuel cell

The present study utilizes a PEM fuel cell. The author recommends PEMFC for stand-alone energy systems. Also, in various models of stand-alone energy systems, authors utilized it, a few of them are [4], [38], [65], [66] it has good efficiency, high life cycle, low weight, low operating temperature, less maintenance, quiet operation, high flexibility, and minimum emissions [67]. In addition, the efficiency of PEMFC is observed in between 40 to 60 %. Therefore, the efficiency of FC is assessed to be 51.30%. Cost and technical parameters are summarized in Table A11. The efficiency and output power of FC is calculated by Eq. (A21), (A22) [64].

3.3.9 Converter

The AC load is considered in this research, whereas the output power of the fuel cell, PV panel and battery is DC power. Therefore, to convert DC into AC power converter is utilized. The converter's efficiency is assumed to be 95% and determined by Eq. (A23)[68]. Cost and technical parameters are summarized in Table A12.

3.4 Economic modelling

3.4.1 Net present cost

HOMER considers the NPC during the simulation and concentrates on all possible RES configurations. NPC is the total cost of an initial investment, operation and maintenance that reflects all the project's cash flows throughout the planned time frame. HOMER calculates the NPC of individual components as well as the whole system. HOMER calculates the NPC using Eq. (A24)[69].

3.4.2 Real discount rate

To account for the time value of money and convert between one-time costs and annualized costs, HOMER Pro incorporates the concept of a real discount rate. The real discount rate is derived using the nominal discount rate () and the inflation rate (f) provided in the analysis. HOMER Pro employs equation (A27) [31], to calculate the real discount rate. The real discount rate is a crucial parameter in financial analysis as it reflects the true value of money over time, accounting for both inflation and the opportunity cost of capital. By using the real discount rate, HOMER Pro ensures that the project's cash flows are appropriately adjusted to account for the changing value of money due to inflation.

3.4.3 Cost of energy

The cost of energy is defined as the average cost per kWh of energy utilized. It suggests the lowest cost at which energy should be sold to recoup entire costs throughout its lifetime. It is used to compare and evaluate various energy systems in means of costs, giving an idea about system feasibility. To compute the levelized cost of energy, the HOMER algorithm compares the annual cost of generated power to the utilizable electricity generated. LCOE can be calculated through (A28)[19].

3.5 Performance indicators

The key objective functions in this study are the financial metrics NPC and COE, which are closely interlinked to performance indicators, i.e., PBP, IRR, and ROI.

3.5.1 Payback period

PBP is mathematically expressed in (A29)[71], indicating the number of years required to recover the system's initial capital cost.

3.5.2 Internal rate of return

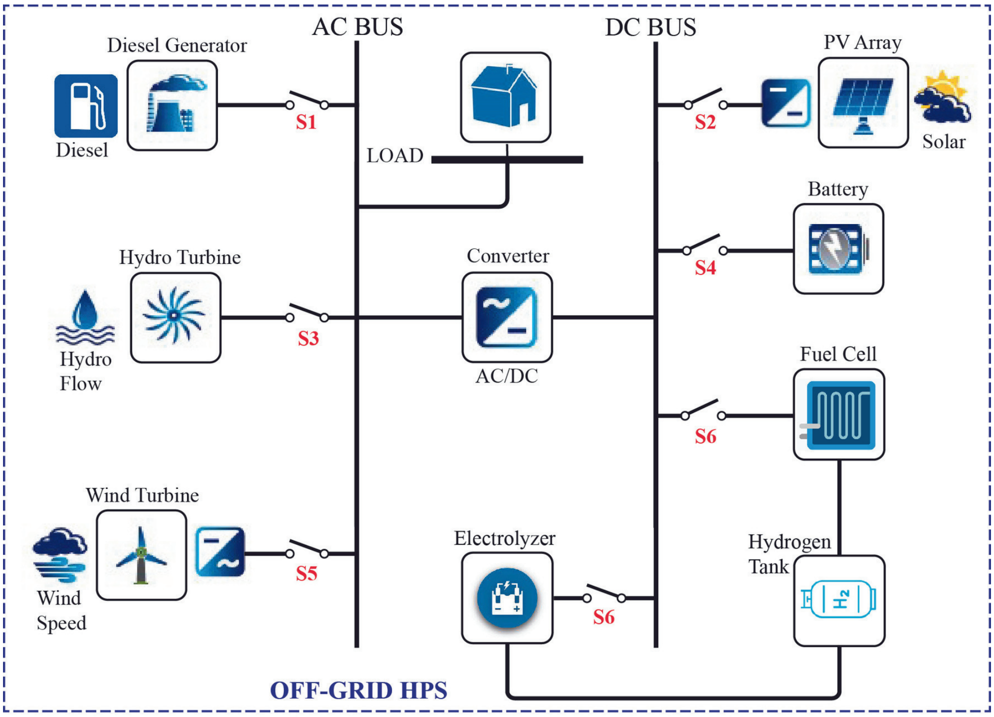
The rate at which the total project investment is returned in terms of revenue is referred to as IRR, calculated by (A30)[71]. Where initial investment in the project is represented by. IRR is used as an indicator to measure the effectiveness of prospective investment to properly identify the system.

3.5.3 Return on investment

ROI is an indicator used for comparing the annual saving cost to the initial investment, and it is the ratio of the average annual difference in nominal cash flows to the difference in capital cost, which can be stated mathematically (A31)[71].

4. Results and Discussions

In this study, HOMER is utilized as a powerful tool to model, optimize, and analyze off-grid hybrid renewable energy systems (HRES) for the electrification of rural areas in Pakistan. HOMER's capabilities allow for exploring various configurations of the system based on the input data provided within the specified search space boundaries. The framework setup encompasses the evaluation of multiple scenarios, and Figure 4.1 illustrates the different configurations considered. The input parameters include solar irradiance, wind speed, hydro flow rate, control parameters, and economic parameters, which are essential for accurately modelling and simulating the performance of the HRES. The effect of ambient temperature on photovoltaic (PV) cells is also taken into account. It is assumed that solar panels are used without a tracking system, and azimuth degree angles are set to zero since the proposed off-grid system does not involve electricity sale or purchase from the grid. Once the optimization process is completed, environmental analyses are performed using RET Screen Expert. This software tool allows for comprehensive environmental assessments, providing insights into the ecological impacts and sustainability aspects of the HRES. By conducting these analyses, the study evaluates the environmental performance of the optimized HRES configuration, considering factors such as carbon emissions, greenhouse gas reduction, and other environmental indicators.



Scenario HRES Model	S1	S2	S3	S4	S5	S6
PV-B		✓		✓		
PV-DG-B	✓	✓		✓		
PV-W-B		✓		✓	✓	
PV-H-B		✓	✓	✓		
PV-H-DG	✓	✓	✓			
PV-W-DG-B	✓	✓		✓	✓	
PV-H-FC		✓	✓			✓

Figure 4.1. *Configurations of Framework setup.*

MG No.	Optimal configuration	DS	Economic Parameters			Financial Parameters			Energy Analysis		Robust Analysis		Environmental Analysis	
			NPC ($)	LCOE ($/kWh)	CAPEX ($)	IRR (%)	ROI (%)	PBP (Yrs.)	EE (%)	RF (%)	CSF (%)	UML (%)	CO_2 Kg/Year	G.A.R (%)
Punjab														
MG-01-P	PV-DG-B	LF	470,867	0.183	149,012	60.7	54.7	1.58	61.9	98.9	0.0984	0.0243	1,549	99.00
MG-02-P	PV-B	LF	485,144	0.189	160,707	55.3	49.4	1.71	75.9	100	0.0407	0.0991	0	100.00
MG-03-P	PV-W-DG-B	LF	403,403	0.157	159,180	66.6	60.4	1.47	52.1	98.9	0.0965	0.0341	1,635	98.94
MG-04-P	PV-W-DG-B	LF	423,135	0.164	166,584	63.6	57.6	1.53	52.8	99.1	0.0999	0.0222	1,226	99.21
MG-05-P	PV-DG-B	LF	464,149	0.18	145,327	62.6	56.7	1.54	59.1	99	0.0999	0.0384	1,341	99.13
MG-06-P	PV-W-DG-B	LF	445,506	0.173	167,200	62.8	56.7	1.54	60	99.2	0.0998	0.0123	1,123	99.27
MG-07-P	PV-W-DG-B	LF	421,679	0.164	170,078	65.2	59	1.5	58	99.1	0.0993	0.0477	1,228	99.21
MG-08-P	PV-DG-B	LF	469,709	0.183	148,636	60.8	54.9	1.58	60.7	99	0.0982	0.0346	1,442	99.07
MG-09-P	PV-DG-B	LF	469,386	0.182	148,620	60.9	55.1	1.58	60.6	99	0.0996	0.0345	1,411	99.09
MG-10-P	PV-B	LF	480,507	0.187	154,228	58.1	52.1	1.66	73.3	100	0.0396	0.0998	0	100.00
MG-11-P	PV-B	LF	459,780	0.179	154,317	58.1	52.1	1.64	74.2	100	0.0412	0.0998	0	100.00
Baluchistan														
MG-01-B	PV-W-B	CC	451,547	0.175	139,736	66.1	59.8	1.48	66.2	100	0.0999	0.0412	0	100.00
MG-02-B	PV-W-B	CC	436,916	0.17	150,151	60.9	55.4	1.59	67.1	100	0.1	0.0149	0	100.00
MG-03-B	PV-W-B	CC	427,343	0.166	139,257	68.8	62.4	1.43	68.8	100	0.0995	0.0125	0	100.00
MG-04-B	PV-B	LF	455,800	0.177	131,985	70.8	64	1.40	67.2	100	0.0309	0.0991	0	100.00
MG-05-B	PV-DG-B	LF	457,522	0.178	139,661	66	59.8	1.48	56	99.2	0.0996	0.0374	1,151	99.26
MG-06-B	PV-W-DG-B	LF	451,676	0.176	162,740	54.9	50	1.72	59.1	99.4	0.0993	0.0297	805	99.48
MG-07-B	PV-W-DG-B	LF	393,623	0.153	158,807	57	53	1.69	63	97.3	0.0996	0.0283	3,816	97.54
MG-08-B	PV-DG-B	LF	429,813	0.167	145,651	55.7	51.2	1.71	59.1	99.1	0.0996	0.0367	943	99.39
MG-09-B	PV-DG-B	LF	458,051	0.178	140,055	65.7	59.5	1.48	57.2	99.4	0.0989	0.0498	817	99.47
MG-10-B	PV-W-DG-B	LF	412,552	0.16	149,635	61.2	56.6	1.58	49	99.2	0.0999	0.0121	1,167	99.25
MG-11-B	PV-W-DG-B	LF	373,899	0.145	151,223	60.9	57.3	1.6	56.6	97.9	0.0996	0.0463	3,025	98.05
Khyber Pakhtunkhwa														
MG-01-K	PV-W-B	CC	462,478	0.18	171,841	63.7	57.6	1.52	74.6	100	0.0998	0.0092	0	100.00
MG-02-K	PV-DG-B	LF	470,037	0.183	150,358	60.1	54.2	1.6	61.9	99.11	0.0996	0.0331	1,236	99.20
MG-03-K	PV-DG-B	LF	466,343	0.181	147,174	61.8	55.7	1.56	63.2	99.09	0.0999	0.0493	1,278	99.17
MG-04-K	PV-DG-B	LF	467,749	0.182	148,955	60.8	54.9	1.58	61.6	99.07	0.0968	0.0376	1,215	99.22
MG-05-K	PV-H-FC	CC	447,332	0.174	291,282	28.8	25.7	3.52	80.4	100	0.0973	0.0567	0	100.00
MG-06-K	PV-H-DG	CC	512,178	0.153	220,243	41.4	38.9	2.44	76.7	91.5	0	0	14,975	91.32
MG-07-K	PV-H-DG	CC	416,606	0.124	158,879	61.6	60.2	1.63	79.8	91.5	0	0	15,472	91.03
MG-08-K	PV-H-FC	CC	414,405	0.161	304,230	33.1	30.5	3.12	78.3	100	0.0966	0.0572	0	100.00
MG-09-K	PV-DG-B	LF	466,282	0.181	146,077	62.1	56.2	1.55	62.1	99.03	0.0975	0.0573	1,455	99.06
MG-10-K	PV-B	CC	483,339	0.188	158,066	56.4	50.5	1.68	74.7	100	0.0389	0.0994	0	100.00
MG-11-K	PV-W-B	CC	452,287	0.176	165,325	54.1	48.9	1.75	73	100	0.0997	0.0123	0	100.00
Sindh														
MG-01-S	PV-W-B	CC	421,565	0.164	147,026	62.7	57.4	1.55	68.1	100	0.0998	0.0323	0	100.00
MG-02-S	PV-W-B	CC	413,602	0.161	148,868	61.9	56.9	1.57	69.5	100	0.1	0.0105	0	100.00
MG-03-S	PV-W-B	CC	404,905	0.157	134,995	69.80	64.4	1.42	67.7	100	0.0999	0.0204	0	100.00
MG-04-S	PV-W-B	CC	422,693	0.164	167,844	63.4	58.1	1.54	71.5	100	0.0986	0.0315	0	100.00
MG-05-S	PV-W-B	CC	462,088	0.179	171,548	51.7	46.6	1.82	69.8	100	0.0978	0.0381	0	100.00
MG-06-S	PV-DG-B	LF	458,667	0.178	140,759	65.3	59.1	1.49	56	99.2	0.0996	0.0372	1,147	99.26
MG-07-S	PV-W-DG-B	LF	415,586	0.161	163,346	65.2	59	1.5	53.7	98.9	0.1	0.0473	1,606	98.96
MG-08-S	PV-W-DG-B	LF	429,962	0.167	167,726	53.2	48.9	1.78	53.9	98.9	0.0984	0.0243	1,543	99.00
MG-09-S	PV-DG-B	LF	459,529	0.179	139,302	66.1	59.9	1.48	54.5	99.14	0.0994	0.0371	1,273	99.18
MG-10-S	PV-W-B	CC	434,079	0.169	165,764	54.3	49.4	1.75	76.4	100	0.098	0.0162	0	100.00
MG-11-S	PV-W-B	CC	414,111	0.161	145,989	63.4	58.2	1.54	67.6	100	0.099	0.0167	0	100.00

