Techno-Economic Analysis of Grid Connected Hybrid Indigenous Resources Based Energy System Across Various Climate Zones of Pakistan

By

Najib Ul Hassan

(Registration No: 00000363475)

Department of Thermal Energy Engineering

US Pakistan Center for Advanced Study in Energy

National University of Sciences & Technology (NUST)

Islamabad, Pakistan

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Supervisor: Dr. Ali Abbas Kazmi

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Signature: ____________________

Name of Supervisor Dr. Syed Ali Abbas Kazmi

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Signature (HOD): ____________________

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Examination Committee Members

1. Name: Dr. Asif hussain Khoja Signature: ______

2. Name: Dr. Naveed Ahmed Signature: ______

3. Name: Dr. Mustafa Anwar Signature: ______

Supervisor's name: Dr. Syed Ali Abbas Kazmi Signature: ______

Date: 28/08/2024

______
Head of Department

23/01/2025
Date

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______
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Student Name: Najib Ul Hassan Signature: ____________

Examination Committee:

a) GEC Member 1: Dr. Asif Hussain Khoja Signature: ____________
(Associate Professor, HoD, TEE Dept.)

b) GEC Member 2: Dr. Mustafa Anwar Signature: ____________
(Assistant Professor, ESE Dept.)

c) GEC Member 3: Dr. Naveed Ahmed Signature: ____________
(Assistant Professor, TEE Dept.)

Supervisor Name: Dr. Syed Ali Abbas Kazmi Signature: ____________
(Associate Professor, HoD, EPE Dept.)

Name of HOD: Dr. Asif Hussain Khoja Signature: ____________
(Associate Professor, HoD, TEE Dept.)

Name of Principal/Dean: Dr. Adeel Waqas Signature: ____________

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LIST OF ABBREVIATIONS

ADB	Asian Development Bank
BSS	Battery Storage System
CSF	Capacity Shortage Factor
CAPEX	Capital Expenditure
GHG	Green House Gases
HRES	Hybrid Renewable Energy System
H	Hydro
IRR	Internal Rate of Return
IEA	International Energy Agency
LCOE	Levelized Cost of Energy
LF	Load Factor
MG	Microgrid
NPC	Net Present Cost
PBP	Payback Period
PV	Photo Voltaic
ROI	Return on Investment
RF	Renewable Fraction
W	Wind

ABSTRACT

This thesis proposes an integrated assessment approach for the deployment of renewable-based microgrids, emphasizing the utilization of grid-connected indigenous resources across various climatic zones. The study evaluates the techno-economic viability of hybrid renewable energy systems, including PV-hydro and battery systems, to determine their potential for achieving sustainable development goals, specifically in rural and urban electrification. By focusing on five distinct climatic zones, the suggested technique calculates the lowest net present cost (NPC) and levelized cost of energy (LCOE), providing a comprehensive understanding of the economic efficiency of these systems. The framework model presented in this study aims to improve energy efficiency through optimal allocation methods, ensuring that resources are utilized in the most effective manner. Impact evaluations are conducted to assess how the implementation of energy projects can bolster the local economy, providing essential insights into the socio-economic benefits of renewable energy deployment. The paper also includes a comparison analysis, juxtaposing the proposed energy systems with traditional energy solutions to highlight cost and technical advantages. This analysis delves into the implications of undetermined parameters on NPC and LCOE, offering a nuanced perspective on the uncertainties and variabilities inherent in renewable energy projects. By addressing these factors, the study provides a robust foundation for policymakers and stakeholders to make informed decisions about the deployment of renewable-based microgrids. The study shows Hunza (GB) with the lowest LCOE at $0.038/kWh, a 54% reduction compared to Multan's $0.0863/kWh. Thar (Sindh) and Kharan (Balochistan) had LCOEs of $0.0526/kWh and $0.07058/kWh, 39% and 18% lower than Multan, respectively. Madyan (Swat) achieved a 45% reduction with an LCOE of $0.0477/kWh. Through this integrated assessment approach, the paper contributes to the broader discourse on renewable energy, providing practical solutions for enhancing energy access and efficiency. It highlights the need for tailored strategies that account for regional climatic conditions, ensuring that energy solutions are both contextually appropriate and economically feasible. The comprehensive nature of this study, encompassing techno-economic analysis, impact evaluation, and sensitivity analysis, offers a holistic view of the potential benefits and challenges associated with renewable-based microgrids. Ultimately, the paper advocates for the strategic deployment of these systems to achieve long-term sustainability goals, improve energy access, and stimulate local economic growth, paving the way for a more resilient and sustainable energy future.

Keywords: Microgrid, Renewable energy resources, Techno-economic analysis, Net present cost, Carbon Emission

CHAPTER 1: INTRODUCTION

1.1 Background

The primary energy source in the world today is electricity, which is necessary for daily activities including healthcare, entertainment, communication, transportation, and so forth. Along with making life easier, electricity serves as a source of energy for homes, businesses, and mills. The main objectives have been described as providing reliable and secure electrical resources, mitigating environmental impacts, and ensuring universal access to power across all electrical sectors, encompassing socio-economic, political, and geographic aspects [1]. The demand for electricity, which is generated by burning conventional natural resources like coal, oil, gas, etc., has increased in parallel with the world's rapid industrialization and population growth. The burning of these conventional natural resources increases greenhouse gas emissions, or GHGs, which in turn contribute to global warming. The Asian region accounts for around 58.4% of greenhouse gas emissions [2]. The limited natural resources utilized for energy production have a substantial negative effect on the environment. Combusting fossil fuels leads to the emission of over 40% of carbon dioxide (CO_2), a byproduct of energy production [3].

In 2022, the International Energy Agency (IEA) estimates that over 774 million people globally would lack any access to electricity, marking a rise of almost 20 million compared to 2021 [4]. The Asian Development Bank (ADB) reports that over 150 million people across Asia have no access to electricity [2]. Renewable energy sources such as solar, wind, biomass, geothermal, fuel cells, hydropower, ocean waves, and tides have developed because of the growing need for energy worldwide and environmental concerns. Renewable energy-based hybrid systems are well-suited for providing electricity to rural and coastal areas, meeting extended periods of high energy demand, and offering greater efficiency and cost-effectiveness compared to single-source power systems [5]. According to data conducted by IRENA, Asia was at the leading edge of worldwide renewable energy capacity, with an addition of 174.9 GW in 2022, which accounted for 48% of the total global capacity [6].

Pakistan is in the South Asian region and has a population over 225 million. A failure to balance the supply and demand of electricity has led to an energy crisis since 2006. Around 60 percent of the country's electricity comes from thermal power facilities that rely on fossil fuels [7]. During peak summer months, Pakistan's energy demand reaches 6000 MW. The country's distribution capacity is only about 22,000 MW, leaving a 3000 MW deficit [8]. Numerous industries have closed as a result across the nation. This situation had an enormous impact on the country's development. Over 60% of Pakistan's electricity is generated using fossil fuels that are imported from other countries. This method is not economically efficient and has negative impacts on the environment. Shown in Fig. 1(a), other forms of sustainable energy such as offshore wind, biogas, and solar panels only add a small amount—1.79%, 0.5%, and 0.5%, respectively—to the generation mix, despite hydroelectricity holding the second place with a share of 29.01%. Pakistan aims to produce 30% of its electricity from renewable sources by 2030 (Fig. 1(b)) [9]. In addition, nuclear power generates 7.38% of the current total generation.

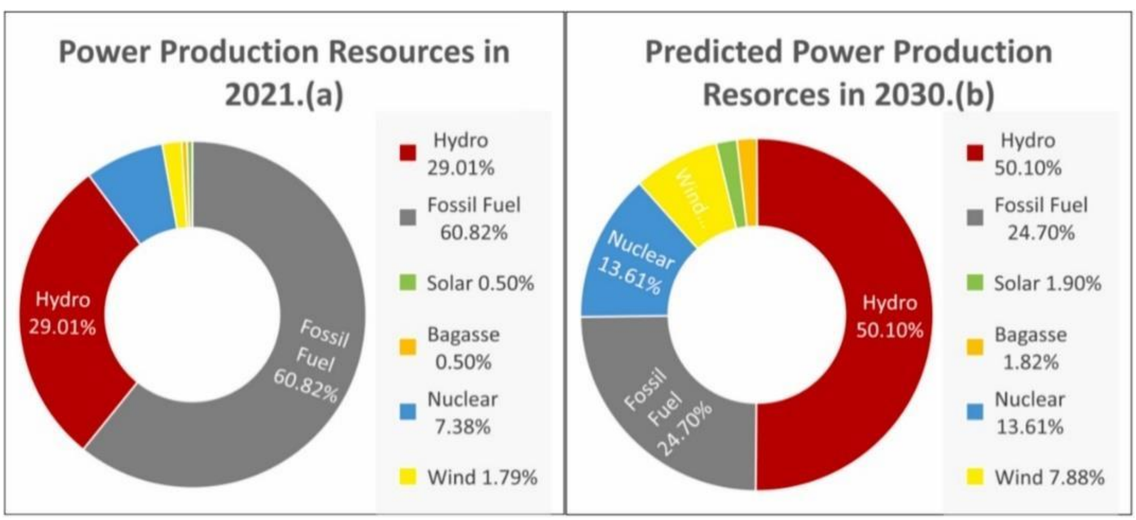

Figure 1.1: Energy production method used in Pakistan by renewable and non-renewable resources [9].

