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Life Cycle Assessment and the Economic Sustainability of Renewable Energy Resources

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Abstract – With over a billion people still lacking reliable access to electricity, the need for decentralized power generation solutions is crucial. This research explores the benefits of hybrid energy systems compared to standalone biogas, solar, and wind systems, especially in regions without centralized grids. Specifically, we examine the KPK Province Regions and model a hybrid power system that balances economic viability and technological feasibility, while considering the full Life Cycle Assessment (LCA) of wind, PV, and biogas. This designed system significantly boosts clean energy generation while minimizing harmful emissions' environmental impact. The Peshawar case study provides valuable insights into selecting a cost-effective hybrid system configuration. The study also includes a comprehensive cost analysis covering factors like capital investments, replacement costs, operational and maintenance expenses, fuel costs, and salvage value. Ultimately, this investigation results in a well-designed hybrid power system. Our findings reveal that the energy mix in this region includes Waziristan Wana (50% PV and 50% Wind Turbines), Abbottabad (61.6% PV and 37.6% wind), Bannu (33% PV and 66% wind), D.I. Khan (33% PV and 67% wind), Dirr (83% PV and 13% wind), Haripur (60% PV and 40% wind), Kohat (35% PV and 65% wind turbines), Lucky Marwat (37% PV and 62% wind turbines), Mardn (66% PV and 33.1% turbine power), Mansehra (60% PV and 40% wind turbines), Miranshah (28.1% PV and 71.1% wind turbines), Murre (60% PV and 60% wind turbines), Nowshera (60% PV and 39.1% wind turbines), Shawal (20% PV and 80% wind turbines), Swabi (65% PV and 35% wind turbines), and Zarmlna (25% PV and 75% wind turbines). This data highlights potential areas in Pakistan for future wind turbine and solar projects to meet electricity demands. Information on wind speed, Global Horizontal Irradiance (GHI), and temperature has been sourced from NASA. This study specifically focuses on addressing the electricity needs of Khyber Pakhtunkhwa (KPK) Province through solar and wind turbine installations.

Keywords – Homer Pro, KPK, Power System, Life Cycle Assessment (LCA), Sustainability, Renewable Energy, Environmental Effect, Cost Analysis

i. INTRODUCTION

In a time marked by rapid industrial and technological advancement, the challenge of providing clean and affordable electricity to all remains daunting, particularly for over a billion people lacking access to power. Decentralized power generation solutions are critical, especially for those unconnected to national or regional grids. Collaborative efforts have reduced the number of people without electricity to less than one billion [1]. Enhancing the accuracy of Life Cycle

Assessment (LCA) is crucial, requiring the provision of essential data, grid interaction modeling through optimization methods, and geospatial techniques [2]. These systems address the intermittent of individual sources and improve economic and environmental efficiency [3]. For instance, combining wind turbines and solar panels can result in a more consistent electrical energy output, enhancing grid integration. Hybrid systems have demonstrated economic advantages, as seen in a $5 million system in western Minnesota that connected solar power with a wind turbine inverter. Buildings like Guangzhou's Pearl River Tower employ wind turbines and solar panels for energy generation [4,5]. "Life Cycle Assessment (LCA) offers a thorough method for assessing the environmental effects of a product over its entire lifespan.", supporting sustainable development. LCA proceeds through goal and scope definition, [6,7]. Inventory analysis, impact assessment, and {While LCA studies may yield conflicting results due to variations in systems and data limitations, these discrepancies can contribute to a valuable knowledge repository for decision-makers [8]. In the context of photovoltaic (PV) integration, a literature review identified knowledge gaps in comprehensive system design and performance evaluation. HOMER software played a role in evaluating various hybrid renewable energy system configurations and energy management strategies [9,10].

ii. MATERIALS AND METHOD

This research employs a combination of qualitative and quantitative research techniques, including surveys and an extensive literature review. It utilizes both life cycle assessment (LCA) and economic analysis to evaluate the sustainability and economic viability of renewable energy sources within Pakistan. The literature review consolidates previous studies on solar, wind, and biomass energy in Pakistan, with a specific focus on assessing economic feasibility and societal advantages. Each energy source undergoes a comprehensive life cycle assessment (LCA) to gauge its environmental impact throughout its entire life cycle. The economic analysis delves into various factors such as initial investment, operational expenses, incentives, and revenue generation for renewable energy projects in Pakistan. Life Cycle Assessment (LCA) is a systematic examination of how a product, service, or process impacts the environment across its complete life cycle. Its primary objective is to evaluate and quantify the environmental aspects and potential consequences associated with a product or process from its inception through its utilization and eventual disposal. This rigorous analysis serves as a valuable tool for making informed decisions regarding sustainability and minimizing adverse environmental effects.