Table 4.1. *Best Optimal MG's configuration with Techno-economic analysis for selected remote areas.*

MG No.	Optimal configuration	DS	Economic Parameters			Financial Parameters			Energy Analysis		Robust Analysis		Environmental Analysis	
			NPC ($)	LCOE ($/kWh)	CAPEX ($)	IRR (%)	ROI (%)	PBP (Yrs.)	EE (%)	RF (%)	CSF (%)	UML (%)	CO_2 Kg/Year	G.A.R (%)
Azad Jammu & Kashmir														
MG-01-A	PV-H-FC	CC	397,708	0.155	267,879	36.6	34.6	2.83	75.4	100	0.0994	0.0493	0	100.00
MG-02-A	PV-H-B	CC	420,347	0.125	164,443	60.7	57.6	1.62	72.8	100	0.0224	0.0980	0	100.00
MG-03-A	PV-H-FC	CC	447,818	0.174	310,928	32.7	29.9	3.16	75.9	100	0.0998	0.0538	0	100.00
MG-04-A	PV-H-DG	CC	435,969	0.130	194,744	48.5	46.9	2.01	73.9	94.5	0	0	9,645	94.41
MG-05-A	PV-H-FC	CC	407,958	0.159	302,332	34.4	32	3.03	78.2	100	0.0959	0.0559	0	100.00
MG-06-A	PV-H-B	CC	415,781	0.123	186,198	53.1	49.9	1.82	76.2	100	0.0738	0.0999	0	100.00
MG-07-A	PV-B	CC	444,807	0.174	125,158	76.4	68.9	1.32	65.3	100	1.1	0.6372	0	100.00
MG-08-A	PV-DG-B	LF	461,286	0.179	143,772	63.6	57.5	1.53	60	99.1	0.0999	0.0483	1,306	99.16
MG-09-A	PV-DG-B	LF	465,495	0.181	144,557	63.1	57	1.54	60.4	99.1	0.0979	0.0484	1,566	98.99
MG-10-A	PV-DG-B	LF	466,865	0.181	144,894	62.9	56.8	1.54	60.3	98.8	0.1	0.0433	1,665	98.93
Gilgit Baltistan														
MG-01-G	PV-H-B	CC	402,481	0.120	183,459	54.3	51.2	1.78	70.1	100	0.0697	0.0998	0	100.00
MG-02-G	PV-H-FC	CC	400,975	0.156	318,083	28.3	25.4	3.57	83.1	100	0.1	0.0633	0	100.00
MG-03-G	PV-H-FC	CC	402,193	0.156	333,689	26.8	24	3.74	82.7	100	0.1	0.0664	0	100.00
MG-04-G	PV-H-FC	CC	385,512	0.150	311,958	29	26.3	3.5	83.1	100	0.1	0.0633	0	100.00
MG-05-G	PV-H-FC	CC	380,104	0.148	306,488	29.7	27	3.42	82.8	100	0.0997	0.0672	0	100.00
MG-06-G	PV-H-B	CC	411,304	0.123	187,576	52.6	49.6	1.83	77	100	0.0685	0.0989	0	100.00
MG-07-G	PV-H-DG	CC	419,619	0.125	184,629	52	50.3	1.89	76.9	98.3	0	0	13,028	92.45
MG-08-G	PV-H-FC	CC	391,458	0.152	315,165	28.7	25.9	3.53	81.9	100	0.0999	0.0708	0	100.00
MG-09-G	PV-H-FC	CC	411,613	0.161	320,147	27.9	25	3.62	81	100	0.0995	0.0711	0	100.00
MG-10-G	PV-H-B	CC	411,257	0.123	195,649	50.3	47.3	1.91	77.7	100	0.0685	0.0998	0	100.00

Table 4.1. *Cont.*

4.1 Techno-economic optimization

Technical and economic optimization involves optimal system component sizing without sacrificing cost and reliability. Although HOMER proposed hundreds of different system configurations, only the one with the lowest LCOE, NPC, and minimum capacity shortage value was chosen for each division. Table 4.1 lists all the selected sites and their corresponding optimal configurations. An appropriate MG configuration is chosen for each understudy region to quantify the analysis. Sections (A4.1.1-A4.1.7) cover techno-economic optimization with component sizes and other parameters in detail..

4.1.1 PV with battery storage

Six sites were reported as optimal for PV with battery system in the optimal results. The most feasible site was the Haveli with LCOE and NPC of 0.174 $/kWh and $444,807, respectively. The highest LCOE 0.189 $/kWh, and NPC, $485,144, were reported at Kasur, with the same configuration. Table 4.1 shows that Haveli is proven to be the most feasible solution with a 7.8% lower cost than Kasur. This is due to the high solar radiation in Haveli as compared to Kasur. Another reason is the climatic difference: Haveli lies in a mixed-dry area, and Kasur lies in an extremely hot dry area. However, during the winter months in places like Kasur, a foggy day limits the solar irradiance and decreases the sunshine hours, which directly effects the performance of PV. Table A13 shows the configuration's component sizes and other technical information. Figure 4.2(a) compares NPC and LCOE for PV systems with battery storage. Figure 4.3(a) illustrates, for proposed configuration, in the presence of sunlight PV produces the electricity used by load and battery used to store it. During off-peak hours, battery supplies the load and fulfils energy demand.

4.1.2 PV, DG with battery storage

Feasibility studies suggest PV and DG with battery backup are also feasible in different regions. Optimization results reveal that Awaran has the lowest LCOE 0.167$/kWh and NPC $429,813, and DI Khan has the highest LCOE 0.183 $/kWh and NPC $470,037, respectively. Awaran has 8.74% lower LCOE than DI Khan. The reason behind higher LCOE and NPC is lowest average solar irradiance in DI Khan. There is 99.3% share of PV in Awaran and lowest of 99.1% in DI Khan. Table A14 shows the configuration's component sizes and other technical information. Figure 4.2(b) depicts a comparison of NPC and LCOE for PV, DG with battery storage. For the proposed system configuration, Figure 4.3(b) shows that PV is the primary source of energy used to serve the load and battery used to store it, but during downtime, battery is not enough to serve the load. So, DG as backup is used to supply the load and fulfil energy demand. Battery and DG are vital in maintaining a minimum dispatch strategy to provide the most effective electrification solution.

4.1.3 PV, Wind with battery storage

Feasibility studies reveal that Balochistan and Sindh areas have a significant potential for wind resources. Optimization results shows Bhmraani is most feasible and South Waziristan is least feasible site having lowest LCOE of 0.157 $/kWh, NPC $404,905 and highest LCOE of 0.18 $/kWh, NPC $462,478, respectively. Bhmraani has 12.8% lower LCOE than South Waziristan. The reason behind higher LCOE and NPC is lowest average wind speed in South Waziristan. The average monthly wind speed for Bhmraani was recorded 5.58 m/s, the highest among all wind-based microgrids. There is 5.1% share of wind in Bhmraani and lowest of 3.3% in South Waziristan. Table A15illustrate configuration's component sizes and technical information. Figure 4.2(c) shows a comparison of NPC and LCOE for PV, wind systems with battery storage. Figure 4.3(c) illustrates that PV and wind are used to generate electricity for proposed configuration, and a battery is employed as a backup for anonymous hours. Annual maximum share of wind energy is observed as 24.9% in Tharparkar. In winter, wind speed is low, however in summer, significant amounts of energy are generated by wind.

4.1.4 PV, Hydro with battery storage

Hydel power is a widely adopted energy source because of its lowest operational costs and it is the primary source of energy in Pakistan. In this study, an optimal PV-Hydro configuration with battery backup is determined to be the most viable for Chilas, with LCOE and NPC of 0.120 $/kWh and $420,347, respectively. This site has the highest yearly streamflow rate compared to other sites (see Table 4.1), resulting in the lowest LCOE. While proposed configuration offers the least NPC due to the highest energy share of hydel i.e. 61%, while 39% share by PV because of lower average solar irradiance of the day. Figure 4.2(d) depicted a comparison of NPC and LCOE for PV, hydro system with battery storage. Table A16 shows the configuration's component sizes and other technical information. Hydro is available all year round, but its production falls during the peak winter months, prohibiting it from meeting the energy demand shown in Figure 4.3(d). During the day, PV also contributes to the load, while the battery takes over at night.