The energy problem is particularly bad in Pakistan's rural areas, where 62.5% of the country's population resides [10]. These regions receive low-quality electricity, with load-shedding lasting up to eighteen hours a day. Research revealed that almost 60% of Pakistan's territory lacks access to the National Power Grid, resulting in a significant decline in the overall quality of life [11]. Due to this, the country urgently needs alternative power sources.

Pakistan is situated at longitudes 61° and 76° E and latitudes 24° and 27° N [12], occupies a strategic geographical position that blesses it with a wealth of renewable energy potential [13]. Solar radiation is abundant throughout the year, with significant variations in intensity depending on location. Pakistan has rich potential of different type of RESs especially solar and wind in southern and southwest which can be utilized to power different BTS in furlong areas [14]. Wind speeds are particularly strong in coastal areas and mountain passes such as in GB in the North [15]. Additionally, hydropower potential exists in the north, while biomass resources are available in agricultural regions. These indigenous resources offer a clean and sustainable alternative to traditional fossil fuels.

However, the intermittent nature of some renewable sources, like solar and wind, presents a hurdle. Solar panels generate no power at night, and wind turbines require sufficient wind speed to operate. To address this intermittency, HRES integrate multiple renewable energy sources along with a connection to the national grid. This allows the system to leverage the strengths of each source – solar can meet daytime demands, while wind can contribute during peak hours. The grid acts as a backup, providing power when renewable generation falls short and absorbing excess energy during periods of high production.

By combining Hybrid renewable energy systems (HRES), utilizing a mix of renewable sources like solar photovoltaic (PV) and hydropower, have been identified as potential solutions for providing least-cost sustainable energy technologies that incorporate battery energy storage systems [16]. These systems are highly effective for rural and urban electrification as they help achieve sustainable development by reducing fossil fuel usage and minimizing greenhouse gas (GHG) emissions [16]. This research aims to analyze the techno-economic feasibility of various HRES configurations, focusing on their applicability in different climatic regions of Pakistan. The proposed systems integrate solar power, Wind Power, hydropower, and battery storage to optimize the use of available renewable energy sources. Extensive analysis is conducted to identify the most optimal system configuration, considering factors such as net present cost (NPC), levelized cost of energy (LCOE), and GHG emissions. This approach ensures that the chosen configurations provide cost-effective, reliable, and environmentally sustainable energy solutions for diverse climatic conditions in Pakistan.

1.2 Motivation

Due to the increasing global energy demand and environmental concerns, it is imperative to replace traditional fossil fuels with sustainable renewable energy sources. Pakistan, despite having abundant solar and wind energy resources, is facing a significant energy crisis exacerbated by an inadequate power infrastructure and an unsustainable dependence on fossil fuels. The pressing need to address the energy shortfall, especially in rural areas where load shedding negatively affects quality of life, is the driving force for this research. This study intends to utilize the nation's unique renewable resources by investigating hybrid renewable energy systems (HRES), which integrate solar, wind, hydropower, and battery storage to offer a reliable and affordable energy solution.

HRES has the potential to provide a reliable, sustainable, and environmentally friendly alternative to traditional energy systems, which motivates this research. The proposed solutions aim not just to close the energy deficit, but also to reduce greenhouse gas emissions and combat climate change. The Aim of this study are to identify the optimal system designs concerning system reliability in providing energy security, economic viability, and acceptable environmental impacts by focusing on the techno-economic aspects of different HRES configurations. Finally, this work seeks to contribute towards the achievement of the set 30 percent renewable energy generation by 2030 to enable sustainable development in Pakistan and provision of healthy living for the people.

1.3 Problem statement

This has been attributed to the growing need for electricity across the globe, advanced industrialization besides population growth leading to the increased consumption of fossil fuels thereby causing Green House emissions and global warming. In Pakistan this problem is more sensitive because of energy shortage, which is evident in the form of power scarcity in the country and even if sometimes generated there is a wide gap between demand and supply. Over 60% of electricity in Pakistan is produced from imported oil and coal which is un-economical and unsustainable. Also, there are power outages in rural areas, most of them are not connected to the national grid, hence worsening the standards of living.

Pakistan has a tremendously abundant resource, particularly in the field of renewable energy especially in solar and wind that can no longer be ignored in the regular energy structure to form sustainable energy solutions. However, the problem arising here is that these renewable energies are intermittent and thus are not ideal when it comes to warranting steady power output. These problems are going to be addressed in this study by examining the techno-economic feasibility of integrated renewable sources such as solar, wind, and hydropower together with battery storage which is known as the hybrid renewable energy systems (HRES). Analyzing multiple configurations of HRES to achieve generation and energy storage, the study will also compare net present cost, levelized cost of energy, and greenhouse gas emission to offer Pakistan's diverse climatic zones a reliable, cost-effective, and sustainable solution.

1.4 Objectives

The objectives are listed below

- To analyze the grid connected hybrid energy system using geospatial information and simulated data.

- To alleviate the energy shortage, which lasts for up to 16 hours through hybrid-based energy system to satisfy the load demand.
- To evaluate the potential reduction in carbon emissions achieved through the implementation of hybrid-based energy system.

SUMMARY

Approximately 10% of people from the total population of world have no access to electricity. Those people belong to remote areas. Pakistan is one among those third world countries. Pakistan's energy generation is primarily reliant on fossil fuels, which, due to the country's enormous population and rapid industrialization, are unable to fulfil actual energy demands. Northern areas of Pakistan have a lot of potential of hydel power and solar energy. While in Punjab solar energy is more abundant, Sindh and Balochistan Solar as well as wind energy is available. In this Chapter, the introduction background of current energy scenario across globe and Pakistan is presented. Moreover, a geographical and energy economics details of Pakistan is presented. The aims and objectives discussed in terms of enhancing the national energy mix (NEM) and electrifying all the un-electrified areas. The goal of this research is to carry out a techno-economic optimization and sustainability assessment to assess the performance of hybrid renewable standalone energy infrastructure based on sites across different climatic zones.

CHAPTER 2: LITERATURE REVIEW

This chapter examines the literature and theoretical background of hybrid energy sources (HESs) around the world, as well as the reported feasibility studies in literature, the main performance indicating parameters, performance analysis of installed hybrid renewable MG's infrastructure in various countries, and the impact of climatic parameters on system performance. This chapter also includes a detailed explanation of the principles used throughout the feasibility study as well as an overview of hybrid energy sources. The literature review for this study is carried out in three folds: a primary fold, finding the significance of On-Grid HRESs and their role in sustainability assessment and development. As a secondary fold, present the techno-economic evaluation of On-grid HRESs concerning various assessment indicators.

2.1 Techno-economic Evaluation of on-grid HERS

In the literature, various authors have proposed RE-based MGs as a substitute to fossil fuel-based energy systems for On-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 RE-based systems. In this scenario, a battery energy storage system is emphasized.

In this paper Dwipen Boruah et al [17] offers a feasibility study of the grid-connected photovoltaic (PV) facility with battery energy storage in India that effectively utilizes the concept of a net-zero energy control system to exclude the usage of the grid and fossil fuel backup systems. The Life Cycle Cost & LCOE analysis has clearly shown that the most feasible intervention is a 200 kWp PV plant with a 250-kWh battery and net metering which costs INR 4 million. $ 0.21/kWH and the payback period are expected to be six years. 15 years. up planners and project consultants use Solar Labs, PV System, HOMER grid software, and Excel sheets to plan the system and/ or to model the finances.

This means that the strategy is feasible to be implemented in the long-term global business of commercial PV power generation.

Musong L. Katche et al [18] focuses on the techno-economic analysis of grid-connected PV hybrid systems for large Institutional consumers and takes Moi University Kenya as the case study. The least expensive system with no battery storage, which is a solar PV/grid, has LOCE at KSH 8. 74/kWh (USD 0. 072), an NPC of KSH 27,974,492 (USD 230,813) and a payback period of 5. 08 years. It has been noted that this solution reduces the university's electricity bill to an 83.94% while cutting down on energy consumption by 67.1% using renewable energy.

Chauhan et al [19]focuses on techno-economic analysis of an Integrated Renewable Energy System (IRES) for electrical and cooking energy demands of the remote rural people of Chamoli district, Uttarakhand, India. It assesses the potential of local renewable resources and selects the appropriate model of the small wind turbines for the site. Nine possible renewable energy combinations are evaluated using economic, technological, and social criteria. A sensitivity analysis finds the most important parameter affecting system performance.

In this study N. Chinna Alluraiah [20] develops an efficient hybrid microgrid system for supplying sustainable electricity to Doddipalli hamlet, located in Chittoor, Andhra Pradesh, India. The system incorporates a hydrogen tank for effective energy management. By utilizing the HOMER program, many setups were assessed, and the most efficient system (comprising of photovoltaic panels, wind turbines, and the electrical grid) was found to have the lowest levelized cost of energy ($0.0751/kWh), the least net present cost ($6.92M), and a significant renewable energy proportion (97.8%). In synthesizing the system, several components are realized including a 13.9 kW solar PV system, four 800 kW wind turbines, 10 kg hydrogen storage tank, 700 kW electrolyze, and 94 kW power converter. This design accurately minimizes CO_2 emission while providing cheaper and more reliable electricity at the same time.

Prashant Malik et al [21] investigates the technological, economic, and environmental feasibility of a grid-connected hybrid microgrid in the western Himalayan region that employs solar, wind, and biomass resources. The biomass gasifier/photovoltaic hybrid system is the most cost-effective of the five designs, costing $0.099/kWh and saving 27.8 Mt CO_2/year compared to a diesel-only system. Sensitivity analysis shows how the system responds to changes in solar radiation, real interest rates, biomass gasifier lifespan, and capacity limitations. The findings help planners and policymakers improve biomass-based hybrid systems.