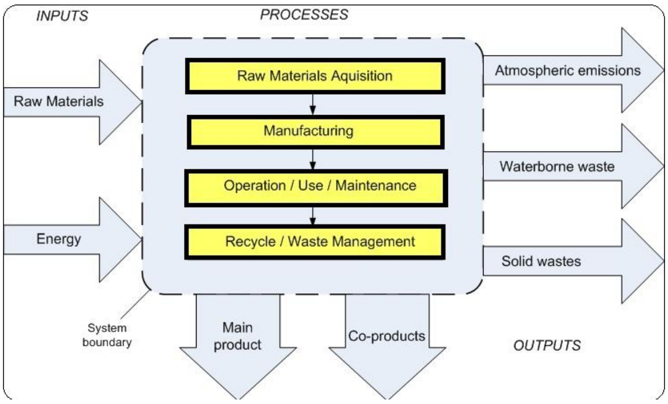

Figure 2.1: Represent LCA Farm work.

Load Profile :

The life cycle assessment (LCA) of photovoltaic (PV), biogas, and wind energy systems involves a thorough evaluation of their environmental impacts throughout their entire lifecycle. This assessment encompasses factors such as resource extraction, manufacturing, operation, and end-of-life management to determine their sustainability. The insights from these LCAs play a crucial role in guiding decisions regarding renewable energy adoption. The selection of the study area in Wana involved meticulous data collection on electricity consumption from 100 households, utilizing reliable sources like NASA and the Pakistan Meteorological Department. The primary objective was to design a hybrid energy system capable of meeting the electricity needs of diverse communities in Pakistan. Load assessments, based on actual electricity bills, revealed that these 100 households in the Peshawar Region had primary and peak loads of 625.05 kWh and 68.59 kW peak, respectively. Furthermore, the dataset integrated weather information, including wind speed and solar radiation, as well as data on biogas production, accounting for 100 cows and 100 goats, with each household owning one cow and one goat. These comprehensive datasets were used for simulations within the Homer software. In the research schematic, we depicted a "Generic Flat PV" system with a 10-kW capacity, 13% efficiency, and a 25-year lifetime, accompanied by a "Generic 1 kWh Lead Acid" energy storage system. The schematic also includes electrical load data and incorporates a 10-kW "EOCYCLE EO10" wind turbine, allowing for a comprehensive performance assessment under varying environmental conditions. Additionally, a 500-kW biogas generator is employed to explore biomass energy, broadening the research's scope

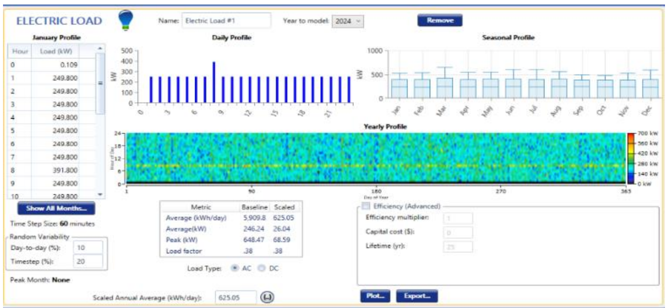

Figure 2.2: Represent Daily Load Profile, seasonal Profile, and Day of Year

The Wind Turbine (Eocycle E010) comes with an initial capital cost of $6,000, a replacement cost of $5,000, and a rated capacity of 10 kW. The Biogas Genset is priced at an initial capital outlay of $1,000, with a replacement cost of $1,000. It possesses a lower heating value of 5.5 MJ/kg, a density measuring 0.720 kg/m³, a carbon content of 5.0%, and operates at a rated capacity of 10 kW. The PV (Photovoltaic) system is characterized by an initial capital cost of $600, a replacement cost of $500, a temperature coefficient of -0.5, and a rated capacity of 10 kW. The Lead Acid Battery is equipped with an initial capital cost of $250, a replacement cost of $250, a string size of 2, and a rated capacity of 10 kW. Regarding manure production, Cows (100) generate 4.38 tons per year per head, while Buffalos (50) produce 3.285 tons per year per head.

iii. Result and Discussion:

In the methodology section of the research, I conducted an extensive Life Cycle Assessment (LCA) on three energy sources: solar panels, wind turbines, and biomass. This LCA involved a comprehensive examination of the environmental impacts and performance of each energy source across their entire life cycles, including production, installation, operation, and eventual disposal. Following this, I analyzed the LCA results to gain deeper insights into the environmental sustainability and overall efficiency of these energy sources considered to be of concern, but the values were less than 2.5, indicating no significant multicollinearity.