4.1.5 PV, Hydro with DG backup

In northern areas of Pakistan, the sunshine hours are fewer in the winter season as compared to rest of all areas. The hydro-flow will become very low which will affect the output of turbine. Also, snowfall in several locations badly affects PV systems, which leads to a significant capacity shortage and reliability challenges. So, DG is used in this study to deal with this problem. Muzaffarabad seems to be most feasible area for this configuration having LCOE and NPC of 0.130 $/kWh and $435,969, respectively. Table A17 shows the configuration's component sizes and other technical information. NPC and LCOE for PV, hydro, and DG backup systems are observed in Figure 4.2(e). DG has only a share of 5.5%; DG only operates in extreme winter months. While in summer season all the demand is fulfilled by PV and hydel depicted in Figure 4.3(e).

4.1.6 PV, Wind, DG with battery storage

A significant amount of solar and wind power makes the energy system more resilient and diversified when combined with DG. Energy security and reliability can be greatly improved by utilizing diversified energy sources. Optimization results reflect Chagai as most feasible and Kalat as least feasible, having LCOE of 0.145 $/kWh, NPC $373,899 and 0.176 $/kWh, NPC $451,676, respectively. The region's LCOE is 17.6% less than Kalat's. The reason behind higher LCOE and NPC is lowest average wind speed and solar irradiance in Kalat. There is maximum renewable share of 99.76% and lowest 0.231% share of DG in Kalat. To provide the most cost-effective solution, the battery and DG's role is to keep dispatch strategy at minimum level. Table A18 shows the configuration's component sizes and other technical information. The comparison study for NPC and LCOE for PV, wind, DG configurations with battery storage is provided in Figure 4.2(f).

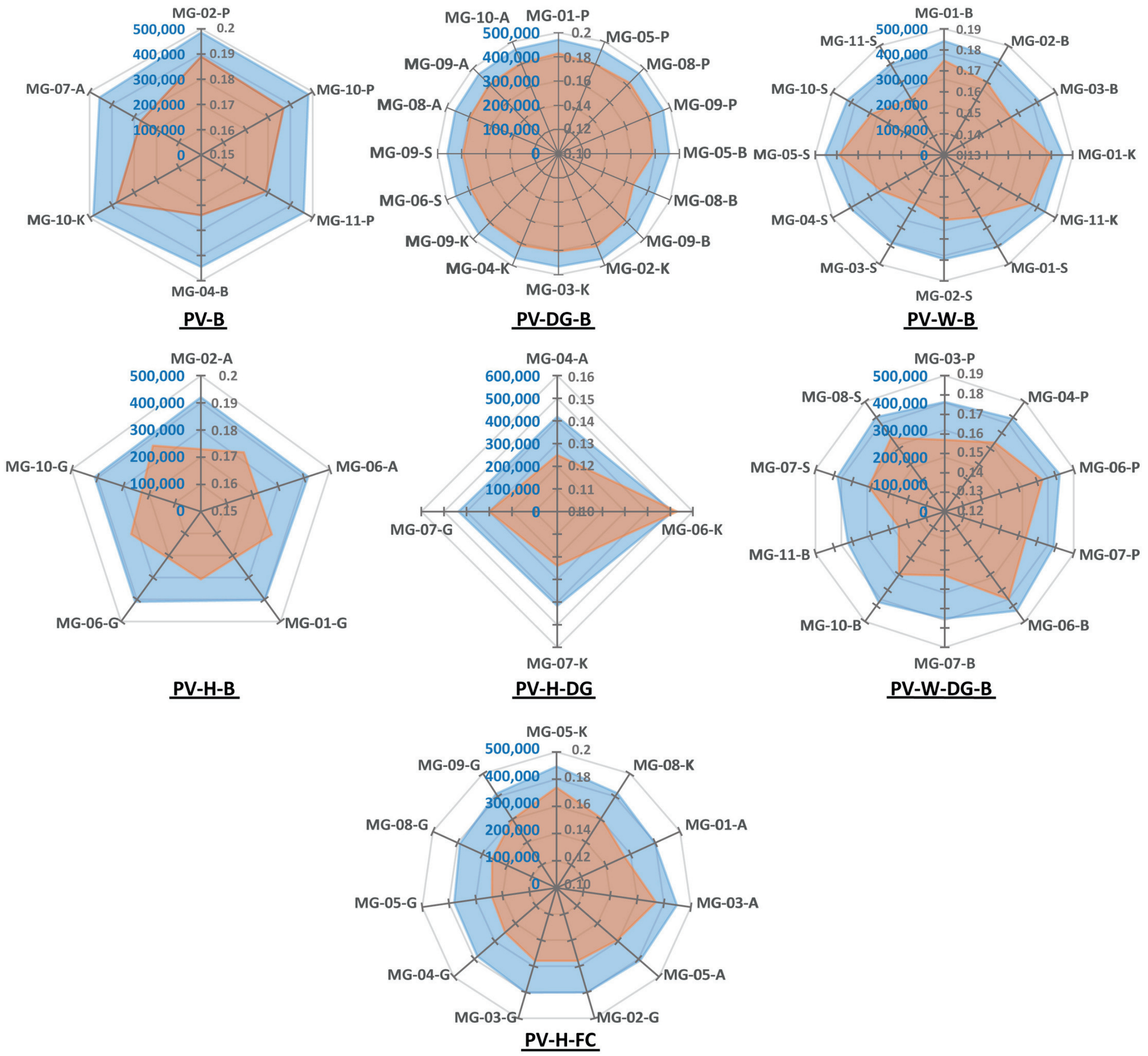


Figure 4.2. *Radar diagrams for NPC and LCOE for Proposed MG's configurations.*

4.1.7 PV, Hydro, Fuel cell with hydrogen storage

Northern areas have high Hydel potential and good solar output in summer, but the problem arises in extreme peak winter months when water bodies freeze. Hydel potential drops almost 10 times lower. The temperature remains almost below than 0⁰C, due to this reason due to this reason both RERs generates too low power and to fulfil the energy demand backup must be required. A new emerging Fuel cell technology is the best solution, as it supplies the power as hydrogen is supplied. Fuel cell is a powerful and useful technology ocused on overcoming the capacity shortage and reliability issues. Ishkoman seems to be the most feasible area for this configuration having LCOE 0.148 $/kWh and NPC $380,104. Meanwhile, similar configuration at Buner experienced highest LCOE of 0.174 $/kWh and NPC of $447,332. From Table 4.1, it comes to knows that Ishkoman is proved to be the most feasible solution with 14.94% lower cost than Buner. Figure 4.2(g) illustrates the NPC and LCOE comparative studies for PV hydro configurations with fuel cells. Table A19 shows the configuration's component sizes and other technical information. It is the optimal configuration of areas with too low temperatures in winters and supplies uninterrupted power as shown in Figure 4.3(g).

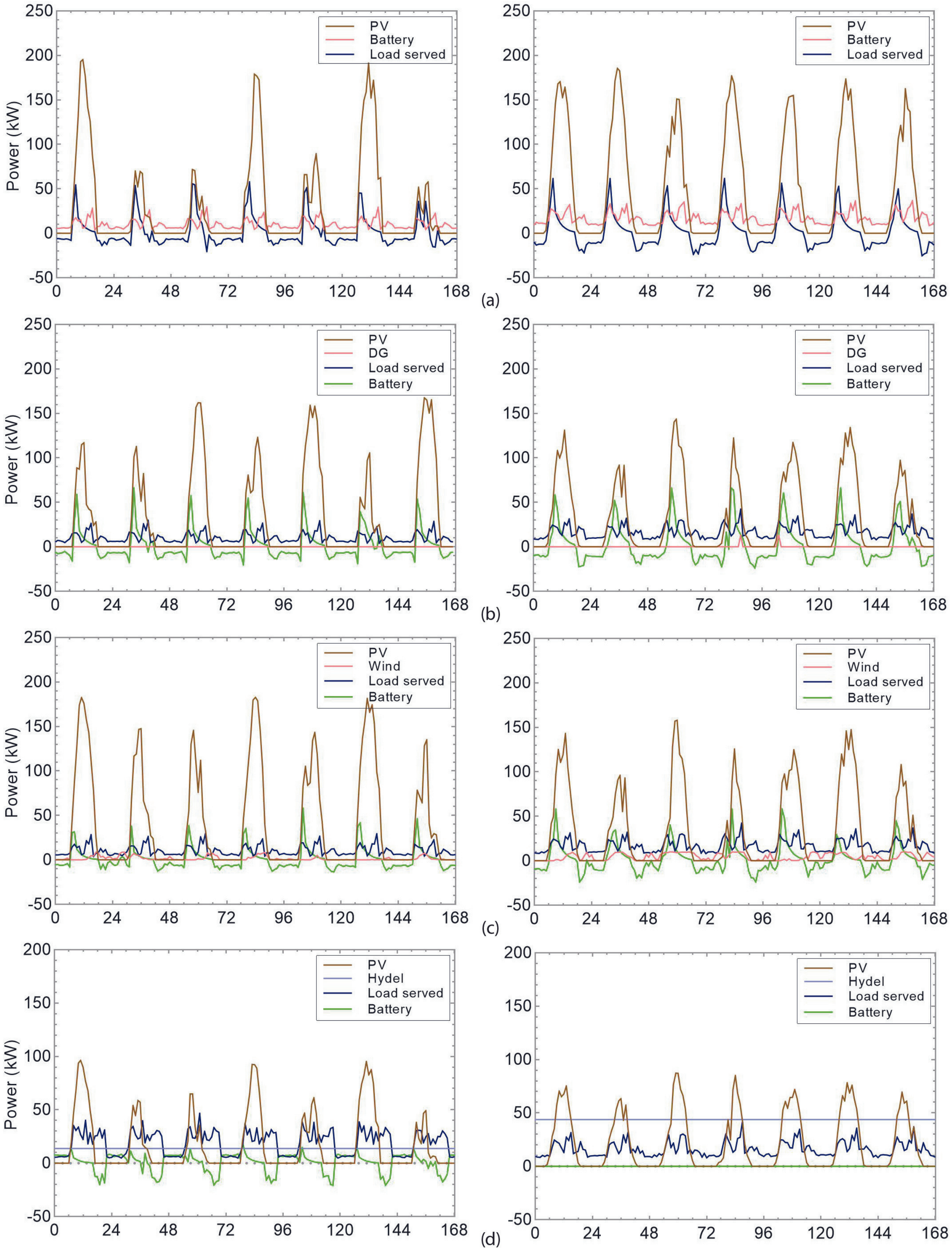


Figure 4.3. *Energy contribution of category-wised proposed MG's configurations with lowest LCOE; (a) PV-B, (b) PV-DG-B, (c) PV-W-B, (d) PV-H-B, (e) PV-H-DG, (f) PV-W-DG-B, and (g)PV-H-FC, respectively.*

