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Unlocking the Power of Nature: A State-of-the-Art Analysis of Optimal Wind and Solar Sites in Pakistan for Sustainable Power Generation

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Abstract
Pakistan, with its growing energy demands and reliance on fossil fuels, faces significant challenges in achieving sustainable power generation. The country has considerable potential for harnessing renewable energy, particularly from wind and solar sources, due to its geographic and climatic conditions. This paper presents a comprehensive state-of-the-art analysis of optimal wind and solar sites across Pakistan, evaluating their potential for large-scale power generation. Through a review of existing literature, government reports, and case studies, we identify the regions with the highest wind and solar energy potential, such as the Gharo-Keti Bandar wind corridor and the sun-rich provinces of Balochistan and Punjab. The paper explores key factors influencing site selection, including wind

speeds, solar irradiance, topography, and environmental considerations. It also highlights technological advancements, such as improved wind turbine efficiency and solar panel innovations, which could enhance power generation in these regions. Furthermore, the study addresses the socio-political and infrastructural challenges in the development of wind and solar projects, including regulatory barriers, grid integration issues, and land acquisition. The findings suggest that targeted investments in both policy reforms and technological solutions could unlock the full potential of Pakistan's renewable resources. Finally, this review offers strategic recommendations for advancing the country's transition to a sustainable energy future, emphasizing the need for collaborative efforts between the public and private sectors, along with international partnerships. This analysis provides a valuable framework for stakeholders aiming to improve Pakistan's energy security and reduce its carbon footprint through the exploitation of wind and solar energy.
Keywords: Renewable Energy, Wind and Solar Sites, Energy Potential, Grid Integration, Policy Recommendations, Carbon Footprint, Sustainable Energy Future.

Introduction

Pakistan, with its burgeoning population and rapidly increasing energy demand, is grappling with an energy crisis that hampers economic growth, stability, and quality of life. Despite possessing abundant natural resources, the country's energy infrastructure remains heavily reliant on conventional fossil fuels, which account for a large share of the national electricity generation mix. The overdependence on coal, oil, and gas not only strains the economy, but also contributes to rising greenhouse gas emissions, exacerbating the impacts of climate change [1]. As the country continues to face energy shortages, high electricity costs, and environmental degradation, the need for an urgent transition to sustainable and renewable sources of energy has never been more critical. Climate change represents one of the most pressing challenges facing humanity today. Nearly 80% of global greenhouse gas (GHG) emissions stem from the production and consumption of energy, with fossil fuels—such as coal, oil, and natural gas—accounting for approximately 90% of total carbon dioxide (CO_2) emissions [2]. The complex connection between rising GHG emissions and the resulting climate change, along with its subsequent environmental impacts, has made addressing this issue particularly difficult. Over the past 250 years, large-scale agriculture, land-use changes, and the growing consumption of fossil fuels have led to a substantial increase in GHG concentrations. In developing countries, the heavy reliance on nonrenewable energy sources has accelerated the rise in emissions, contributing to a concerning pace of environmental degradation. Ice core data shows that current levels of CO_2 and methane are higher than they have been in the last 650,000 years [3]. While fossil fuels remain an affordable energy source, the threat of global warming has prompted a shift towards exploring alternative, sustainable energy solutions. This drive for sustainability has intensified the global push for renewable energy. The key challenge, however, lies in effectively generating clean energy from renewable resources. Among the renewable options—wind, solar, geothermal, and biomass—solar energy stands out as the most abundant, sustainable, and environmentally friendly choice, making it the most promising candidate for large-scale power generation [4]. The increasing adoption of solar energy for both electricity generation and thermal applications reflects this growing potential, with global reports confirming a transition towards renewable energy, particularly solar power. In addition to its widespread availability, ongoing advancements in renewable energy technologies—especially in photovoltaic systems—have enhanced their power generation capabilities while significantly reducing costs, thus creating new opportunities to exploit solar energy more efficiently. However, simply having cost-effective, efficient solar technology is not enough to guarantee the successful development of solar farms [5]. Various factors such as technical feasibility, economic viability, and environmental considerations must be taken into account when assessing the potential for solar energy harvesting. These factors are influenced by geographical location, biophysical conditions, and the region's socio-economic infrastructure. Nevertheless, overemphasizing any single dimension—such as favoring locations with developed infrastructure to lower costs or prioritizing socio-economic concerns—can bias the decision-making process. Ideally, the identification of suitable sites for solar farm development should be the first step, with the consideration of economic and environmental factors as secondary criteria. Existing site selection methods typically use these criteria to rank locations, but this approach may exclude potentially viable options from the decision-making process [6].