In this paper Catalina Alexandra Sima et al [22] examines a genuine case study of an energy community located on a university campus in the coastal region of Romania. The text examines the incorporation of sustainable energy sources, intelligent power grids, and blockchain technology for the purpose of controlling energy distribution and financial activities. A strategic investment strategy was carried out to fulfill the load requirement while minimizing expenses and ensuring the reduction of carbon emissions. The defined optimization issue seeks to maximize the campus's profit derived from energy exchanges with the grid, considering the energy consumption patterns of the university. The simulation results are derived from real measurements.

Aswin Anil Bindu et al [23] investigates the possibility of repowering India's wind farms, which were constructed in the early 2000s, with turbines that are larger and more efficient to make the most of the enormous wind potential in the country. In addition, it suggests increasing overall energy output by optimizing land utilization by installing photovoltaic (PV) panels in between turbines to create a more efficient use of land. The utilization of WAsP software for wind resource evaluation ensures that this objective is successfully accomplished. The utilization of this dual-use technique, which gathers energy from both the sun and the wind, helps to promote the development of more environmentally friendly energy sources. Before deciding whether repowering and adding solar panels would be financially feasible and would result in long-term benefits, a comprehensive economic analysis is carried out to determine the answer to these questions.

2.2 From Perspectives of Pakistan

In this study Mansoor Urf Manoo et al [24] compares numerous single systems as well as several systems connected to the electrical grid while focusing on a Pakistani educational institute. The conducted simulations further show that the cost-related indicators, the net present cost as well as the energy cost, are least for the hybrid system connected to the grid, with a value of M$ 1. 536859 and $0. 155/kWh, respectively. Photovoltaic, wind, and fuel cells were proven to be the most viable and cost-effective solution. The report also emphasizes the effectiveness of employing solar and wind resources for hydrogen generation and identifies hydrogen as a more cost-effective long-term energy storage solution than batteries.

In This article Mazhar Ali et al [15] addresses the issue of energy availability for 1.8 million people in Gilgit-Baltistan, Pakistan, by providing cost-effective hybrid renewable energy solutions for 14 sites. According to the analysis, combining wind and hydro with battery backup provides the lowest cost of electricity (COE) ranging from 0.0470-0.0968 $/kWh. Furthermore, 8349 acres of forest are necessary to offset annual CO2 emission and thus large glacier mass reduction and socioeconomic cost from fossil fuel. The authorities are recommending a community-based hybrid system to generate clean, green energy, and at the same time enhance the energy availability in the region.

Abdul Munim Rehmani et al [25] addresses Pakistan's energy crisis by developing simulation-based hybrid systems using photovoltaic, wind, and biomass technologies and comparing their net present cost (NPC), levelized cost of energy (COE), and energy payback period. Four strategies were tested using HOMER Pro as an optimization tool. The solar and biomass system is the most expensive (NPC Rs 18.4M, COE Rs 18.09, and 2.79 years to pay for itself). It costs less to build the wind and biomass systems (NPC Rs 17.8M, COE Rs 17.53, payback 2.28 years). The system that used PV, wind, and biomass all together worked the best, with an NPC of Rs 14.6 million, a COE of Rs 14.40, and a payback time of 2.54 years.

In This article Mansoor Urf Manoo et al [24] suggests different hybrid energy models, such as grid-connected and off-grid systems, to fulfill the power requirements of an educational institution in Pakistan. Analyzed data on electricity demand, geography, and climate to conduct simulations and optimizations for techno-economic feasibility. The hybrid system connected to the grid exhibited the most economical net present cost, amounting to M$ 1.536859, and the lowest cost of energy, which was $0.155 per kilowatt-hour. The study determined that photovoltaic, wind, and fuel cells are the most cost-effective and practical approach, with solar and wind resources also demonstrating efficiency in producing hydrogen and generating power. Hydrogen has proven to be a more economically efficient alternative for storing energy over extended periods, in comparison to batteries.

Gwadar experiences frequent power outages and relies on 70 MW of electricity imported from Iran due to a lack of a utility grid. Three hybrid energy models for Gwadar were evaluated by Muhammad Sharjeel Ali et al [26] using HOMER software for their technological and economic feasibility. Model 1 (PV, wind, batteries) produced 57.37 GWh per year at an LCOE of $0.401 per kWh. Model 2 (PV, wind, grid) generated 81.5 GWh/year with the lowest LCOE of $0.0347/kWh and a renewable fraction of 73.3%, whereas Model 3 (PV, wind, diesel) generated 30.4 GWh/year with the lowest NPC and a payback period of 4.98 years. Model 2 emerged as the best option due to its economic and renewable advantages.

In this study Rafiq Ahmad et al [27] employs particle swarm optimization (PSO) to optimize a hybrid renewable energy system (HRES) for electrifying a rural Pakistani residential building. It assesses off-grid and grid-tied arrangements that minimize the levelized cost of electricity (LCOE) by integrating wind and photovoltaic (PV) systems with battery storage. Dynamic simulations with MATLAB Simulink ensure an optimal energy balance. On an annual basis, the grid-connected HRES generates 146.081 MWh at a levelized cost of energy (LCOE) of $0.29 per kWh, whereas the off-grid system generates 133.533 MWh at an LCOE of $0.91 per kWh. It is important to note that the study highlights the significance of local meteorological data and incorporates multiple case studies to ensure durability.

Jameel Ahmad et al [28] aims at whether a grid-connected hybrid microgrid system that uses wind, photovoltaic, and biomass energy can work in Kallar Kahar, Punjab, Pakistan. The research models the system, does optimization, and provides sensitivity analysis using Homer Pro software to make sure it is robust and cost-effective. With more than 50 MW of power, the hybrid system evenly distributes the load and sends any extra power to the national grid. With an average cost of $0.05744/kWh, the system costs 180.2 million USD for a peak load of 73.6 MW. The study shows that there is a lot of room for making energy production more efficient and less expensive in both homes and businesses.

SUMMARY

This chapter investigates the global literature and theoretical background of hybrid energy sources (HESs), with a focus on feasibility studies, key performance indicators, and climatic effects on system performance. It emphasizes the importance of On-Grid HRESs for sustainability, as well as the role of battery energy storage, given the intermittent nature of renewable energy. The case studies highlighted include grid-connected PV systems with battery storage in India, PV hybrid systems for Kenyan institutions, and Integrated Renewable Energy Systems (IRES) for rural India. Studies in Pakistan compare the economic feasibility of hybrid systems, demonstrating the efficacy of PV, wind, and fuel cells in educational institutions and community settings. Three hybrid models were tested in Gwadar, with the PV, wind, and grid-connected model proving to be the most efficient due to its low LCOE and high renewable fraction. These findings highlight the potential for HESs to provide sustainable, cost-effective energy solutions in a variety of regions.

CHAPTER 3: METHODOLOGY

The rapid acceleration in distribution generation around the world enables several amendments in regulatory frameworks to be introduced in both the developing and developed world.

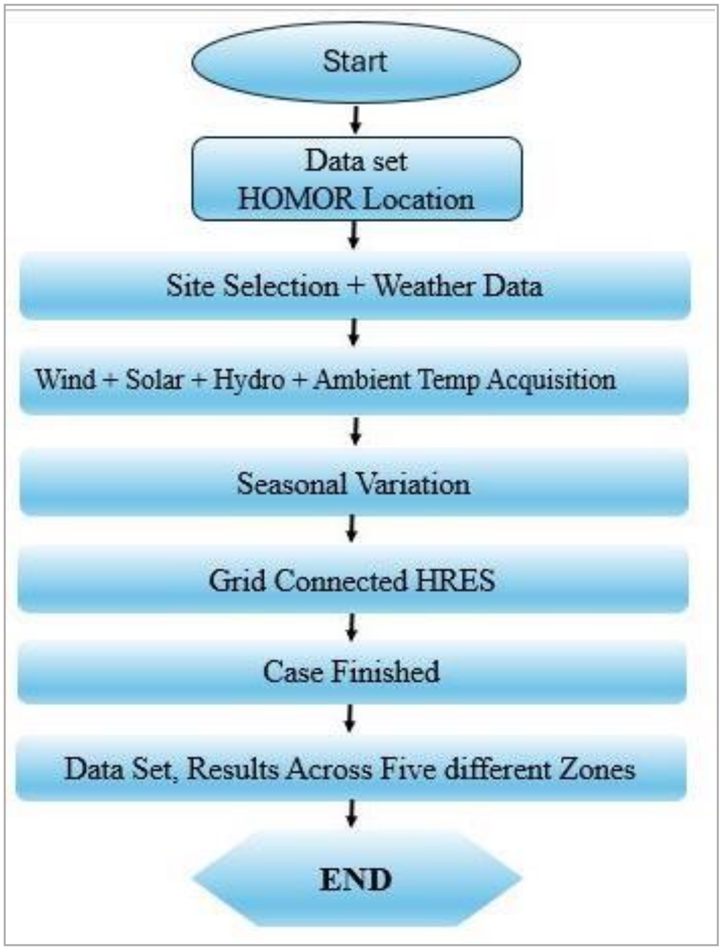

Figure 3.1: Flowchart of Methodology.