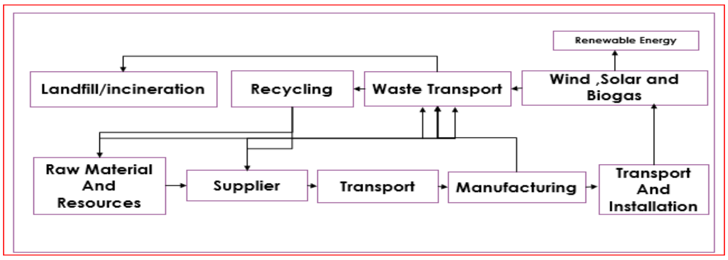

Figure No 3.1: LCA of Wind, Solar (PV), and Biomass

Relationship Among Various Life Cycle Stages: The depicted chart illustrates the inferred correlation coefficients among various phases within the life cycle of these energy sources. This abstract representation provides insight into the degree of interconnection between different stages concerning their environmental impact or reliance. Specifically, a heightened correlation coefficient between 'Manufacturing-Operation' signifies a robust association in terms of environmental consequences during these stages.

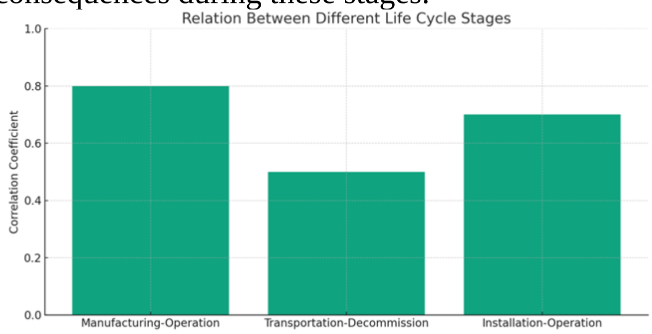

Figure No 3.2 Relation Between Different LCA

Comparative Environmental Impact Analysis of Renewable Energy Technologies (Carbon Footprint, Water Usage, and Other Environmental Effects): This comparative chart visually presents the environmental impact assessment of renewable energy technologies, including wind, photovoltaic (PV), and biogas. The graph offers a clear representation of how these technologies differ in their environmental effects. It compares 'Wind,' 'PV,' and 'Biogas' in terms of carbon footprint (gCO2eq/kWh), with values of 11, 49, and 45 respectively. Additionally, it showcases water usage (liters/kWh) with values of 0.4, 2, and 4 for 'Wind,' 'PV,' and 'Biogas,' and other environmental indicators (arbitrary scale) with values of 1, 3, and 2 for the same technologies.