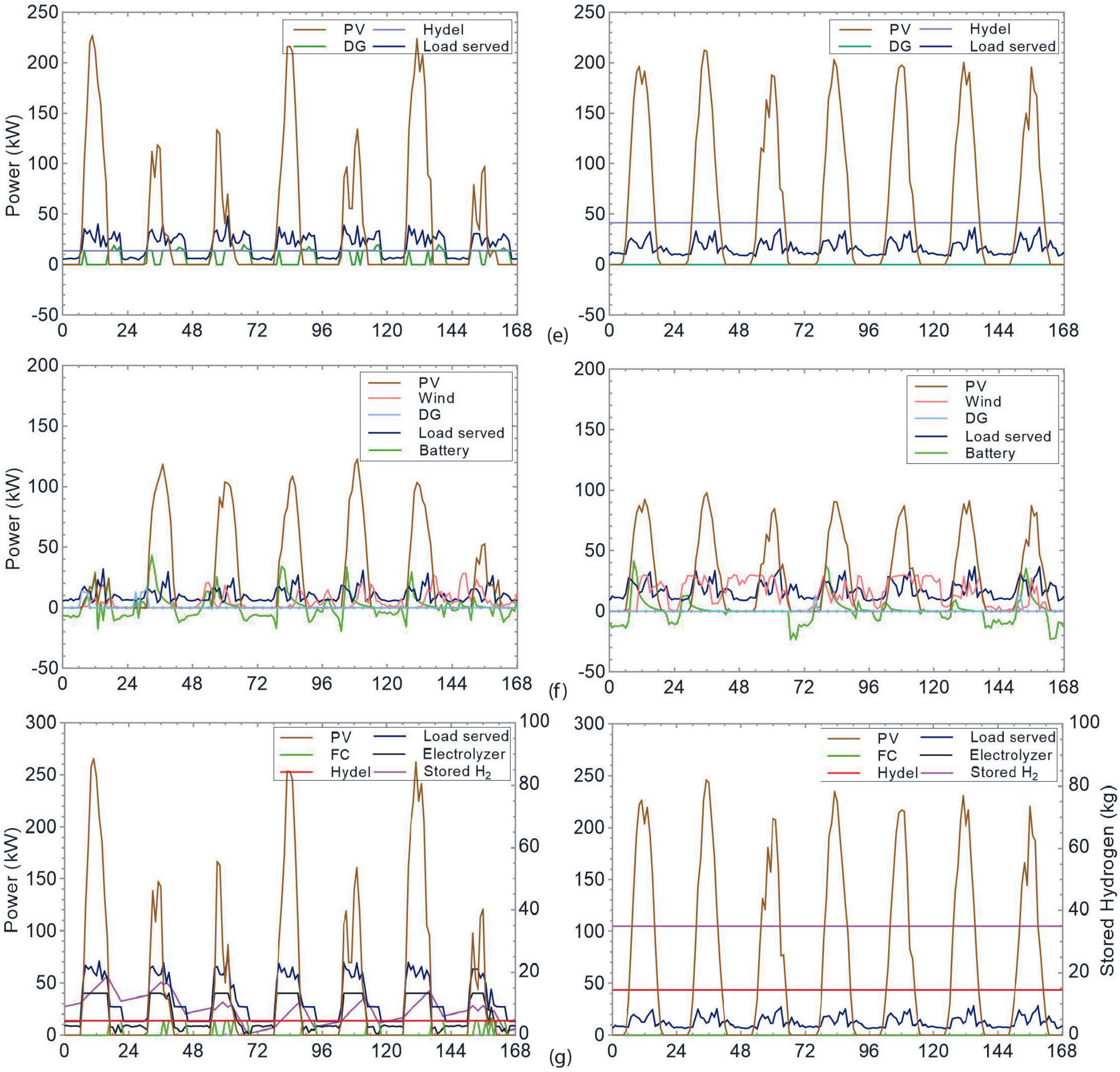


Figure 4.3. *Cont.*

	F.P w.r.t 100% investment by investor			F.P w.r.t 30% investment by investor and 70% loan				F.P w.r.t 100% investment by investor			F.P w.r.t 30% investment by investor and 70% loan		
	IRR	ROI	PBP	IRR	ROI	PBP		IRR	ROI	PBP	IRR	ROI	PBP
MG	(%)	(%)	(Yrs.)	(%)	(%)	(Yrs.)	MG	(%)	(%)	(Yrs.)	(%)	(%)	(Yrs.)
Punjab							**Baluchistan**						
MG-01-P	60.7	54.7	1.58	45.05	42.45	6.92	MG-01-B	66.1	59.8	1.48	48.23	55.85	7.24
MG-02-P	55.3	49.4	1.71	40.91	48.81	7.64	MG-02-B	60.9	55.4	1.59	51.54	49.98	7.28
MG-03-P	66.6	60.4	1.47	53.23	34.91	8.93	MG-03-B	68.8	62.4	1.43	51.4	57.72	7.11
MG-04-P	63.6	57.6	1.53	52.86	34.27	8.93	MG-04-B	70.8	64	1.40	51.57	49.87	6.68
MG-05-P	62.6	56.7	1.54	42.87	36.91	6.91	MG-05-B	66	59.8	1.48	42.11	37.96	6.88
MG-06-P	62.8	56.7	1.54	52.52	39.93	8.74	MG-06-B	54.9	50	1.72	52.39	45.41	8.04
MG-07-P	65.2	59	1.5	53.2	32	9.04	MG-07-B	57	53	1.69	52.89	31	8.39
MG-08-P	60.8	54.9	1.58	51.05	45.89	7.03	MG-08-B	55.7	51.2	1.71	42.44	34.41	7.26
MG-09-P	60.9	55.1	1.58	50.44	45.86	7.04	MG-09-B	65.7	59.5	1.48	50.84	66.28	6.88
MG-10-P	58.1	52.1	1.66	47.3	46.61	7.72	MG-10-B	61.2	56.6	1.58	52.13	43.72	8.48
MG-11-P	58.1	52.1	1.64	47.25	46.59	7.70	MG-11-B	60.9	57.3	1.6	51.61	27.6	9.19
Khyber Pakhtunkhwa							**Sindh**						
MG-01-K	63.7	57.6	1.52	45.29	44.46	6.88	MG-01-S	62.7	57.4	1.55	51.52	47.73	7.92
MG-02-K	60.1	54.2	1.6	45.08	42.45	6.92	MG-02-S	61.9	56.9	1.57	51.56	43.25	8.04
MG-03-K	61.8	55.7	1.56	44.91	42.31	6.91	MG-03-S	69.80	64.4	1.42	51.12	53.34	7.46
MG-04-K	60.8	54.9	1.58	44.05	38.34	6.93	MG-04-S	63.4	58.1	1.54	54.68	48.96	7.95
MG-05-K	28.8	25.7	3.52	34.96	31.69	12.85	MG-05-S	51.7	46.6	1.82	51.25	38.05	8.3
MG-06-K	41.4	38.9	2.44	37.36	20.13	11.91	MG-06-S	65.3	59.1	1.49	42.72	39.21	6.81
MG-07-K	61.6	60.2	1.63	48.49	27.15	9.94	MG-07-S	65.2	59	1.5	48.79	24	8.94
MG-08-K	33.1	30.5	3.12	30.5	27.98	11.94	MG-08-S	53.2	48.9	1.78	49.1	25.87	8.91
MG-09-K	62.1	56.2	1.55	46.11	47.18	6.86	MG-09-S	66.1	59.9	1.48	43.98	45.09	6.75
MG-10-K	56.4	50.5	1.68	51.46	47.36	6.69	MG-10-S	54.3	49.4	1.75	51.9	35.9	8.22
MG-11-K	54.1	48.9	1.75	51.51	40.92	8.7	MG-11-S	63.4	58.2	1.54	51.7	46.66	8.66
Azad Jammu & Kashmir							**Gilgit Baltistan**						
MG-01-A	36.6	34.6	2.83	34.87	31.56	12.86	MG-01-G	54.3	51.2	1.78	34.39	31.18	9.82
MG-02-A	60.7	57.6	1.62	45.55	41.99	10.24	MG-02-G	28.3	25.4	3.57	26.8	24.46	12.92
MG-03-A	32.7	29.9	3.16	38.36	34.63	11.99	MG-03-G	26.8	24	3.74	25.8	23.91	13.01
MG-04-A	48.5	46.9	2.01	24.95	21.95	10.91	MG-04-G	29	26.3	3.5	29	26.5	12.75
MG-05-A	34.4	32	3.03	24.9	18.44	12.95	MG-05-G	29.7	27	3.42	29.6	27.36	12.15
MG-06-A	53.1	49.9	1.82	44.75	40.75	9.79	MG-06-G	52.6	49.6	1.83	41.47	33.37	10.17
MG-07-A	76.4	68.9	1.32	50.31	38.05	7.52	MG-07-G	52	50.3	1.89	38.97	34.02	9.87
MG-08-A	63.6	57.5	1.53	50.41	41.72	6.96	MG-08-G	28.7	25.9	3.53	26.1	23.21	12.96
MG-09-A	63.1	57	1.54	50.25	42.72	6.98	MG-09-G	27.9	25	3.62	28.6	26.13	12.9
MG-10-A	62.9	56.8	1.54	49.88	40.72	6.97	MG-10-G	50.3	47.3	1.91	37.81	34.39	9.97

Table 4.2. Comparison of different financial mechanisms based on IRR, ROI, and PBP.

4.2 Financial mechanism analysis

The debt financing method is explored to enhance the overall efficiency of energy projects. The analysis considers two different business models: one where investors have 100% equity stake and another where debt financing is utilized with a 7:3 ratio between loan and equity. Initially, the study examines the scenario where investors have 100% equity stake, and parameters such as internal rate of return (IRR), return on investment (ROI), and payback period (PBP) are assessed. The results of this analysis are presented in Table 4.2, indicating that for the MG-01-P project, the PBP is 1.58 years under the first business model. On the other hand, the study explores the debt financing business model, where investors obtain a loan and have their own equity share. In this case, the PBP increases to 6.92 years compared to the equity-only model. Additionally, the IRR decreases from 60.7% to 45.05%, and the ROI decreases from 54.7% to 42.25%. These findings highlight the impact of debt financing on the financial performance indicators of energy projects. The longer payback period, reduced IRR, and lower ROI under the debt financing model reflect the influence of debt obligations on project economics. While debt financing can provide access to capital and enable project implementation, it also introduces financial obligations that affect the project's financial returns.

4.3 Environmental analysis

In the sustainability assessment of the proposed sites, the study considers social, economic, and environmental aspects. Environmental analysis focuses on greenhouse gas (GHG) emissions, with a specific emphasis on carbon dioxide (CO2) emissions due to their significant contribution to global warming. The assessment covers the entire life cycle (25 years) of the hybrid renewable energy systems. To calculate CO2 emissions, the study utilizes emission factors associated with overall fuel usage and system simulations. Since DG (diesel generator) is considered as the primary source of energy in certain scenarios, the emissions resulting from its operation are quantified. Two different load profiles for warm and cold areas are considered, and the study calculates the CO2 emissions if all the energy demand is met by the DG. For warm areas, the emissions are estimated to be 154,887 kg/year, while for cold areas, the emissions are estimated to be 172,537 kg/year. Among all the sites examined, MG-07-K (Chitral) is identified as having the highest carbon emissions, with an estimated value of 15,475 kg/year. This suggests that the reliance on DG as the main energy source in Chitral leads to higher carbon emissions compared to other sites. By quantifying CO2 emissions, the study provides valuable insights into the environmental impact of the proposed hybrid renewable energy systems. This information aids in assessing the sustainability and carbon footprint of the energy projects, allowing for comparisons and identification of sites with higher emissions. The findings highlight the importance of transitioning towards renewable energy sources to reduce carbon emissions and mitigate climate change.