3.1 Site Selection and Weather Data

The study assesses hybrid microgrid systems in five different geographic regions of Pakistan, each chosen for its unique climatic characteristics, to determine their adaptability and efficiency. Madyan and Swat (Climate Zone 5A) provide a climate conducive to solar and hydroelectric power; Gilgit, Hunza (Climate Zone 7) presents tough and variable conditions ideal for testing wind and solar energy; Multan, Shuja Abad (Climate Zone 1B) is characterized by hot and dry weather, creating challenges for solar energy efficiency; Kharan, also called (Climate Zone 0B), offers extreme desert and high-temperature conditions, requiring robust system components. The study's goal is to provide adaptable solutions to various climatic difficulties by evaluating the performance of these systems under such varying situations. The research focuses on maximizing energy output, increasing system resilience, and ensuring sustainability in each specific setting. Thar, Islamkot (Climate Zone 2B) provides a wide area suitable for integrating solar and wind energy. Together, these locations provide a diverse testing ground for understanding the performance and scalability of renewable energy systems in varied environmental and meteorological scenarios, paving the way for novel and regional-specific renewable energy solutions. The details regarding site selection data are illustrated in Table 3.1 regarding site selection data used in the methodology.

Table 3.1: Site Selection Data used in the Methodology

S.No	Name	Area	Region	Climate	Coordinates
1	MG-1-KP	Swat	Madyan	5A	35.5N,72.2E
2	MG-1-GB	Gilgit	Hunza	7	35.9N,74.3E
3	MG-1-PJ	Multan	Shuja Abad	1B	30.2N,71.4E
4	MG-1-BH	Balochistan	Kharan	0B	24.7N,70.2E
5	MG-1-SD	Thar	Islamkot	2B	28.6N,56.4E

The climatic assessment of the selected regions emphasizes variations in solar radiation, wind speed, and temperature, all of which are critical for the strategic deployment and efficiency optimization of hybrid microgrid systems. This detailed study allows for the identification of the most appropriate renewable energy resources for each region, resulting in maximum energy yield. Furthermore, it makes it easier to design customized solutions that can endure regional environmental pressures, increasing the reliability and durability of microgrid systems.

3.2 Load Analysis

The load assessment for 20 houses when the houses contain standard electrical appliances provides a good picture of the overall load. Every house has 12 lights, 4 fans, one television, 4 chargers for phone 1 refrigerator 1 iron 1 microwave oven 1 geyser 1 mixer 1 electric heater 1 washing machine 1 AC and one water motor. The ratings for these devices include lights at 9W, fans and TVs at 55W each, phone chargers at 70W, refrigerators at 140W, irons at 1000W, microwave ovens at 600W, geysers at 1000W, mixers at 1000W, electric heaters at 800W, washing machines at 850W, air conditioners at 600W, and water motors at 750W. When applied 20 houses in that case it gives big energy load sum, so, the energy system should be efficiently constructed and effective to supply electricity to the houses. The break-down of load shape suggests system load balancing in accordance with the given activities within the household including lighting and cooling systems, basic appliances, and entertainment appliances where proper energy management proves crucial. The home appliances ratings are illustrated in Table 3.2.

Table 3.2: Home Appliances ratings.

S.No	Devices	Units	Houses	Ratings (Watts)
1	Bulb	12	20	9
2	Fan	4	20	55
3	TV	1	20	55
4	Ph. Charger	4	20	70
5	Refrigerator	1	20	140
6	Iron	1	20	1000
7	Microwave oven	1	20	600
8	geyser	1	20	1000
9	Mmixer	1	20	1000
10	E-heater	1	20	800
11	W-machine	1	20	850
12	AC	1	20	600
13	W.motor	1	20	750

The energy load profiles for Pakistan's five distinct regions—Hunza, Madyan, Kharan, Thar, and Multan—show significant variations due to their unique climatic conditions and energy demands. In Hunza, which has cold winters and mild summers, the energy load peaks during the winter months due to heating requirements. Madyan possesses numbers of load from all the seasons as it is a moderate climate zone, little bit of load may increase in the winter season for heating and in the summer season for cooling. Kharan is characterized by a hot and dry climate and therefore, the energy consumption in the region peaks in summer for refrigeration. Due to cooling demands, Thar's summer load has also risen and because of a dearth in conventional power generation capabilities, it is an urgent case for renewable energies. Last of all, Multan's highly charged load seems to arise in summer owing to air conditioning while winter load is low, again only noted to include lighting and a little heating. All the daily and monthly load profile for twenty homes is given below Fig 3.1 and 3.2.

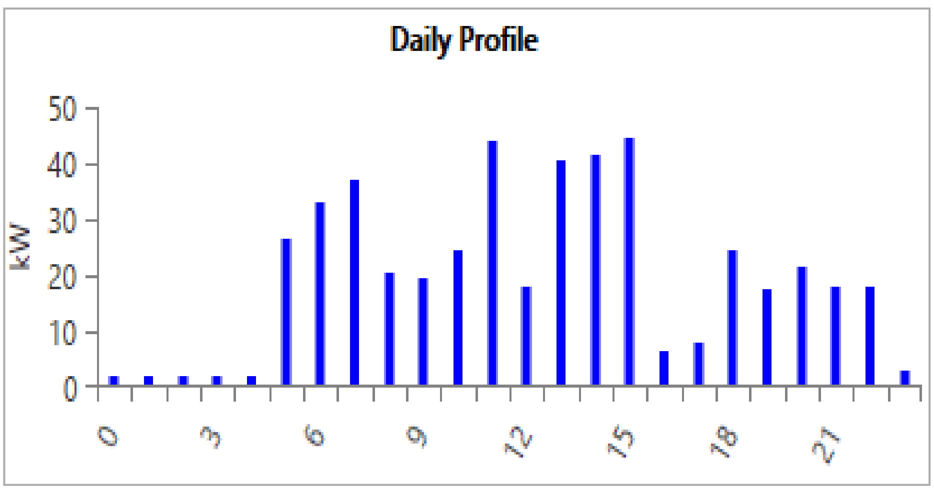

Figure 3.2: Daily Load demand profile across twenty houses.

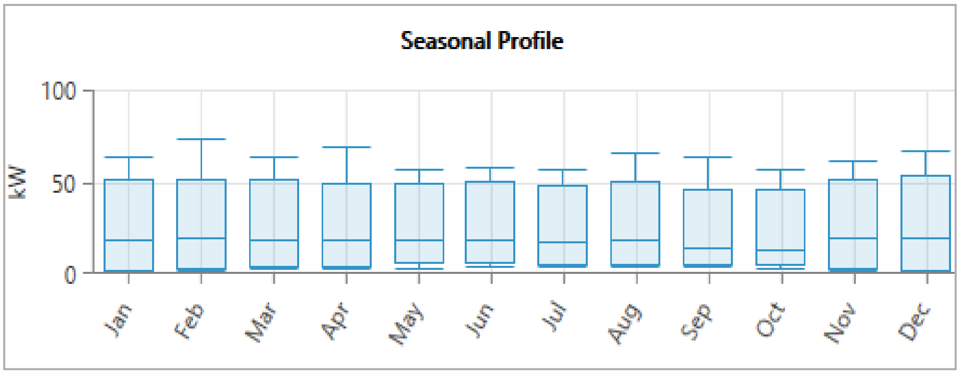

Figure 3.3: Monthly Load Demand Profile across twenty houses.

3.3 Proposed Model for different sites

The system architecture is designed in Homer Pro for techno-economic analysis. PV sources, storage systems, and hydro turbines, as well as a grid-connected system, have been deployed in Swat and Gilgit as shown in Figure 3.4. In Multan, a PV source is installed as shown in Figure 3.5, whereas in Thar and Kharan, a PV source, wind turbine, and storage system are linked to the main grid as shown in Figure 3.6. All renewable resources are chosen based on appropriate weather data to ensure peak performance. The analysis seeks to identify the most cost-effective and environmentally friendly energy solutions for these diverse climatic zones.

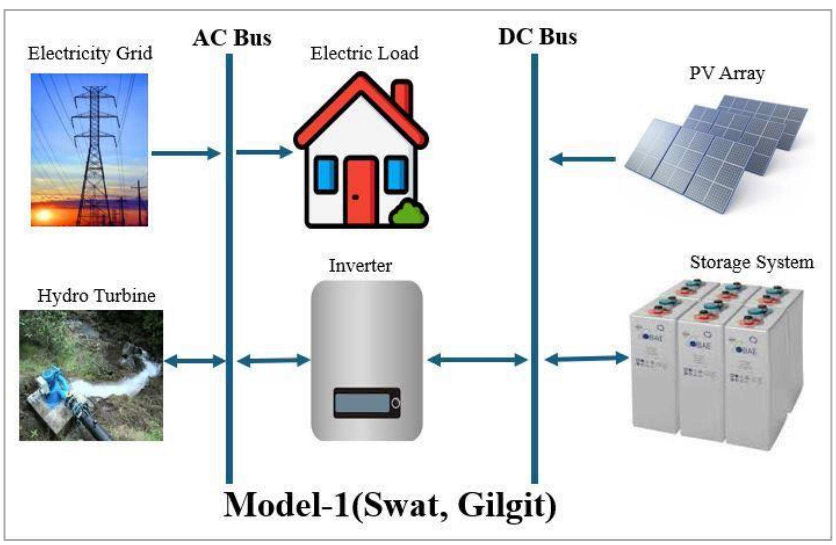

Figure 3.4: Proposed Model for Swat and Gilgit.