Renewable energy, particularly wind and solar power, holds immense promise as viable alternatives to conventional energy sources in Pakistan. These renewable resources are abundant, regionally distributed, and have the potential to provide reliable, cost-effective, and environmentally friendly power generation solutions. Pakistan's geographic location offers favorable conditions for both wind and solar energy production. The country is endowed with some of the best wind corridors in the world, particularly in the southern provinces of Sindh, where consistent high-speed winds make wind power generation highly feasible. In addition, Pakistan experiences significant solar radiation, particularly in regions like Balochistan, Punjab, and Sindh, which receive substantial sunlight throughout the year, making them ideal for large-scale solar power projects [7]. Despite this promising potential, Pakistan has yet to fully capitalize on its renewable energy resources. One of the key challenges lies in the identification and optimal selection of sites for wind and solar power generation. The success of renewable energy projects depends largely on choosing locations that maximize the efficiency and output of wind turbines and solar panels. For wind power, factors such as wind speed, direction, consistency, and terrain play a pivotal role in determining the energy yield. Similarly, for solar power, high levels of solar irradiance, land availability, and minimal environmental disruptions are key considerations. Furthermore, socio-political issues such as land ownership, regulatory frameworks, and local community engagement also influence the feasibility and success of renewable energy projects.

This paper presents a comprehensive state-of-the-art analysis of the optimal sites for wind and solar power generation in Pakistan. It explores the key factors that must be considered when selecting the best locations for renewable energy projects, including meteorological data, geographical features, environmental impacts, and infrastructure availability. The paper also examines the technological advancements that can enhance the efficiency of wind and solar

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energy systems, such as the development of higher-capacity wind turbines, improved solar panels, and energy storage solutions. In addition, it provides an in-depth discussion of the socio-economic, regulatory, and infrastructural challenges that need to be addressed to unlock the full potential of these renewable energy sources in Pakistan. The analysis presented in this paper draws on existing research, case studies of current renewable energy projects in Pakistan, and international best practices to provide a holistic view of the opportunities and challenges facing the country's renewable energy sector. By identifying the most promising wind and solar sites and offering strategic recommendations for their development, this paper aims to inform policymakers, energy developers, and stakeholders involved in the transition to renewable energy in Pakistan. Given the global emphasis on reducing carbon emissions and mitigating climate change, Pakistan's transition to renewable energy is not only crucial for its own energy security and economic stability but also contributes to global efforts to combat climate change. This paper ultimately seeks to contribute to the development of a sustainable energy future for Pakistan, where wind and solar energy play a central role in meeting the country's energy demands, improving environmental outcomes, and promoting sustainable development.

Methods for the Selection

Multi-criteria decision-making (MCDM) techniques are frequently used in renewable energy planning, particularly in the site selection process for solar farms [8]. In MCDM, a set of predefined alternatives is evaluated against a series of criteria, with the alternatives being ranked or classified according to these criteria using various valuation methods. Common techniques include the Analytical Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Elimination and Choice Expressing Reality (ELECTRE), and fuzzy-based methods [9]. These methods, individually or in combination, help identify, classify, or rank potential sites for solar farm development. For instance, AHP has been used to identify the best solar site among three locations in Turkey [10], and fuzzy-based TOPSIS was employed for the same purpose [11]. In another study [12], ELECTRE was used to select a site for a hybrid wind/solar farm. Similarly, a combination of AHP, TOPSIS, and ELECTRE methods was applied in Murcia, Spain, to determine the optimal location for solar farm development, with AHP helping to weigh the criteria and TOPSIS and ELECTRE used to evaluate and rank suitable locations. A large body of literature explores the use of MCDM methods in renewable energy site selection.