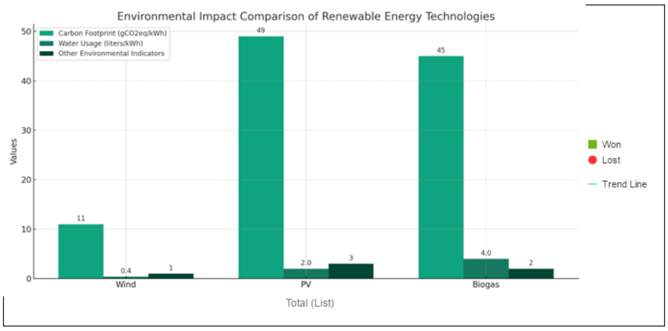

Figure No 3.3 Environmental Impact Comparison of Renewable Energy

The optimization results encompass three main components: different system variables, system architectures, and cost considerations. These results are specifically tailored to the Peshawar Region and have a projected operational lifespan of 25 years. In Section 3.1, we explore a hybrid system that combines Wind, Biogas, and Photovoltaic (PV) technologies when implemented in the Peshawar Main City region. System Configurations: Each system configuration is defined by the sizes of its components, including Photovoltaic (PV), EO10 (another renewable source, possibly wind or hydro), Bio, 1kWh LA (a storage system), and Converter, as well as its dispatch strategy (LF for Load Following or CC for Cycle Charging). Economic and Operational Metrics: NPC (Net Present Cost): This metric represents the total cost of each system throughout its lifetime. It includes the initial capital investment, operating expenses, maintenance costs, and fuel expenses, all discounted to present value. LCOE (Levelized Cost of Energy): LCOE represents the average cost per kilowatt-hour (kWh) of electricity produced by factoring in the total NPC and the total electricity generation over the system's lifetime. Operating Cost: This metric quantifies the annual expenses associated with operating and maintaining the system. CAPEX (Capital Expenditure): CAPEX refers to the initial capital investment required for purchasing and installing the system. Here's an example of how these metrics are presented for each system configuration: Configuration 1: PV 242 kW, EO10 13 kW, Bio 500 kW, 880 batteries, Converter 63.2 kW, LF dispatch; NPC $1.05 million, LCOE $0.355/kWh, Operating cost $45,233 per year, CAPEX $460,270. Configuration 2: PV 265 kW, EO10 14 kW, Bio 500 kW, 1,276 batteries, Converter 58.8 kW, CC dispatch; NPC $1.11 million, LCOE $0.377/kWh, Operating cost $41,335 per year, CAPEX $576,649. Configuration 3: PV 327 kW, EO10 500 kW, 926 batteries, Converter 72.3 kW, LF dispatch; NPC $1.22 million, LCOE $0.415/kWh, Operating cost $60,029 per year, CAPEX $446,554. The provided table allows system designers to compare different configurations, considering factors like NPC, LCOE, initial investment (CAPEX), and operating costs. Dispatch strategies (LF or CC) are also crucial in determining how the system meets energy demand efficiently. The overall goal is to optimize system configurations for economic efficiency while ensuring a reliable energy supply.

PV (kW)	EO10	Bio (kW)	1kWh LA (#)	Converter (kW)	Dispatch	NPC ($)	LCOE ($/kWh)	Operating cost ($/yr)	CAPEX ($)
242	13	500	880	63.2	LF	$1.05M	$0.355	$45,233	$460,270
265	14		1,276	58.8	CC	$1.11M	$0.377	$41,335	$576,649
327		500	926	72.3	LF	$1.22M	$0.415	$60,029	$446,554
393			1,692	69.9	CC	$1.36M	$0.462	$52,964	$676,319
	57	500	1,404	162	LF	$1.88M	$0.639	$88,767	$734,501
	151		3,920	127	CC	$2.68M	$0.910	$59,032	$1.92M

Figure No 3.4 Hybrid Power System Optimization Outcome in Peshawar, Khyber Pakhtunkhwa, Employing Homer Software.

Electrical Prospective:

"To meet the energy demand, the system draws power from different sources: 1.31% from biogas, 71.3% from photovoltaic (PV) panels, and 27.4% from wind turbines. The entire load of 816,420 kWh/yr. is fulfilled by renewable sources, encompassing solar, wind, and batteries. The figure presents data on electricity production from various renewable sources. System Architecture Overview: This section lists the components of the energy system, including solar photovoltaic (PV) panels, a biogas generator, a battery storage system, and a system converter. Production and

Consumption: It provides details on the annual energy output from different components: Generic flat-plate PV: Solar panels generate 381,066 kWh/yr, accounting for 71.3% of total production. Generic 500kW Biogas Genset: Biogas generator output is 7,000 kWh/yr, equivalent to 1.31% of the total. Ecoycle EO10: Another form of renewable generation contributes 146,676 kWh/yr or 27.4% of the total. This could be wind or hydroelectric generation. In total, the annual energy production from all sources amounts to 534,742 kWh. Consumption: This section lists the total annual consumption, which is 228,006 kWh, entirely attributed to the AC primary load that the system is designed to serve. Renewable Penetration and Storage: Excess Electricity: The system produces 274,203 kWh/yr, which is 51.3% of the total production, not used by the system's loads. Unmet Electric Load: This represents the portion of the load not served due to insufficient production or storage, totaling 138 kWh/yr. Capacity Shortage: This denotes the total energy not provided due to the system's inability to meet the load or storage capacity, at 197 kWh/yr. Renewable Fraction: This indicates that all the energy produced comes from renewable sources. Max. Renewable Penetration: This is a hypothetical maximum renewable penetration rate, expressed as a percentage, showing the potential integration of renewable energy. Monthly Electric Production: The bar chart illustrates monthly energy production from each generator/component: PV (Brown): Likely the largest portion, consistent with flat plate PV's high annual production. EO10 (Grey): The second-largest contributor, with monthly variations possibly due to seasonal factors. Bio (Blue): This represents the biogas generator's contribution, which remains relatively constant throughout the year. Economic Metrics: Total NPC (Net Present Cost): The system's total cost over its lifetime, discounted to present value, amounts to $1,045,017.00. Levelized COE (Cost of Energy): The average cost per unit of energy produced over the system's lifetime is $0.3545/kWh. Operating Cost: The annual operational cost of the system is $45,232.71.