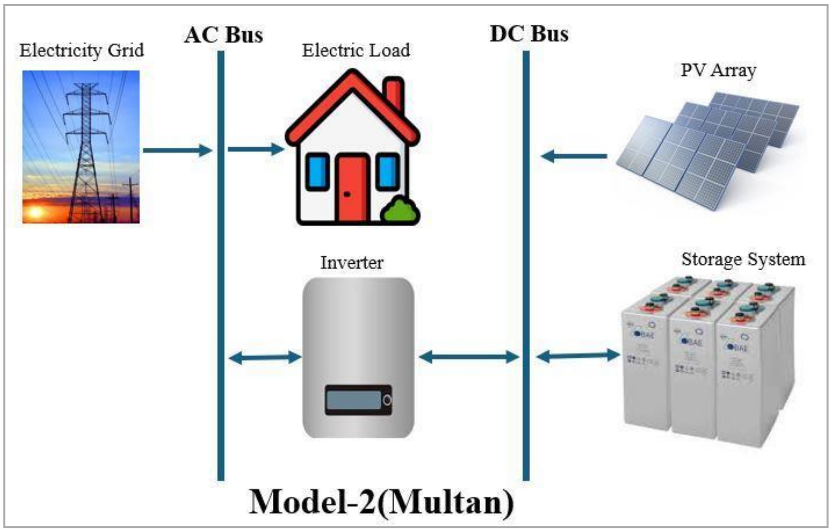

Figure 3.5: Proposed Model for Multan.

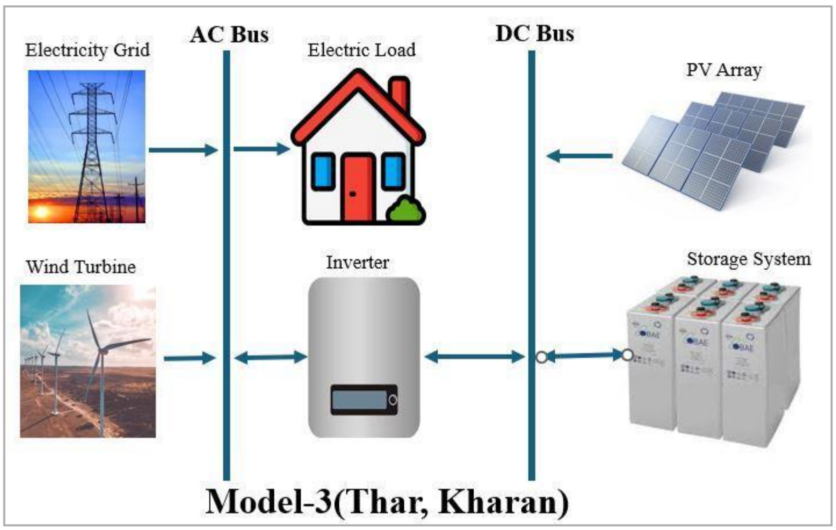

Figure 3.6: Proposed Model for Thar and Kharan.

3.4 Components Data

Below Table 3.3 shows the detailed parameters of different components used in study.

Table 3.3: Components Data of Proposed System

Parameter	Value	Units
PV panel (SunPower475SPR-X22-475-COM)		
Capacity	475	W
Capital	250	$
Replacement	190	$
O&M cost	4.5	$/yr
Temp. effect	-0.352	%/C
NOCT	45.7	C
Efficiency	18	%
Lifetime	25	Year
DE rating	0.05	%/year
Wind turbine (Bergey Excel 6kW)		
Capacity	6	kW
Capital	7500	$/kW
Replacement	7500	$/kW
O&M cost	90	$/year
Lifetime	20	Year
Hub height	30	M
Battery (Fortress Power eVault LFP-15)		
Nominal Capacity	14.4	kWh
Capital	5000	$/kWh
Replacement	4000	$/kWh
O&M cost	50	$/yr
Lifetime	10	Year
Efficiency	98	%
Hydro Turbine (Natel FreeJet FJ-7A 49kW)		
Capacity	49	kW
Capital	89572	$
Replacement	67130	$
O&M cost	4508	$/kW
Lifetime	30	Year
Efficiency	59.52	%
Converter (Auto-size)		

Capacity	1	kW
Capital	160	$/kW
Replacement	160	$/kW
O&M cost	10	$/yr
Lifetime	15	Year
Efficiency	95	%

3.5 Solar Radiation Analysis

In Swat, Madyan, solar radiation averages 4.76 kWh/m²/day and temperatures are mild at 6.28°C. This enhances photovoltaic system performance by reducing thermal losses, which might occur in hotter climates. Gilgit, Hunza has a strong solar potential, with an average radiation rate of 5.24 kWh/m²/day. However, the average temperature is 3.76°C, emphasizing the importance of colder climate-friendly technologies. Multan and Shuja Abad have a high level of solar radiation, with an average of 5.82 kWh/m²/day. However, solar panel efficiency can be greatly impacted by the high temperatures, which reach approximately 33.2°C. In Kharan, solar radiation exceeds 5.5 kWh/m²/day with severe temperatures of 37.4°C, requiring robust and heat-resistant system components.

Thar, Islamkot, with an average solar radiation of 5.67 kWh/m²/day and wind speeds of 5.5 m/s, offers a unique potential to mix solar and wind energy efficiently. Punjab, Multan, and Balochistan, Kharan have significantly higher average solar radiation levels of 4.92 and 5.54 kWh/m²/day, respectively, along with higher average temperatures of 27.45°C and 22.01°C. To ensure maximum solar efficiency in such temperatures, it is necessary to have appropriate cooling systems in place.

The region of Sindh, specifically Thar, experiences an average solar radiation of 5.20 kilowatt-hours per square meter per day. Additionally, it has the greatest average temperature of 28.01 degrees Celsius. These conditions emphasize the necessity for solar harvesting systems with high capacity and efficient thermal management solutions. Moreover, the utilization of energy storage devices is crucial in these regions to uphold a steady energy provision despite elevated temperatures. The project aims to enhance the performance and sustainability of hybrid microgrid systems in different climatic conditions by addressing climate-related challenges.

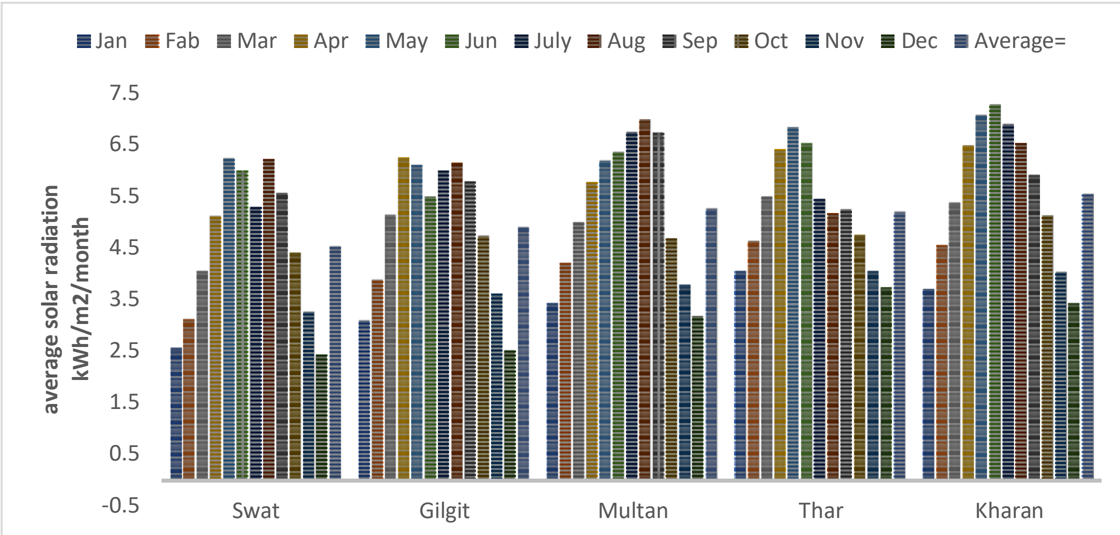

Figure 3.7: Average Solar Radiation Data.

3.6 Wind Speed Assessment

There is significant variation in the potential for wind resources; in Hunza, the average wind speed is lower in Swat, Madyan, and Gilgit, suggesting a restricted amount of wind energy. On the other hand, regions with better wind conditions, such Sindh, Thar, Punjab, and Multan, could effectively be used to augment solar energy, especially during times of low sun irradiation. The total dependability and effectiveness of the hybrid microgrid systems are improved by this complementing strategy. Using wind energy in these areas can also lessen reliance on solar energy alone, resulting in a more resilient and balanced energy mix that can adapt to changing environmental conditions and demand.

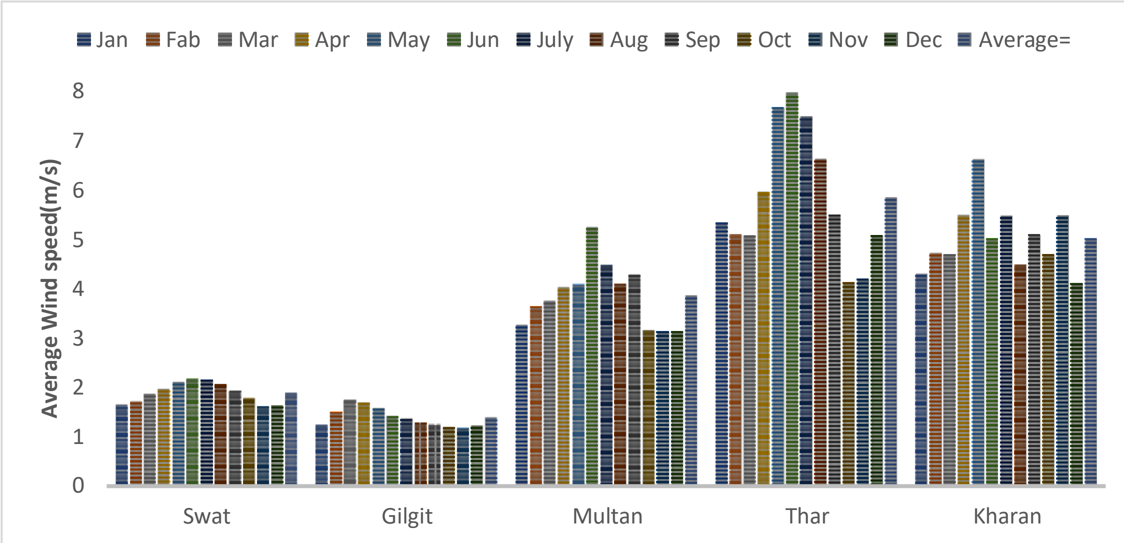

Figure 3.8: Average monthly wind speed Assessment.