In contrast to relying solely on DG, the combination of PV (solar), wind, or hydel (hydro) energy sources in the proposed hybrid renewable energy systems leads to zero carbon emissions. This is because these renewable energy sources do not involve the use of diesel generators, which significantly contributes to carbon emissions. The study demonstrates that by incorporating PV, wind, or hydel energy, the average gross annual CO2 emissions can be reduced by up to 99%. This ndicates a substantial reduction in carbon emissions and highlights the environmental benefits of transitioning to renewable energy sources. The summarized results for carbon emissions across all proposed MGs are presented in Table 4.1. Additionally, Figure 4.4 provides a visual representation of the percentage reduction in CO2 emissions at each respective site. These findings underscore the significant contribution of renewable energy sources in mitigating greenhouse gas emissions and promoting a more sustainable and environmentally friendly energy generation system.

4.4 Social parameters analysis

In this study, the author conducted an analysis to examine the relationship between job creation and its impact on individuals and communities. The findings indicate that job creation has a significant positive impact on people's lives. The study reveals that job creation leads to increased income and economic stability for individuals. This, in turn, can contribute to improved living standards and a reduction in poverty levels. When individuals have access to employment opportunities and stable income, they are more

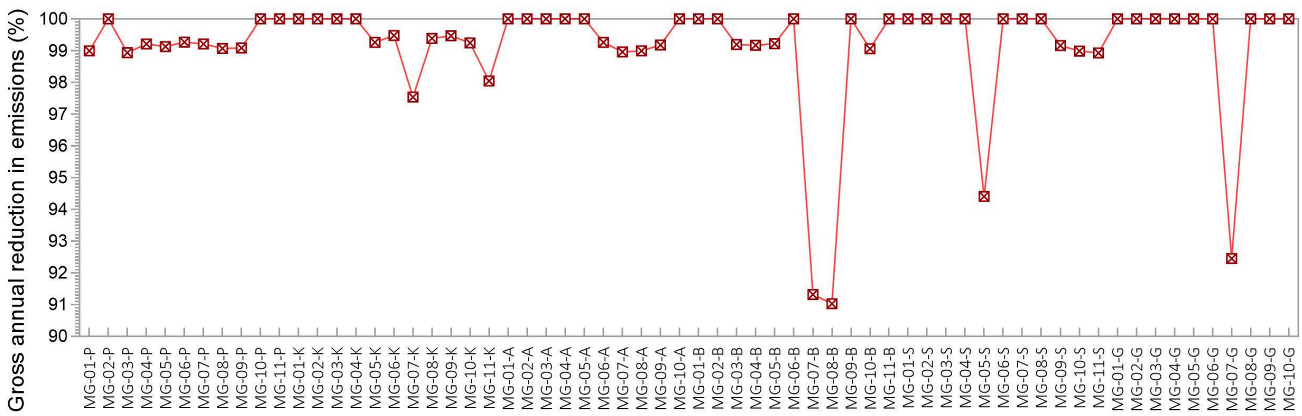


Figure 4.4. *Gross annual CO2 emissions reduction for proposed MG's.*

Job Creations/Yr=	MG-1	MG-2	MG-3	MG-4	MG-5	MG-6	MG-7	MG-8	MG-9	MG-10	MG-11
Punjab	0.009876	0.0095	0.00757	0.009674	0.00920	0.00923	0.00874	0.00957	0.00956	0.00986	0.008
Baluchistan	0.011059	0.01121	0.01185	0.00836	0.00856	0.00806	0.00964	0.00948	0.00881	0.00720	0.00821
KPK	0.014556	0.00987	0.01023	0.00980	0.05834	0.05996	0.05677	0.05830	0.00993	0.00941	0.01368
Sindh	0.011274	0.01181	0.01136	0.01211	0.00819	0.00857	0.00787	0.00794	0.00845	0.01082	0.01108
AJK	0.056363	0.05802	0.05717	0.05799	0.05812	0.05956	0.01078	0.00942	0.00952	0.00948	-
GB	0.057449	0.06330	0.06264	0.06330	0.06285	0.06166	0.06090	0.06168	0.06057	0.06412	-

Table 4.3. *Gross annual CO2 emissions reduction for proposed MG's.*

likely to experience positive social outcomes, such as improved access to basic amenities, better healthcare, and enhanced educational opportunities for themselves and their families. The analysis conducted in this study provides valuable insights into the social impacts of job creation in the context of the proposed hybrid renewable energy systems. By summarizing the results for the social criterion across all the proposed MGs in Table 4.3, the study highlights the overall positive effects on individuals and communities. Understanding the social behavior and impacts of job creation is essential for policymakers, project developers, and stakeholders involved in renewable energy projects. The findings of this analysis contribute to the broader understanding of the social and economic benefits that can arise from the implementation of renewable energy solutions, particularly in rural areas. By creating employment opportunities, renewable energy projects can foster sustainable development, improve livelihoods, and enhance social well-being.

4.5 Breakeven grid distance analysis

In this study, the feasibility and cost-effectiveness of proposed hybrid renewable energy systems (HRES) and grid extension are assessed for remote areas where communities currently live without electricity. The breakeven grid distance is calculated to determine whether it is more economical to implement the HRES or extend the grid infrastructure. To investigate the breakeven distance, the study conducts a grid extension analysis. The specific distances are outlined in the table for different regions: Punjab, Balochistan, KPK, Sindh, AJK, and GB. Figure 4.5 visually presents the breakeven distance for each division, providing a clear illustration of the point at which the cost-effectiveness of the HRES surpasses that of grid extension. By comparing the costs and benefits of both opti-ons the study determines the breakeven distance, beyond which implementing the HRES becomes a more economically viable choice. These results help inform decision-makers and stakeholders regarding the most suitable approach for electrification in remote areas. By considering the breakeven distances and cost-effectiveness, policymakers can make informed decisions on whether to invest in grid extension or prioritize the implementation of HRES to provide reliable and sustainable electricity access to these underserved communities. Table 4.4 provides the specific distances, measured in kilometers, at which the HRES is considered more cost-effective than grid extension in the respective regions. This information aids in determining the optimal electrification strategies and highlights the economic advantages of adopting HRES in remote areas.

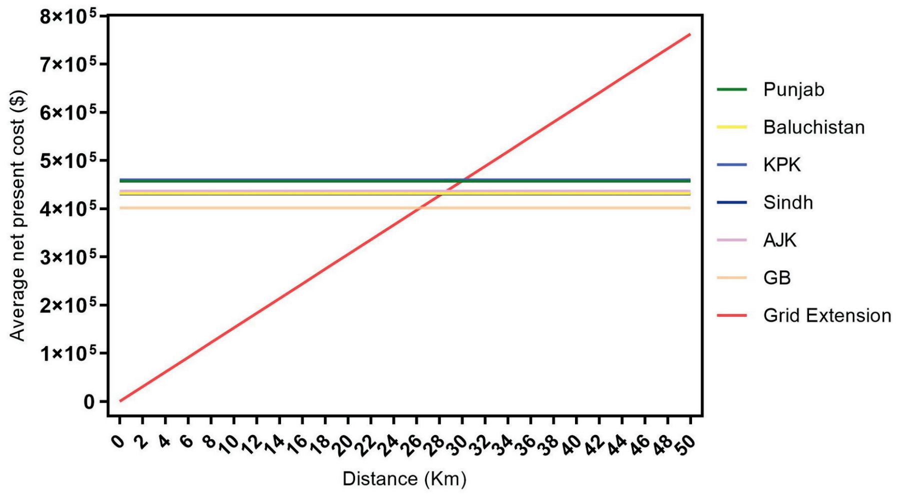


Figure 4.5. *Geographical region-based comparison between breakeven grid distance and grid extension..*

Km	MG-1	MG-2	MG-3	MG-4	MG-5	MG-6	MG-7	MG-8	MG-9	MG-10	MG-11
Punjab	30.867	31.803	26.444	30.169	30.426	29.204	27.642	30.791	30.770	31.499	30.140
Baluchistan	29.600	28.641	28.013	29.879	29.992	29.609	25.803	28.175	30.026	27.044	24.510
KPK	30.317	30.812	30.570	30.662	29.324	33.575	27.310	27.165	30.566	31.684	29.649
Sindh	27.635	27.113	26.543	27.709	30.291	30.067	27.243	28.185	30.123	28.455	27.146
AJK	26.071	27.555	29.356	28.579	26.743	27.256	29.158	30.239	30.514	30.604	-
GB	26.384	26.285	26.365	25.271	24.917	26.962	27.507	25.661	26.982	26.959	-

Table 4.4. *MG's based breakeven grid distance for grid extensions.*

4.6 Sensitivity analysis

A number of sensitive parameters influence the system's total NPC, LCOE, and technical performance. HOMER analyses sensitive parameters, and their corresponding values can be incorporated into HOMER. Further analysis was conducted to determine how the parameters affected the technical and financial results. The uncertain parameters for the present study are estimated to be the nominal discount rate, inflation rate, solar irradiance, wind speed, load demand, and project lifetime.

4.6.1 Nominal discount rate and inflation rate

The sensitivity analysis conducted for discount and inflation rates, the reference values of 9.75% for the discount rate and 8.5% for the inflation rate were used. The analysis examined the impact of varying these rates with an expected variance of 1% on the levelized cost of energy (LCOE) and net present cost (NPC) of the hybrid renewable energy systems (HRES). When the discount rate is increased, the LCOE of the HRES also increases, moving from $0.167/kWh to $0.199/kWh. However, the overall NPC decreases from $548,606 to $412,050, as shown in Figure 4.6(a). This indicates that a higher discount rate leads to increased costs of energy generation but reduced overall project cost. The relationship between the discount rate and LCOE demonstrates the importance of discount rates in determining the economic viability of the HRES.

On the other hand, the inflation rate at the time of project commissioning affects the capital cost of the HRES. As the inflation rate increases, the LCOE decreases from $0.199/kWh to $0.168/kWh. However, the overall NPC increases from $410,469 to $548,000, as illustrated in Figure 4.6(b). This suggests that a higher inflation rate results in reduced costs of energy generation but higher overall project costs. The relationship between the inflation rate and NPC highlights the significance of considering inflation rates when assessing the financial aspects of the HRES.

4.6.2 Solar irradiance and Wind speed

A sensitivity analysis was performed to examine the effects of varying average solar irradiance and wind speed on the hybrid renewable energy system (HRES). The reference values used for the analysis were 5.29 kWh/m2/day for solar irradiance and 4.0 m/s for wind speed, with an expected variation of ±2% and ±10% for each parameter, respectively. The analysis revealed that changes in solar irradiance have a noticeable impact on the levelized cost of energy (LCOE) and net present cost (NPC) of the HRES. As solar irradiance increases by 2%, the LCOE decreases from $0.18290/kWh to $0.18035/kWh, and the NPC decreases from $470,024 to $465,898, as depicted in Figure 4.6(c). This suggests that higher solar irradiance levels lead to reduced costs of energy generation and overall project costs.

Similarly, changes in wind speed also influence the LCOE and NPC of the HRES. When the wind speed increases by 10%, both the LCOE and NPC decrease significantly. Specifically, the LCOE decreases from $0.183/kWh to $0.162/kWh, and the NPC decreases from $471,086 to $415,989, as shown in Figure 4.6(d). This indicates that higher wind speeds result in lower costs of energy generation and overall project costs. Comparing the sensitivity of LCOE and NPC to solar irradiance and wind speed, it is observed that LCOE and NPC are more sensitive to changes in solar irradiance than in wind speed. This suggests that variations in solar irradiance have a greater impact on the financial outcomes of the HRES compared to changes in wind speed.