In addition to MCDM, Geographic Information Systems (GIS) are increasingly being integrated for spatial planning in solar farm site selection [13]. The combination of GIS and MCDM offers several advantages [14], one of the most significant being the development of a GIS-based decision support system for selecting solar sites. This system can assist in planning infrastructure development near these locations, thereby facilitating the use of clean energy [15]. Other benefits include optimizing solar farm efficiency by ensuring adequate solar irradiance and moderate temperatures, proximity to consumption areas, and minimizing the environmental and social impacts of the project. Despite the advantages of using MCDM methods, there are challenges in

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evaluating solar sites based on criteria during the initial phase. One issue is that a location may appear optimal in terms of energy generation potential but lack the necessary infrastructure, such as roads or transmission lines, making it suboptimal from an infrastructure perspective. Additionally, infrastructure-related criteria may be less relevant in cases where new cities or towns are being planned. For instance, in countries like Pakistan, where rapid urbanization requires the development of new urban areas to alleviate pressure on existing cities, infrastructure criteria for site selection may be less important. Finally, clustering of solar sites is often overlooked in the site selection process, which is essential for determining the size and classification of solar farms. To address these challenges, it is important to use a step-by-step approach to site selection, initially applying screening criteria to exclude regions with dense solar resources and challenging terrain. Subsequently, clustering methods, such as K-means [16], can be employed to identify contiguous, high-density solar areas of the appropriate size. However, K-means clustering has limitations, particularly when dealing with irregularly shaped areas, which are common in solar farm development. Figure 1 shows the methodology for solar site selection.