3.7 Ambient Temperature Analysis

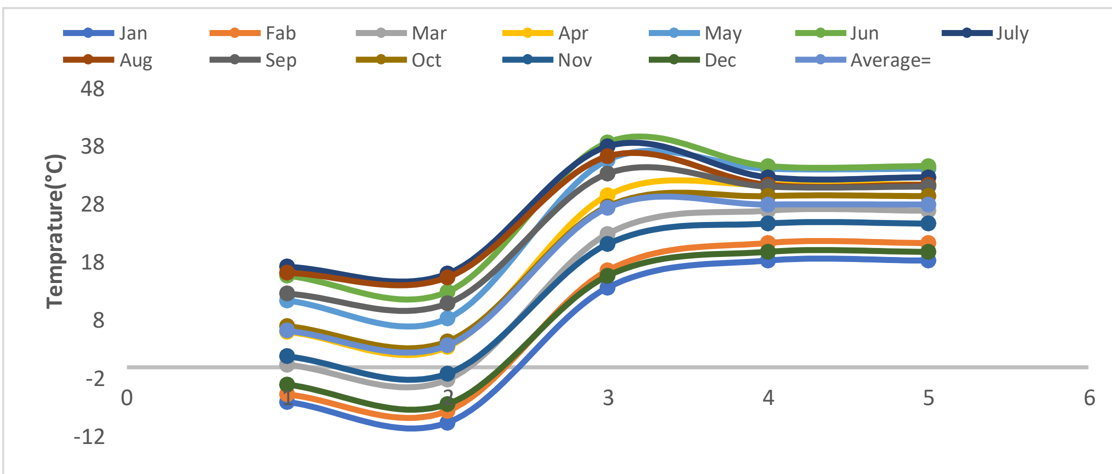

Figure 3.9: Average monthly Ambient Temperature Analysis.

3.8 Hydro Energy Analysis

The hydro energy analysis for five distinct regions in Pakistan—GB, SWAT, Kharan, Thar, and Multan—reveals a wide range of potential due to varying climatic and geographic conditions. GB has abundant mountainous areas and rivers that flow throughout the year; thus, the production of electric power through hydropower is easy to harness due to the difference in altitude and water flow. SWAT also has reasonable amount of hydro potential because of its number of streams and rivers which are appropriate for mini to medium hydro power plants in the Swat valley. While Kharan has tremendous potential in the generation of hydro resources, the climatic conditions are arid and dry which makes the generation of hydroelectricity less viable. Thar is famous for its desert therefore it is not suitable for hydroelectric power generation as it has the least water resources. Multan is warm and arid; however, hydro energy faces limitations; the major source of water is used for irrigation purposes. Thus, the prospect of hydro energy is quite different in these regions, as Hunza and Madyan show good prospects, while Kharan, Thar, and Multan have limited feasibility [29].

3.9 Inflation and Discount rate

While conducting the hybrid renewable energy systems analysis using HOMER software for the assessment of the systems to be installed in different regions of Pakistan, the inflation rate was taken to be 13.5 % and a discount rate of 10%[30]. In Hunza where the weather condition is cold the hybrid system proved to be very efficient by incorporating both Solar and hydro energy. Swat presented the favorable features for solar-hydro hybrid systems; the plentiful hydroelectric resources, favorable climate, and moderate temperature were major positives for this system. Kharan receives very low rainfall and being one of the hottest regions of the country, it mainly focused on the implementation of solar power which is so robust to hot and dry or any other worst climate. Thar region due to its hot desert climate was suitable for solar energy exploitation and got the highest renewable energy fractions. Finally, Multan being in a hot and dry zone of Pakistan had the highest solar energy potential and hence the highest efficiency of the integrated solar PV systems in the hybrid model.

SUMMARY

The study evaluated hybrid microgrid systems based on five assessable climatic zones of Pakistan, including Madyan, Hunza, Multan, Kharan, and Thar, regarding their flexibility and effectiveness in various weather contexts. In the analysis, there are load assessments for twenty houses, the solar radiation, wind speed, the ambient temperature and the hydro energy potential. The outcomes highlight regional-specific renewable energy solutions and focus on the use of solar, wind, and hydro energies to get maximum power generation and system robustness. The study also considers inflation and discount rates in making their recommendations and findings to improve the economic performance of the proposed systems for microgrids, and their applicability in various climates.

CHAPTER 4: RESULTS AND DISCUSSION

HOMER is used to model, optimize, and analyze grid-connected hybrid renewable energy systems for electrifying rural and urban areas in Pakistan's five climate zones. HOMER provides many configurations based on the input data provided in the search space boundaries. Tables in the earlier chapter give comprehensive information on the input parameters utilized for the modeling and optimizing the proposed HRES. Before doing simulations, sun irradiance, wind speed, hydro flowrate, control parameters, and economic parameters were all taken into consideration. High ambient temperature has also been considered because cell temperatures significantly affect the efficiency of PV cells. Furthermore, solar panels are employed without a tracking device. For the maximum efficiency of fixed Solar PV Pannel, the azimuth degree angles are expected to be 180^o degrees, and Pakistan lies between 24^o – 37^o altitude so the best tilt angle for swat is 24^o, for GB 30.4^o, for Multan 27^o, for thar 28.5^o and for kharan 26^o.

4.1 Technical Analysis

In the technical analysis section, we discuss energy analysis and robust analysis.

4.1.1 Energy Analysis

Below Table 4.1 highlights that among both the regions, namely GB (Hunza) and Sindh (Thar), has maximum level of the renewable fraction (RF) of 100% indicating that the determined provinces' energy systems are fully supplied by renewable energy sources.

Table 4.1: Energy Analysis.

S.No	Regions	EE(%/Yr)	RF(%/Yr)
1	Swat (Madyan)	36.1	94.9
2	GB (Hunza)	39.5	100
3	Punjab Multan	23	79.3

4	Sindh (Thar)	38.4	100
5	Balochistan (Kharan)	24	99.7
	National Average	**32.90**	**97.26**

GB (Hunza) also comes on top in the Energy Efficiency (EE) with a score of 39. 5% per year. Punjab (Multan) has the lowest EE at 23% and the lowest RF at 79.3%, indicating a high reliance on nonrenewable energy. The national average values of 32.90% for EE and 97.26% for RF demonstrate a great overall performance in renewable energy usage across the regions.

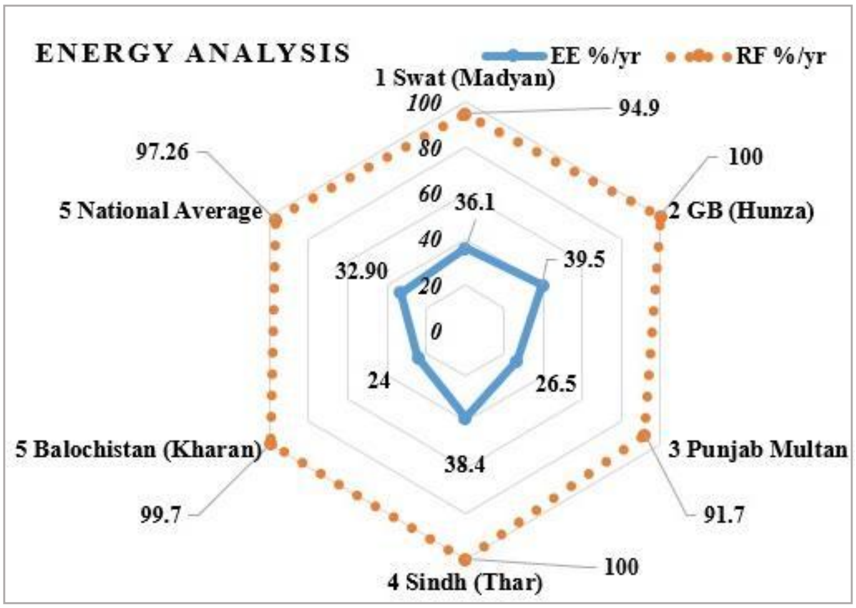

Figure 4.1: Energy Analysis in the Study.

This data highlights the potential of places such as Hunza and Thar to serve as models for renewable energy adoption, maximizing both efficiency and sustainability. Multan, on the other hand, has lower efficiency and renewable fractions, indicating areas for improvement in terms of integrating additional renewable resources and improving energy efficiency measures. The overall national performance shows a favorable trend toward cleaner energy but highlights the need for specific initiatives in regions that are struggling to achieve consistent progress. The energy analysis in the study is illustrated in Figure 4.1.

4.1.2 Robust Analysis

Table 4.2 and Figure 4.2 illustrate the CSF and UML of Madyan, Hunza, Multan, Thar, and Kharan. In every situation, the CSF and UML values are equal to zero, showing that the energy systems continually meet demand and maintain energy availability. The zero-rating demonstrates the resilient structure and effectiveness of the energy systems in these locations, allowing them to adapt to fluctuations in demand and supply without compromising their performance.