4.6.3 Load demand and project lifetime

In future scenarios, factors such as population growth or rising living standards can lead to an increase in the system's load. The sensitivity analysis conducted on the hybrid renewable energy system (HRES) reveals the impact of load variations on the LCOE and NPC. As the load increases, the LCOE of the HRES decreases from \$0.185/kWh to \$0.170/kWh, indicating that higher loads result in reduced costs of energy generation, as shown in Figure 4.6(e). However, the overall NPC increases from \$439,479 to \$466,568, implying that higher loads lead to increased project costs. This relationship between load and LCOE/NPC highlights the economic implications of meeting increased energy demand.

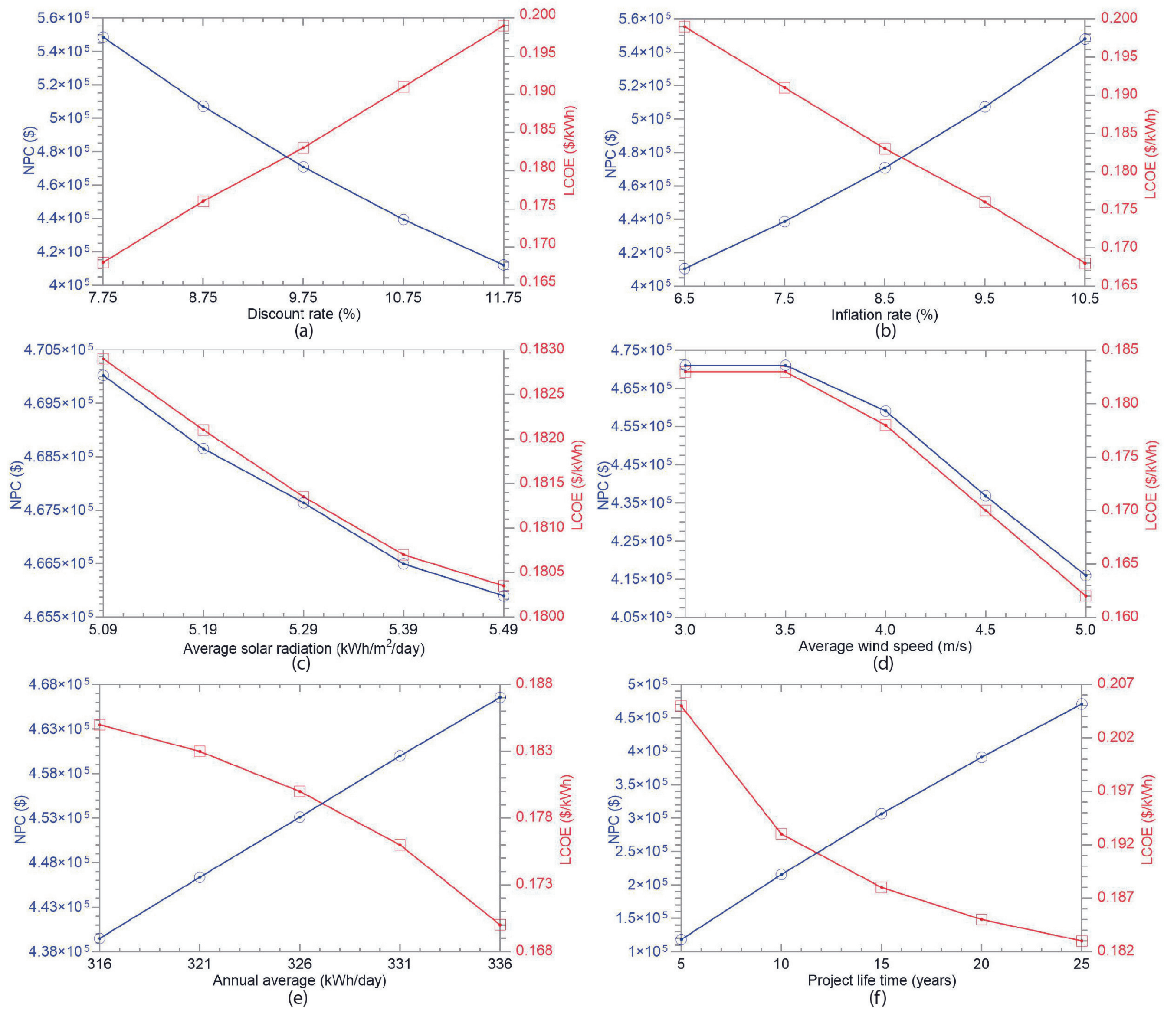


Figure 4.6. *Effect of variation in (a) DR, (b) IR, (c) Solar radiation, (d) Wind speed, (e) Load, and (f) Project life on NPC and LCOE.*

Additionally, the project lifetime is identified as another sensitive parameter that affects the economic parameters of the HRES. When the project's lifetime is decreased, the LCOE decreases from $0.205/kWh to $0.183/kWh, while the NPC increases from $118,094 to $470,867, as depicted in Figure 4.6(f). This suggests that shorter project lifetimes lead to lower costs of energy generation but higher overall project costs. The observed trends can be attributed to the economies of scale and the relationship between quantity and unit pricing. As the load or quantity of energy demand increases, the per-unit pricing tends to decrease, resulting in lower LCOE. Conversely, when the project lifetime decreases, the overall costs are distributed over a shorter period, leading to higher unit pricing (LCOE) and overall project costs (NPC). These findings highlight the importance of considering future load projections and project lifetime when evaluating the economic viability of the HRES. By understanding the sensitivity of LCOE and NPC to load variations and project lifetime, stakeholders can make informed decisions regarding system design, capacity planning, and financial feasibility assessments..

4.7 Robust analysis

To assess the robustness and reliability of the proposed hybrid renewable energy systems (HRES), a comprehensive analysis was conducted across the five different climatic zones of Pakistan. The analysis aimed to evaluate the system's ability to meet the load demand consistently throughout the year, considering variations in solar irradiance and load demand due to weather conditions. Table 4.1 presents the results of the analysis, including the unmet load and capacity shortage factor for each configuration. The unmet load indicates the portion of the load demand that could not be met by the HRES, while the capacity shortage factor represents the extent of capacity shortfall in meeting the load demand.

Based on the findings, it is concluded that the unmet load and capacity shortage factors are all below 1% for all the configurations. This implies that the proposed energy systems are capable of fulfilling the energy requirements of the remote communities across all seasons. The robustness analysis confirms that the HRES configurations can reliably meet the load demand, considering the variations in solar irradiance and load throughout the year. The results provide assurance that the proposed HRES configurations are technically robust and capable of providing reliable electricity supply to remote communities in different climatic zones of Pakistan. This information is valuable for decision-makers, stakeholders, and investors in planning and implementing sustainable energy solutions in these regions.

4.8 Comparison of proposed energy systems

Table 4.5 provides insights into the average levelized cost of electricity (LCOE) for different configurations of the hybrid renewable energy systems. Among the various configurations, the optimal system with a combination of PV-Hydro and battery backup demonstrates the most cost-effective and feasible option, with the lowest average LCOE of 0.12269 $/kWh. This configuration benefits from the utilization of both solar PV and hydropower resources, along with energy storage in batteries. On the other hand, the region with the maximum share of PV resources experiences the highest LCOE of 0.18233 $/kWh. This is primarily attributed to the high initial and replacement costs associated with the battery storage system, which is necessary to ensure continuous power supply when solar irradiance is low or during nighttime hours. The analysis also reveals that the Punjab region has the highest average LCOE of 0.17645 $/kWh. This can be attributed to the significant share of expenditures allocated to the battery storage system in this region. Additionally, the high temperatures experienced in Punjab during the summer season contribute to thermal losses in the PV system, leading to reduced electrical performance and increased costs.

In contrast, the Gilgit Baltistan region has the lowest average LCOE of 0.14125 $/kWh. This is primarily due to the availability of abundant hydropower potential, which offers the

Parameters	NPC ($)	LCOE ($/kWh)
System Configuration		
PV-B	468,229.51	0.18233
PV-DG-B	462,609.37	0.17975
PV-W-B	433,634.49	0.16849
PV-H-DG	446,093.10	0.13301
PV-H-B	412,233.98	0.12269
PV-H-FC	407,916.03	0.15861
PV-W-G-B	417,102.10	0.16199
Province division		
Punjab	453,933.18	0.17645
Baluchistan	431,703.82	0.16772
KPK	459,912.36	0.17118
Sindh	430,617.04	0.16727
AJK	436,403.41	0.15811
GB	401,651.58	0.14125

Table 4.5. *Average NPC and LCOE for each proposed system configuration and province division.*

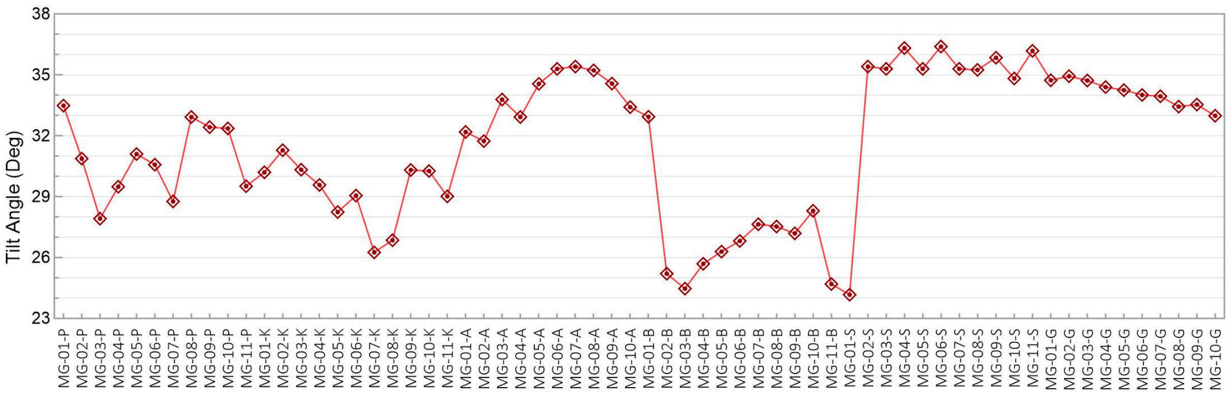


Figure 4.7. *Site-optimal tilt angles for proposed MG's.*

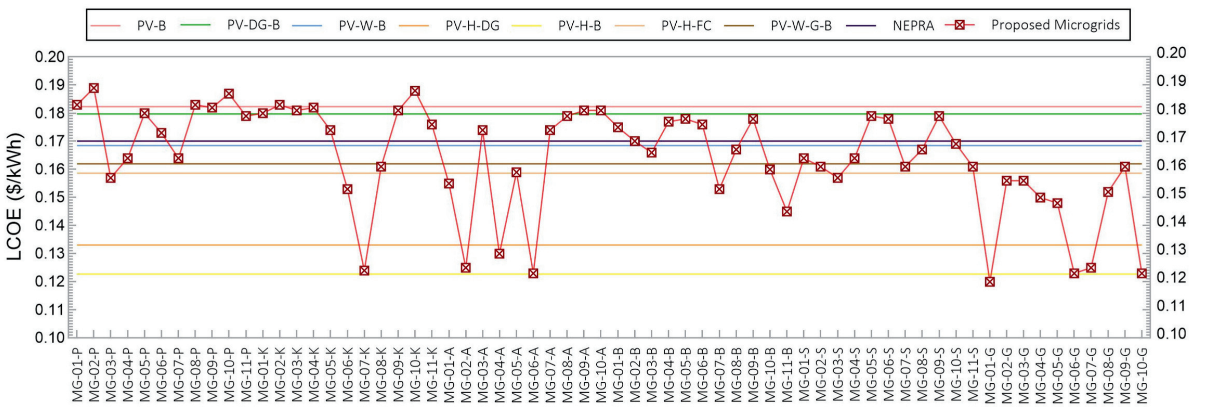


Figure 4.6. *Comparative LCOE-based evaluation of proposed HRES configurations*

advantage of low running costs for hydropower-based plants. Figure 4.7 details of the optimal orientation for PV panels at each respective site, showcasing the most efficient positioning for solar energy generation. Figure 4.8 visually presents a comparative analysis based on the LCOE of the proposed HRES configurations, offering a comprehensive overview of the cost-effectiveness of each system. These findings contribute to the selection of the most economically viable and efficient configurations for the electrification of remote areas, considering factors such as resource availability, cost implications, and regional variations.