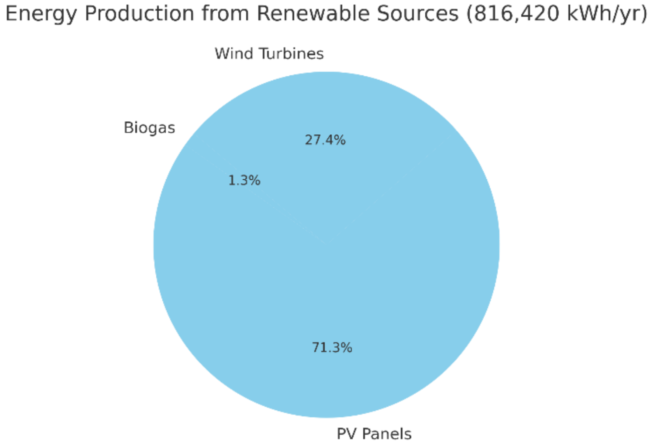

Figure 3.5 Energy Production (Solar PV, Wind Turbine , And Biomass)

Cost Summary :

Winning System Architecture: This section delineates the components of the proposed energy system that are considered the most cost-effective after thorough analysis. It specifies various energy sources and their capacities, such as bio-energy (Bio - 500 kW), photovoltaics (PV - 242 kW), energy storage (1kWh LA - 880), converter capacity (63.2 kW), and a parameter labeled 'EO10 - 13.0'. Base Case Architecture: In contrast to the "Winning System Architecture," this section represents the initial or standard system used for comparison. It features a different configuration of energy sources and capacities, including a larger photovoltaic system (PV - 327 kW), greater energy storage (1kWh LA - 926), and a different converter capacity (72.3 kW). Cumulative Net Cash Flow Graph: The line graph in the figure displays the cumulative net cash flow over 25 years for both the lowest-cost system (likely the "Winning System Architecture") and the base case. The x-axis signifies the time in years, while the y-axis represents the cumulative net cash flow in dollars. Both lines show a declining trend, indicating the incurrence of costs over time. However, the "Lowest Cost System" line is positioned higher, indicating a lower net cash outflow, making it more cost-effective. Cost Summary: This section offers a financial summary that compares the "Base Case" with the "Lowest Cost System." It includes key financial metrics: NPC (Net Present Cost): The total cost of the system over its lifetime, discounted to its present value. Initial Capital: The upfront cost required for system construction and installation. O&M (Operation and Maintenance): Annual operational and maintenance costs. COE (Levelized Cost of Energy): The per-unit cost of energy generated, considering all costs over the system's lifetime. The "Lowest Cost System" exhibits lower values for NPC, initial capital, O&M, and LCOE in comparison to the "Base Case," signifying its superior economic efficiency throughout the project's lifespan. Such analyses are crucial for planning energy projects, particularly when evaluating sustainable and renewable energy sources, as they provide insights into long-term financial implications and the overall affordability of various system configurations

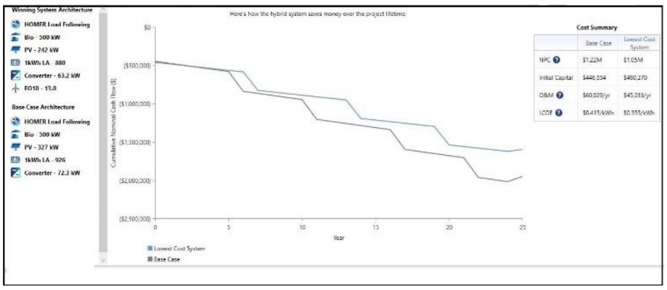

Figure 3.5 Represent the Whole Cost Summary

Total Power Out Put:

The provided figure illustrates the total power output (in KW) of each equipment piece on a daily and monthly basis over several years. Figure No.3.6 (a) displays a comprehensive time series analysis of all variables related to power sources. In the time-series viewer, a "pre-set" refers to a predefined collection of data series that constitute a graph. These presets include specific data series, their order, selection, and whether they should be displayed, all of which are saved for reference. Within this graph, the upper section represents the output of renewable energy sources, where the upper plate specifically depicts global solar power (KW/m2), while the lower plate illustrates data related to renewable penetration and total load. Figure No.3.6 (b) is dedicated to showcasing the total output power generated by renewable energy sources (measured in kW).