Table 4.2: Robust Analysis.

S.No	Location	CSF	UML
	Site	**%/Yr**	**%/Yr**
1	Swat (Madyan)	0.0251	0.0359
2	GB (Hunza)	0.0000	0.0000
3	Punjab (Multan)	0.195	0.4
4	Sindh (Thar)	0.0000	0.0000
5	Balochistan (Kharan)	0.314	0.599
	National Average	0.10682	0.20698

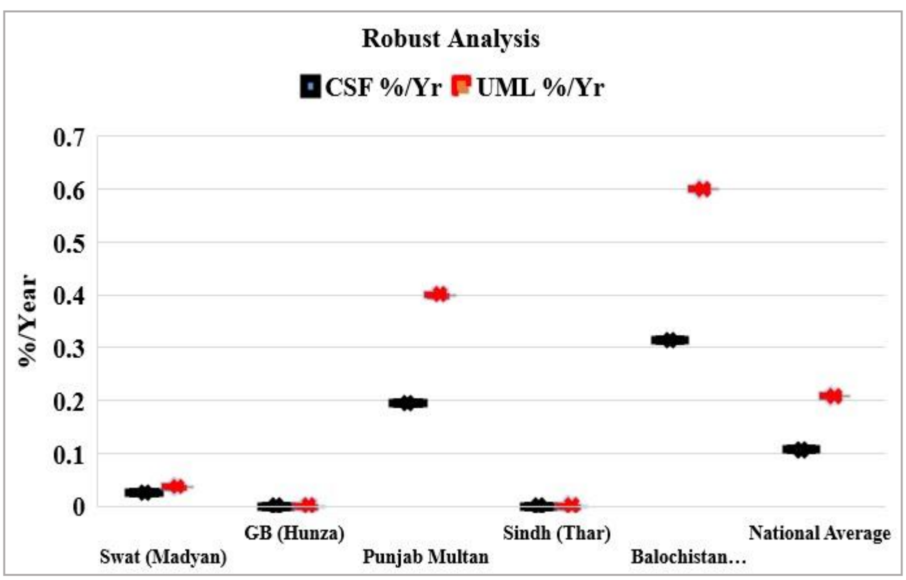

Figure 4.2: Robust Analysis in the Study.

The synchronization of energy storage and the management system in different areas means that reliable energy supply is guaranteed, which shows how efficient the installed technologies are. Also, this dependability leads to the improvement of energy security and some measures required in case of interruption of these resources, highlighting the aspects of the elaborate design and implementation of renewable power sources. The achievements in these places establish a standard for other areas to emulate in attaining reliable and enduring energy solutions.

4.2 Economic Analysis

The data presented in tables 4.3, particularly figure 4.3, illustrate the enormous capacity of various renewable energy system configurations to meet energy demands in a sustainable and economically viable manner. The use of hybrid systems that integrate photovoltaic (PV), hydro, and battery storage in areas such as Swat Madyan and GB Hunza takes advantage of the region's excellent terrain and climate.

Table 4.3: Economic parameters.

S.No	Location	NPC ($)	LCOE ($/kWh)	CAPEX ($)
1	Swat (Madyan)	$498,483.77	0.04770	$224,838.67
2	GB (Hunza)	$467,399.75	0.03800	$266,265.75
3	Punjab Multan	$637,174.55	0.08630	$212,833.33
4	Balochistan (Kharan)	$557,242.96	0.07058	$215,400.00
5	Sindh (Thar)	$521,076.33	0.05260	$291,133.33
National Average		**536,275.47**	**0.06**	**242,094.22**

This results in the generation of electricity at low prices in terms of levelized cost of energy (LCOE), while giving good value to investors.. Thus, it is reasonable to draw the conclusion that the sustainable energy options listed above are very doable. Economic parameters such as NPC and CAPEX highlight the capital-intensive nature of these projects, indicating the significant initial investments necessary. However, the significant IRR and ROI highlight the long-term financial benefits, which can overcome the initial setup costs and demonstrate the economic viability of these renewable energy systems. These positive financial metrics highlight not just the potential for cost recovery, but also the viability and sustainability of switching to hybrid renewable energy systems in these locations.

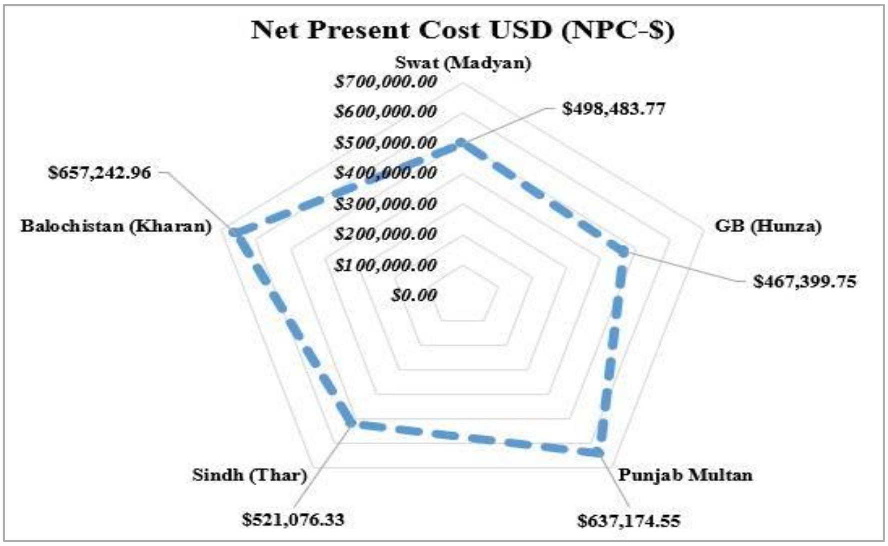

Figure 4.3: NPC across the climatic zones.

Table 4.4 and Figure 4.4 display the economic factors of the regions according to renewable energy projects. The NPC out-turn result indicates the total cost of the project throughout its life cycle and this is reflected in Multan Punjab with $ 637,174. 55, in other words, means that the country requires a more significant investment because of its highly developed and already very diverse energy structure.

The Levelized Cost of Energy (LCOE) measures the cost per unit of electricity generated, with GB (Hunza) showing the lowest at $0.03800/kWh, benefiting from favorable hydropower resources. The capital expenditure (CAPEX) for Thar in Sindh is the highest at $291,133.33, indicating significant startup costs. These prices are representative of the original investment costs. An overall modest LCOE of $0.06/kWh and an average CAPEX of $242,094.22 are highlighted by the national average values, which serve as a benchmark and reflect the disparate economic environments and investment requirements across various renewable energy projects in Pakistan.

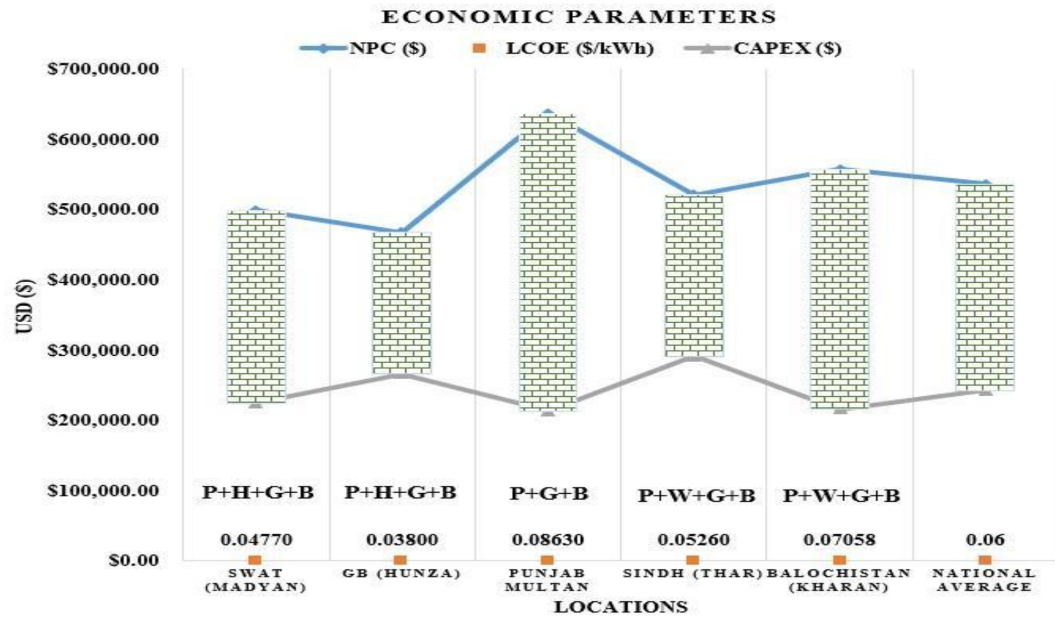

Figure 4.4: Economic Parameters of the proposed systems.

The financial characteristics for various renewable energy scenarios are presented in Table 4.5 and Figure 4.5. ROI (Return on Investment) assesses investment profitability, and Punjab (Multan) has the highest at 22.6%, indicating strong financial returns due in large part to its significant solar potential and efficient battery storage systems. The Internal Rate of Return (IRR) is a measure of the project's profitability, and in this case, Multan has an IRR of 26.8%, indicating a high level of financial feasibility.

Table 4.4: Financial parameters.