5. Existing Policies Overview and Proposed Business Models

Pakistan's energy sector is experiencing notable transformations driven by various policies aimed at promoting renewable energy, improving energy efficiency, and ensuring sustainability. These policies create opportunities for potential business models to flourish and contribute to the country's energy transition.

5.1 Analysis of Existing Relevant Policies

5.1.1 ARE Policy 2019

According to the ARE Policy 2019 in Pakistan, Microgrids (MGs) are a vital component of the country's renewable energy targets. The policy sets ambitious goals, aiming to achieve at least 20 percent of on-grid renewable energy generation capacity by 2025 and increase it to at least 30 percent by 2030. These targets reflect the government's commitment to promoting sustainable energy solutions and reducing reliance on fossil fuels. Under the ARE Policy 2019, MG projects funded by the public sector are required to follow a competitive bidding process. This approach ensures transparency, efficiency, and fair market competition in project selection and implementation. Through competitive bidding, the government aims to attract qualified developers and secure the best value for public investments in MG infrastructure. However, private sector projects are exempt from the competitive bidding requirement, allowing greater flexibility for private investors to develop MG's. This exemption encourages private sector participation and investment in the renewable energy sector, promoting innovation and fostering a more diverse and dynamic market. To ensure effective implementation of the policy, ARE Policy 2019 designates the Alternative Energy Development Board (AEDB) as the focal entity responsible for developing and operating MGs in Pakistan. The AEDB plays a pivotal role in facilitating the deployment of MG projects, coordinating with relevant stakeholders, providing technical expertise, and monitoring the progress towards renewable energy targets.

5.1.2 Net Metering Policy

The Net Metering Policy enables consumers to install renewable energy systems, such as solar panels, and sell excess electricity to the grid. It has stimulated the deployment of distributed generation systems and empowered businesses and individuals to become prosumers, reducing their reliance on the grid and generating additional income.

5.1.3 National Electricity Policy 2021

The National Electricity Policy 2021 in Pakistan addresses several key areas within the electricity sector. It emphasizes the need to diversify the energy mix by promoting a balanced portfolio of energy sources, including hydroelectric, thermal, renewable, and nuclear power. The policy aims to enhance power generation capacity, reduce dependence on imported fuels, and meet the growing demand for electricity. Renewable energy development is recognized as crucial for sustainable development and energy security. The policy encourages the development of renewable energy projects, such as wind, solar, biomass, and small hydropower, by providing incentives, policy support, and streamlined regulatory processes. Energy efficiency and conservation are promoted as essential components of the electricity sector. The policy encourages the adoption of energy-efficient technologies, practices, and demand-side management programs to optimize energy consumption and reduce wastage. The policy also addresses the importance of a reliable transmission and distribution network. It emphasizes investments in grid infrastructure, modernization, and interconnection to improve the efficiency, reliability, and quality of electricity supply. Private sector participation is recognized as significant in the electricity sector, and the policy aims to create an enabling environment for private investments. Regulatory reforms are highlighted as vital for transparency, competition, and consumer protection. The policy encourages regulatory changes to promote market competition, remove barriers to entry, and establish fair tariff structures.

5.1.4 Energy Efficiency and Conservation Policies

Pakistan has implemented several policies and programs to enhance energy efficiency and reduce consumption. The National Energy Efficiency and Conservation Act 2016 and Energy Conservation Building Codes promote energy-efficient practices in industries, buildings, and appliances.

5.2 Microgrids align with policies in several ways

Microgrids, when designed and implemented in alignment with relevant policies, can contribute to achieving policy objectives related to renewable energy, energy access, resilience, and sustainability.

- **Renewable Energy Integration:** Microgrids facilitate the integration of renewable energy sources, such as solar and wind, into the electricity system. This aligns with policies that promote renewable energy development, reduce greenhouse gas emissions, and achieve sustainability goals.
- **Energy Access and Electrification**: Microgrids provide electricity access to remote or underserved areas, supporting policies aimed at universal energy access and bridging the energy divide. They enable communities to have reliable and affordable electricity, promoting social and economic development.
- **Resilient and Decentralized Power Systems**: Microgrids enhance the resilience of the power system by enabling localized generation and distribution. They align with policies that promote decentralized energy systems, reduce dependence on centralized grids, and improve system reliability and resilience.
- **Demand Response and Energy Efficiency:** Microgrids enable demand response programs and energy efficiency measures at the local level. They align with policies promoting energy conservation, demand-side management, and efficient use of resources.
- **Innovative Financing Models:** Microgrids can leverage innovative financing models, such as public-private partnerships, ESCOs, or community-based financing, to overcome financial barriers. This aligns with policies aimed at attracting private investment, mobilizing community participation, and ensuring sustainable financing for energy projects

5.3 Proposed Potential Business Models

5.3.1 Private company (Investor-Owned) Microgrids

This business model involves establishing microgrids owned and operated by a private entity and it manages all the works related to O&M, procurement etc. the whole system is under the underserved areas. This model aligns with policies promoting renewable energy access and decentralized energy generation, as it empowers communities and promotes foreign investors and control over energy resources.

5.3.2 Public-Private Partnerships (PPPs)

PPPs can play a vital role in the development of microgrids. Collaborations between public entities (such as government agencies) and private investors or energy companies can leverage resources and expertise. This model aligns with policies that encourage private sector participation and investments in the energy sector while ensuring public oversight and accountability.

5.3.3 Concession Model

Under this model, the government grants a concession to a private investor (Disco) to operate and maintain a power distribution network for a specific period. The disco is responsible for the infrastructure, service delivery, and revenue collection. Banks may provide funding to the disco for infrastructure development or working capital. The government oversees regulatory compliance and ensures service quality.

5.3.4 Energy Service Company (ESCO) Model

ESCOs can establish and operate microgrids, providing reliable and clean electricity to communities or specific customers. ESCOs can leverage their expertise in energy management, financing, and technology deployment to ensure efficient microgrid operation. This model aligns with policies that promote energy efficiency, renewable energy adoption, and private sector participation.

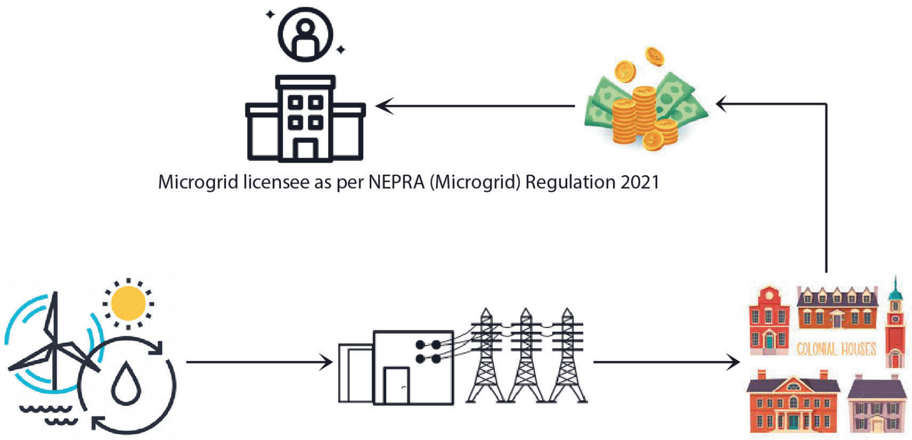
5.3.5 Nationalized Model

In this model, the government may own and operate the power distribution network directly. The disco is a government entity responsible for providing electricity services. Banks may provide loans or financial support to the government for infrastructure development or operational expenses. This model allows the government to have direct control over the electricity distribution sector.

5.3.6 Investor-community-Owned Model

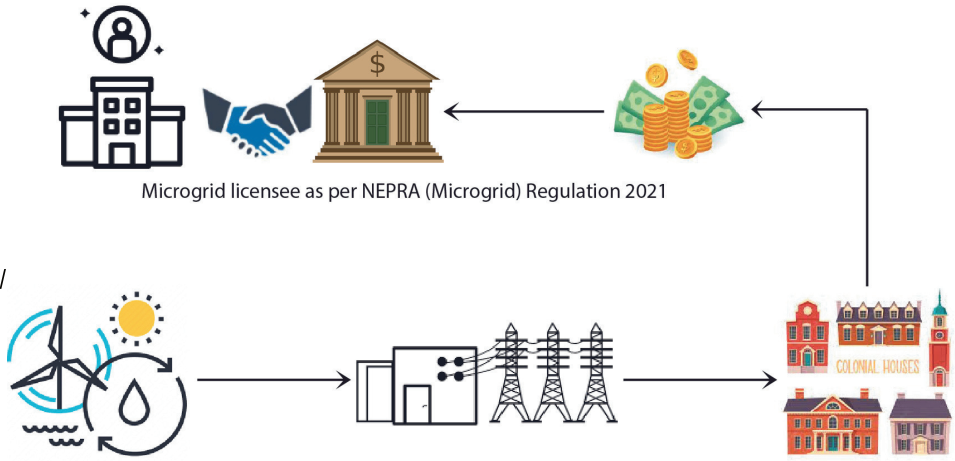
This business model involves establishing microgrids owned and operated by local communities or cooperatives. These microgrids can provide reliable and affordable electricity to underserved areas. This model aligns with policies promoting renewable energy access and decentralized energy generation, as it empowers communities and promotes local ownership and control over energy resources.

The success of any of the proposed business models for microgrids in Pakistan can be influenced by several underlying issues that need to be addressed. These issues include challenges related to grid interconnection, regulations, and standard operating procedures (SOPs) established by the electricity regulator. These factors can potentially impede the economic stimulus and hinder the growth of the microgrid business in the country. By addressing these issues and creating an enabling environment, Pakistan can stimulate economic growth in the microgrid sector, attract investment, promote renewable energy deployment, and enhance energy access for underserved communities.