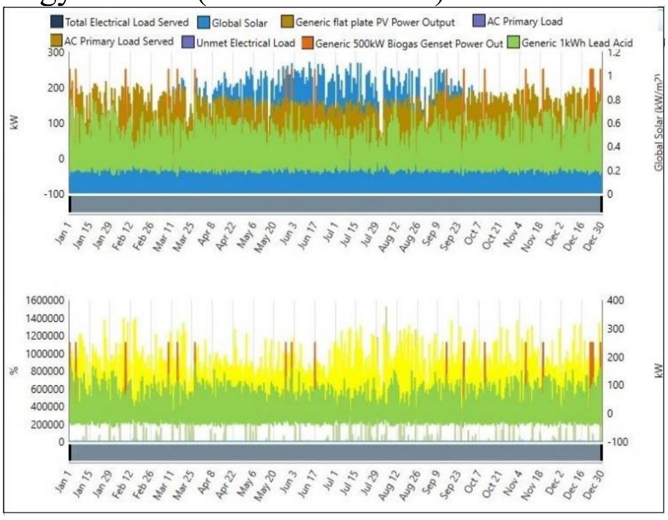

Figure 3.6(a),(b) Total Output Power

Emission:

When evaluating emissions, various substances are assessed, each with its distinct values and units. For instance, carbon dioxide emissions are quantified at 3.96 kg/year, carbon monoxide at 0.0440 kg/year, and nitrogen oxides at 0.0275 kg/year. These emissions bear significant environmental and health repercussions. Carbon dioxide plays a pivotal role in climate change, while carbon monoxide poses a health risk due to its toxic nature and potential contribution to air pollution. Unburned hydrocarbons are involved in ground-level ozone formation and respiratory issues, while particulate matter can negatively impact lung and heart health. Sulfur dioxide emissions can lead to acid rain, causing harm to ecosystems and human well-being, prompting environmental agencies to establish standards. Nitrogen oxides are contributors to smog and acid rain, with specific regulations for nitrogen dioxide. The regulations governing these emissions differ from one country or region to another, underscoring the importance of their reduction for the protection of both the environment and public health.

iv. CONCLUSION

In conclusion, the study finds that the solar, biogas, wind, and battery hybrid system presents the most cost-effective and sustainable solution for powering Peshawar. This system is expected to achieve payback within 15-25 years while maintaining salvage value beyond 25 years. Future research directions encompass real-world testing, optimization of battery storage, environmental impact assessment, comprehensive economic analysis, exploration of additional renewable energy sources, and the promotion of decentralized microgrids. To fulfill Peshawar energy requirements, this system draws power from various sources, with the following contributions: 1.31% from biogas, 71.3% from photovoltaic (PV) systems, and 27.4% from wind turbines. The overarching goal of this research is to reduce dependence on conventional fossil fuels and enhance self-sufficiency in remote areas, harnessing Pakistan's abundant renewable resources. The proportion of biomass in hybrid system configurations is a critical consideration. Furthermore, the study provides insights into different regions within Khyber Pakhtunkhwa (KPK): Abbottabad relies on photovoltaic (PV) sources for 61.6% of its energy needs and wind energy for 37.6%. Bannu's energy mix consists of 33% PV and 66% wind. D.I. Khan utilizes 33% PV and 67% wind. Dirr leans heavily towards PV at 83% and wind at 13%. Haripur utilizes 60% PV and 40% wind. Kohat depends on PV for 35% and wind turbines for 65%. Lucky Marwat employs PV for 37% and wind turbines for 62%. Mardan combines PV for 66% and turbine power for 33.1%. Mansehra's energy mix comprises 60% from PV sources and 40% from wind turbines. Miranshah relies on PV for 28.1% and wind turbines for 71.1%. Murre's energy distribution is divided equally between PV (60%) and wind turbines (60%). Nowshera uses PV for 60% and wind turbines for 39.1%. Shawal relies on PV for 20% and wind turbines for 80%. Swabi employs PV for 65% and wind turbines for 35%. Zarmila's energy mix consists of 25% from PV and 75% from wind turbines. This data highlights potential areas in Pakistan where future wind turbine and solar projects can be implemented for electricity production. Information on wind speed, Global Horizontal Irradiance (GHI), and temperature has been sourced from NASA. The study specifically focuses on addressing the electricity demands of the Khyber Pakhtunkhwa (KPK) Province through the installation of solar and wind turbine systems.

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