S.No	Location	Scenarios	ROI %	IRR %	PBP Yrs
1	Swat (Madyan)	P+H+G+B+C	9	12	7.86
2	GB (Hunza)	P+H+G+B+C	8.5	11.5	8.07
3	Punjab Multan	P+G+B+C	22.6	26.8	3.7
4	Sindh (Thar)	P+W+G+B+C	6.9	10	8.53
5	Balochistan (Kharan)	P+W+G+B+C	13.2	17.2	5.58
National Average			9.86	13.24	7.232

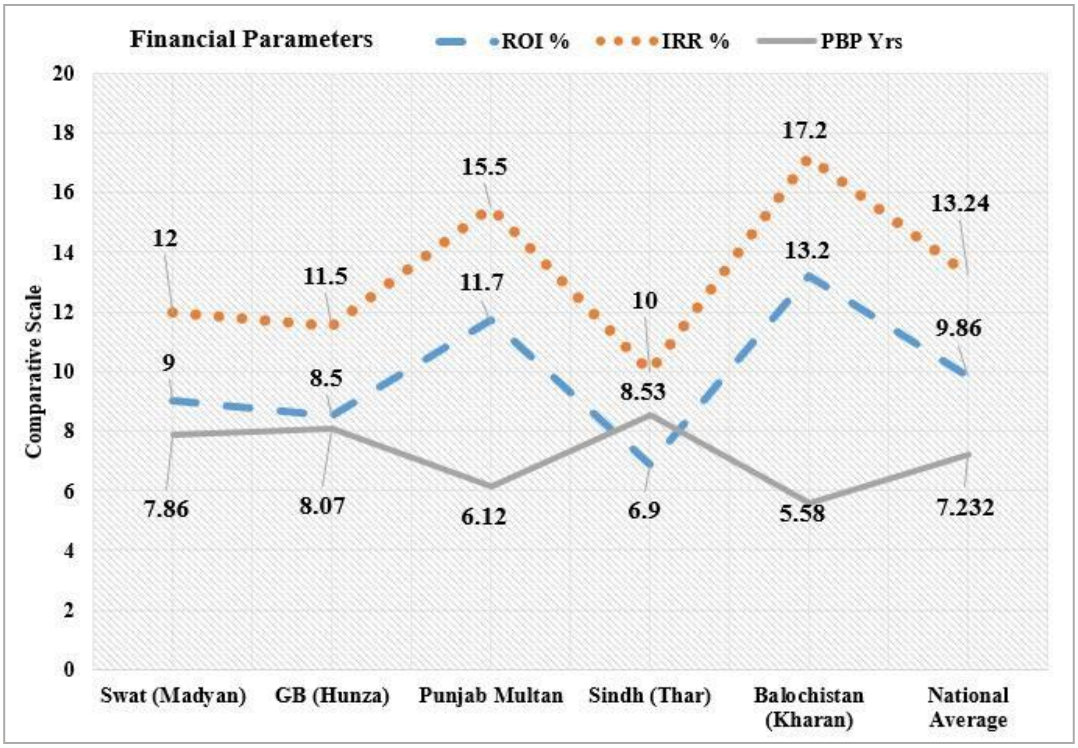

Figure 4.5: Financial Parameter Analysis.

The Payback Period (PBP) refers to the duration needed to recoup the initial investment expenses. Multan has the shortest Payback Period, standing at 3.7 years, which highlights its swift recovery of investments owing to good economic circumstances. The national average values of 9.86% for ROI, 13.24% for IRR, and 7.232 years for PBP provide a comparative perspective, demonstrating that financial performance varies among areas dependent on renewable energy initiatives and local economic factors.

4.3 Emissions Analysis

Table 4.6 and figure 4.6 show an emission analysis depending on the renewable energy sources for several sites. Demonstrating the continuous carbon footprint of mixed-energy systems, Swat (Madyan) and Balochistan (Kharan) display notable CO_2 emissions of 9,211 kg/yr and 370 kg/yr, respectively, ascribed on their reliance on conventional energy sources together with renewable integration.

Table 4.5: Emission analysis.

Location	CO_2	CO	NO	MATTER	SO_2
	kg/yr	kg/yr	kg/yr	kg/yr	kg/yr
Swat (Madyan)	9,211	0	19.5	0	39.9
GB (Hunza)	0	0	0	0	0
Punjab Multan	10,736	0	22.8	0	46.5
Sindh (Thar)	0	0	0	0	0
Balochistan (Kharan)	370	0	1.6	0	0.784

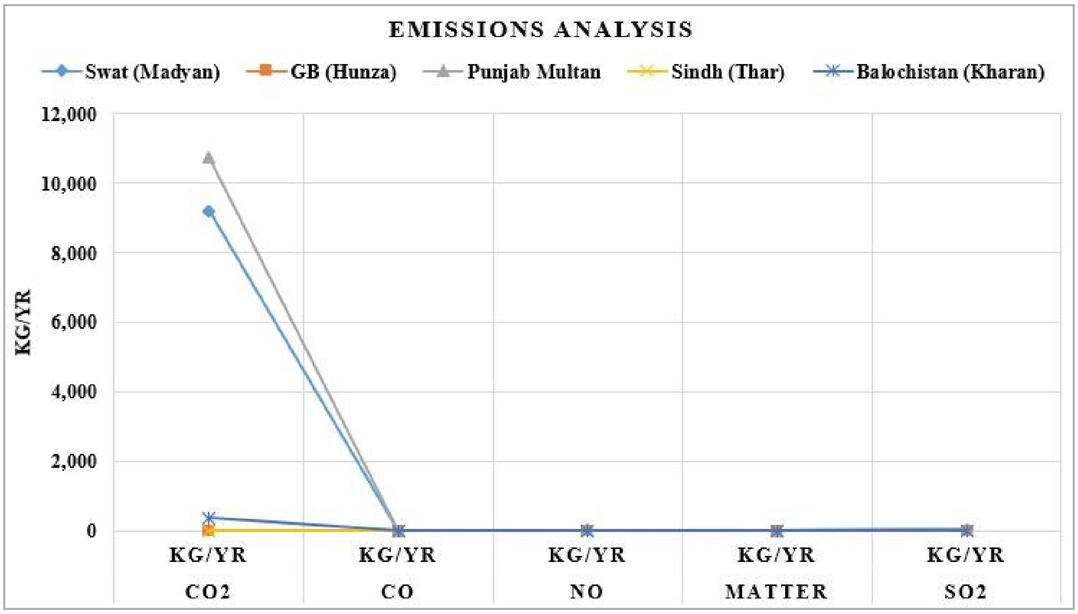

Figure 4.6: Composite and Comparative Emission Analysis.

With 10,736 kg/yr of CO_2 emissions, Punjab (Multan) emphasizes the environmental effect of grid-connected energy systems in spite of efforts toward renewable acceptance. In contrast, GB (Hunza) and Sindh (Thar) have 0% emissions in all pollutants, demonstrating their reliance on clean energy sources such as hydro and solar power. This clear disparity emphasizes the environmental advantages of switching to greener energy sources, therefore stressing the importance of sustainable energy policies and technologies to help to slow down effects of climate change worldwide.

SUMMARY

In this chapter evaluated grid-connected hybrid renewable energy systems (HRES) in five climate zones around Pakistan using HOMER program. In the first section technical analysis contrasts Punjab (Multan) which exhibited reduced renewable integration with GB (Hunza) and Sindh (Thar), for their high renewable energy usage and efficiency. Supported by integrated storage systems, robust analysis verified consistent energy availability over all regions. Following that, emissions study supported cleaner solutions in GB (Hunza) and Sindh (Thar), while economic inequalities included Multan's highest costs compensated by strong financial measures. All things considered, the Chapter supports tailored renewable plans to guarantee Pakistan's environmental benefits, economic feasibility, and sustainability.

CHAPTER 5: CONCLUSIONS AND FUTURE WORK

5.1 Conclusion

To attain Pakistan's 2030 green energy goal and 100% electrification, it is possible to investigate the potential of these systems to realize sustainability development objectives. The study was conducted, which mainly concentrated on the techno-economic and feasibility studies of renewable energy resources. We also addressed the environmental, social factors, breakeven grid distance, and sensitivity analysis for underprivileged distant areas of Pakistan.

This thesis utilized HOMER software to conduct a thorough assessment of grid-connected hybrid renewable energy systems (HRES) in Pakistan's five distinct climate zones. The technical research revealed notable regional differences in the efficiency and use of renewable energy. Specifically, GB (Hunza) and Sindh (Thar) emerged as excellent models, with a 100% renewable proportion and high energy efficiency, while Punjab (Multan) had lesser renewable integration and efficiency. Robust study demonstrated continuous energy availability across all locations, highlighting the resilience of integrated storage systems.

While economic research showed big differences in costs between regions, Multan had higher initial investment costs but showed good financial metrics like Return on Investment (ROI) and Internal Rate of Return (IRR). The emissions research highlighted the environmental advantages of adopting clean energy, as GB (Hunza) and Sindh (Thar) achieved zero emissions from renewable sources, in contrast to regions that heavily rely on mixed-energy systems and have large CO2 emissions.

5.2 Future Work

To optimize efficiency and minimize expenses, future research should prioritize the optimization of HRES configurations through techno-economic analyses, particularly in high-investment regions like Multan. Smart grid solutions and enhanced energy storage integration can enhance dependability in a diverse array of climates. Furthermore, it will create awareness and support to obtain community involvement by highlighting the socio-economic benefits of SE evaluation and emphasizing on skill development &enhancement activities to obtain optimum utilization of advantages which will contribute to Pakistan's future sustainable development goals towards attaining long-term energy security and management of global climatic change.

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