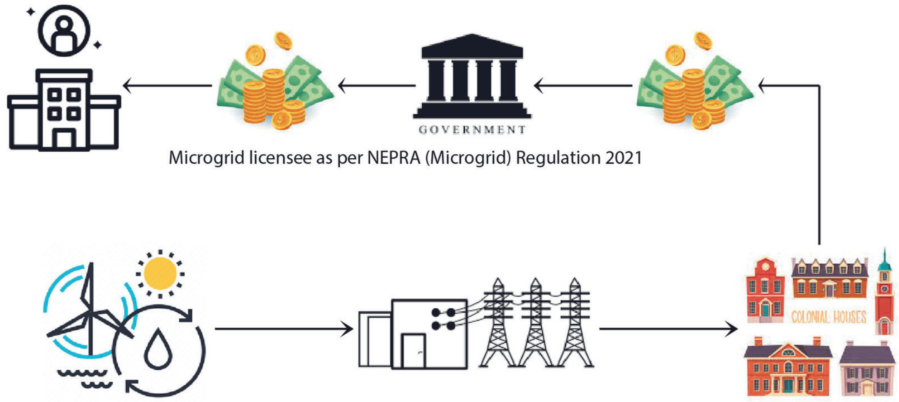
1. MG's owned by the investor and also built and operated by the stackholder.
2. All the services will be provided by stackholder.

***Figure 5.1**. Private company (Investor-Owned) MG Business Model.*



1. MG's owned by the investor and also built and operated by the stackholder.
2. All the services will be provided by private company.
3. Investor works on the capital of a finacing company and capital is managed by bank.

***Figure 5.2**. Public-private partnership MG Business Model*



1. All the services will be provided by DISCO's.
2. Banks may provide funding to the DISCO.
3. Government oversees regulatory compliance and ensures service quality.

***Figure 5.3**. Concession Business Model*

MG Business Model No. 4 - Energy Service Company (ESCO) Model

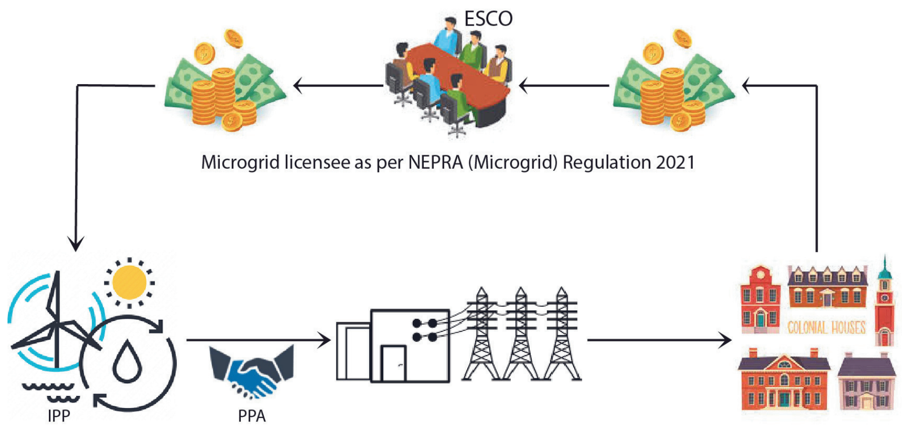


Figure 5.4. *Energy service company (ESCO) Business Model*

1. MG's built and owned by the investor.
2. Land for MG will be owned by the investor.
3. All the services including O&M will be provided by ESCO managed by an investor board.

MG Business Model No. 5 - Nationalized Model

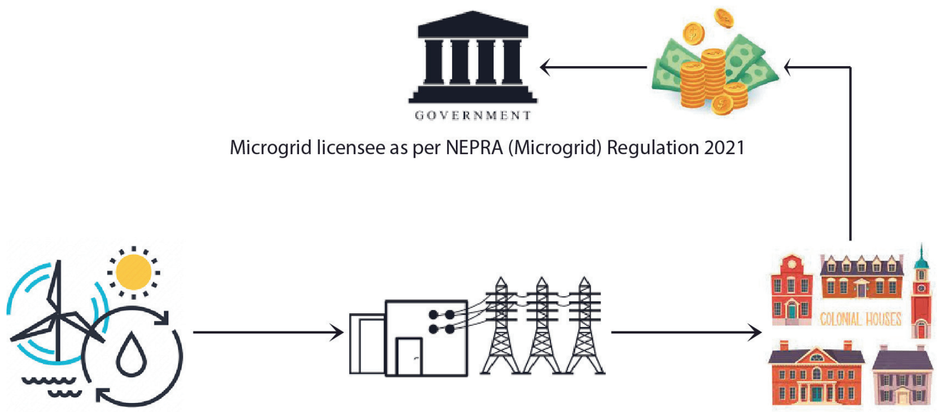


Figure 5.5. *Nationalized Business Model*

1. MG's and generation owned by the government and also built and operated by the government.
2. All the services will be provided by government.
3. Land will be owned by government.

MG Business Model No. 6 - Investor-owned Model with involvement of CBO

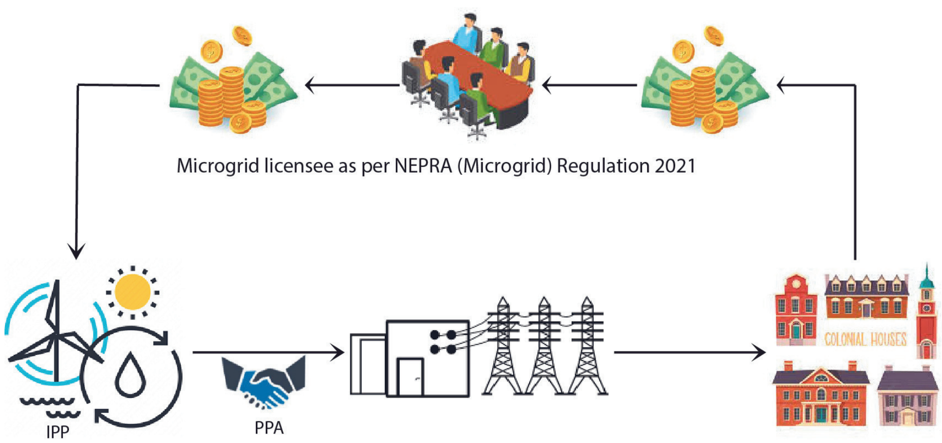


Figure 5.6. *Investor-owned with involvement of CBO Business Model.*

1. MG's built and owned by the investor.
2. Land for MG will be owned by the investor.
3. O&M will be provided by an community based organization managed by the management board.

6. Conclusion and Future Work

To achieve 100% electrification and the 2030 green energy goal for Pakistan, we can explore how these systems can be used to achieve sustainable development goals. Rural electrification is currently and can stay difficult in developing nations like Pakistan. This research is dedicated to designing a technically and economically feasible hybrid off-grid system for remote areas. This comprehensive study is conducted nationwide with diverse renewable energy resources across various climates and territories to utilize them efficiently. The proposed hybrid renewable energy system provides a resilient and reliable power supply. The study mainly focused on the techno-economic and feasibility studies of renewable energy resources. We also covered the environmental and social aspects, breakeven grid distance and sensitivity analysis for underprivileged remote areas of Pakistan. Hydro-based MG's are most feasible in the northern region of the country. PV-wind with battery systems is most feasible for Sindh and Balochistan, while Punjab has good solar potential, so PV with battery systems are most suitable. The proposed PV-hydro with battery system for Chilas offered the least NPC and LCOE of l$402,481 and 0.120$/kWh, respectively, with significant excess energy. In contrast, PV with battery storage system offers the highest NPC and LCOE of $485,144 and 0.189$/kWh. The cost of PV-battery systems is high because of battery systems' replacement and maintenance costs. Furthermore, the problem of low generation during winters associated with cold regions is also encountered by incorporating fuel-cell with hydro and PV. Proposed fuel cell based microgrid for Yasin offered the least NPC and LCOE of $380,104 and 0.148$/kWh. To increase the project's energy efficiency, a customized business model is investigated, and it concluded that debt financing is the best and easiest method; the PBP, ROI and IRR may decrease, but it helps the investor and other stakeholders in the project deployment. PV-B, PV-W-B, PV-H-FC and PV-H-B offer 100% renewable energy systems, making an overall eco-friendly system. There is a small share of DG power in PV-B-DG, PV-W-B-DG, and PV-H-DG. Maximum DG share of 9% is in Chitral, which produces 15,472 Kg/year of GHG emissions. GHG are reduced by up to 99% among all the proposed systems. The quantification is analyzed while the deployment of projects concluded that these systems create good impacts on locals by creating jobs. Further, it is inferred from the study that the favourable way of rural electrification is the deployment of HRES. Before proposing massive transmission and distribution infrastructure investments for remote areas, electricity planners must examine microgrids. In-depth sensitivity analysis inferred that the proposed system is resilient, reliable, secure and robust. It has been observed that if the inflation and discount rates decrease and increase, respectively, there will be a chance for the reduction in project capital costs which decreases NPC and LCOE, which is beneficial for consumers and investors. MG designs should be affordable in each geographical region to achieve a win-win situation for all stakeholders. Pakistan needs a robust policy and regulatory framework to scale up MG deployment.

In the future, we can analyze the energy trading effects while making the system on-grid. Investigate how different policies, such as net metering, feed-in-tariff and carbon credits, impact on the deployment of MG's. It is also can be evaluated the impact of net metering on excess energy and explore how policies can be designed to address energy poverty.

7. Policy Recommendations

For the successful utilization of the proposed study, the following policy recommendations are presented and supported by achieved results.

- ·A comprehensive policy is needed to handle long-term market uncertainty, financial assistance schemes, and centralized grid risks associated with MG deployment in Pakistan. A regulatory framework must handle regulatory obligations, sustainable operation, and cost-recovery procedures.
- ·The geospatial analysis approach is a simplified approach that needs to be used to identify un-electrified remote areas and access renewable potential. Moreover, it can be used for long-term planning for connection with the national grid, and the data can further be used as a reference for future optimal grid expansions. It can support various electric supply companies and concerned authorities for stable renewable penetration in the national grid.
- ·Financial mechanisms needed to implement energy-efficient projects to increase energy efficiency must aim at decreasing the initial capital expense from the investor's perspective. The prime mechanisms of energy projects to increase energy efficiency must include favourable terms for financial leasing, debt financing, tariff regulation, and public-private and municipal-private partnership.

·The environmental aspects need assessment in various areas where DG is coupled with RES as per proportion in favour of RES to provide uninterrupted power supply throughout the year, aiming at reducing carbon emissions as per SDG-7.:

- The break-even distance (BED) should be accessed before building a new infrastructure for remote areas and evaluating the MG deployment before investing huge investments in transmission and distribution networks.
- ·Improved sensitivity analysis must be carried out that can affect the system's NPC and LCOE from the viewpoint of customers, investors, and researchers. Hence it is recommended to take steps towards industry indigenization to keep the parameters in a viable range across future horizons.
- ·Techno-economic feasibility plays a vital role in the successful commissioning of RE projects. The former is required to make the energy system affordable for customers and investors interested in investing in RE projects.
- ·Today MG are deployed with no such compulsory standards given by governing bodies. Such a standard must be applicable for designing and planning of future MG, so they can easily integrate into a centralized grid. These standards must be considered for the continuity of supply and frequency regulation. Furthermore, these factors can improve the network security of our future. That can prevent cyber-attacks on our network.
- ·Provide incentives to stack holders willing to invest in energy projects to power remote areas by making a proper channel for utilizing microgrid applications.
- The proposed Hybrid renewable energy system can help to achieve Pakistan's 2030 green energy goal. Therefore, the government should start state-level R&D programs aiming to explore the potential of different RE resources to meet the country's energy demand and encourage relevant ministries to implement such projects successfully.

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