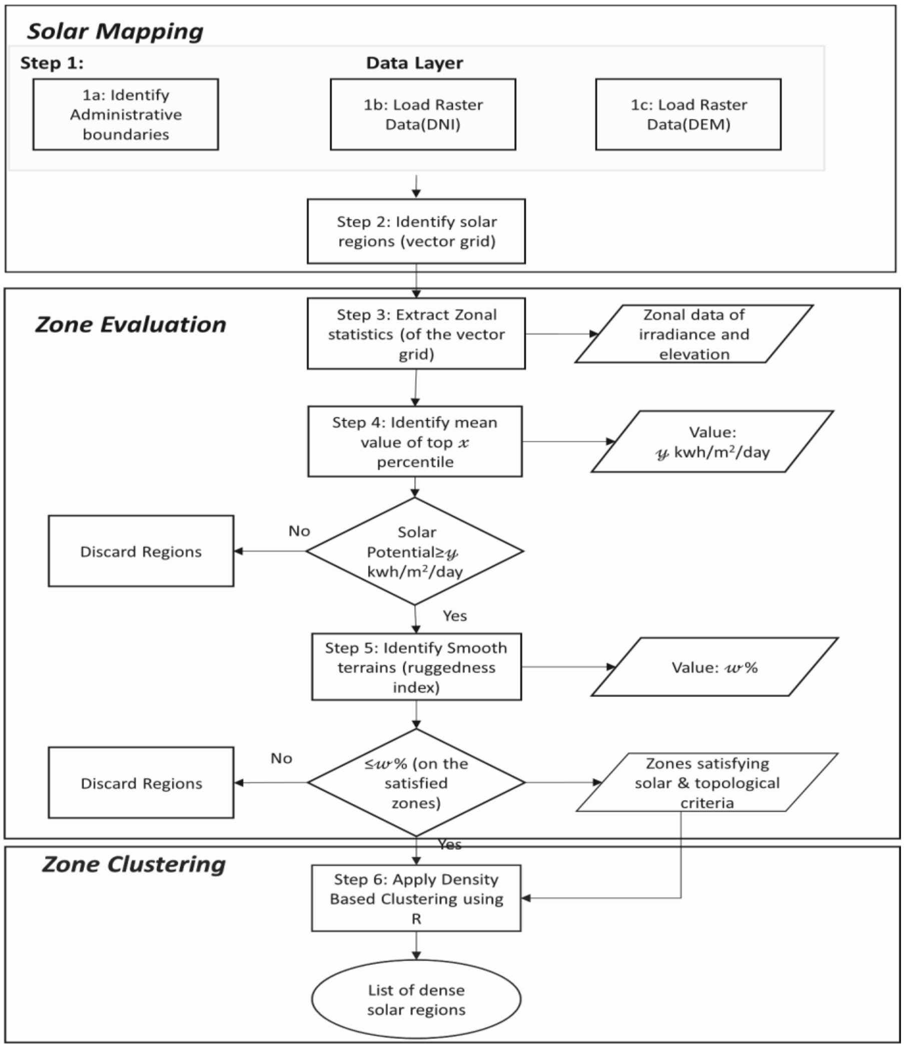

Figure 1: Methodology for Solar Site Selection

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Solar Potential of Pakistan

The proposed methodology has been applied to various geographical regions of Pakistan, with the country selected for this study due to its ongoing power market analysis under the China-Pakistan Economic Corridor (CPEC), aimed at identifying the supply-demand gap until 2030 [17]. The primary focus is on transitioning from fossil fuels to incorporating more renewable energy into the national energy mix. Currently, renewable energy contributes only 1.1% to Pakistan's energy supply [18]. Pakistan is well-suited for harnessing solar energy, thanks to its regions that receive high solar irradiance. A recent solar energy mapping, conducted with the help of the World Bank's Energy Sector Management Assistance Program (ESMAP), highlights the country's significant solar potential [19]. On average, Pakistan receives solar radiation of 5 to 7 $kWh/m^2/day$, totaling approximately 1800 to 2200 kWh/m^2 annually [20]. Despite these favorable conditions and the decreasing costs of solar energy technology, Pakistan's solar energy generation capacity remains virtually nonexistent, and the use of solar energy is still in its infancy. Several factors contribute to the low utilization of solar power for both electricity and thermal applications. One key reason is the lack of a comprehensive solar potential survey, which was only made available in 2016 [21]. Moreover, for decades, the government has primarily focused on thermal and hydroelectric power generation, giving less emphasis to other renewable energy sources. The first policy supporting renewable energy was introduced in 2006, but it failed to provide sufficient support to incentivize the private sector and individuals to invest in and operate solar energy farms [22]. Within the CPEC energy project portfolio, coal power plants have received the most attention, with only 1,000 MW out of 17,000 MW planned for solar energy [23]. Of this 1,000 MW, the 300 MW Quaid-e-Azam solar farm has been developed, but further phases are under review due to suboptimal location and other environmental and technical challenges [24]. In addition to the Quaid-e-Azam solar farm, several small-scale solar projects have recently been developed and commissioned. The first on-grid solar power plant, with a capacity of 178 kW, was launched in 2010 at the Pakistan Engineering Council building [25]. In 2016, the parliament building became solar-powered, with the installation of 1 MW of solar panels. Both of these projects were granted Feed-in Tariffs (FiT) by the National Electric Power Regulatory Authority (NEPRA) to sell surplus energy to the national grid. Given the country's solar potential and the government's commitment to developing solar farms, 28 solar companies, with a combined capacity of 1556 MW, have received Letters of Intent (LoI) from the Alternative Energy Development Board [26]. However, it is crucial to assess the viability and optimality of the proposed solar farm locations in terms of their solar potential. Figure 2 shows the solar irradiation map of Pakistan.

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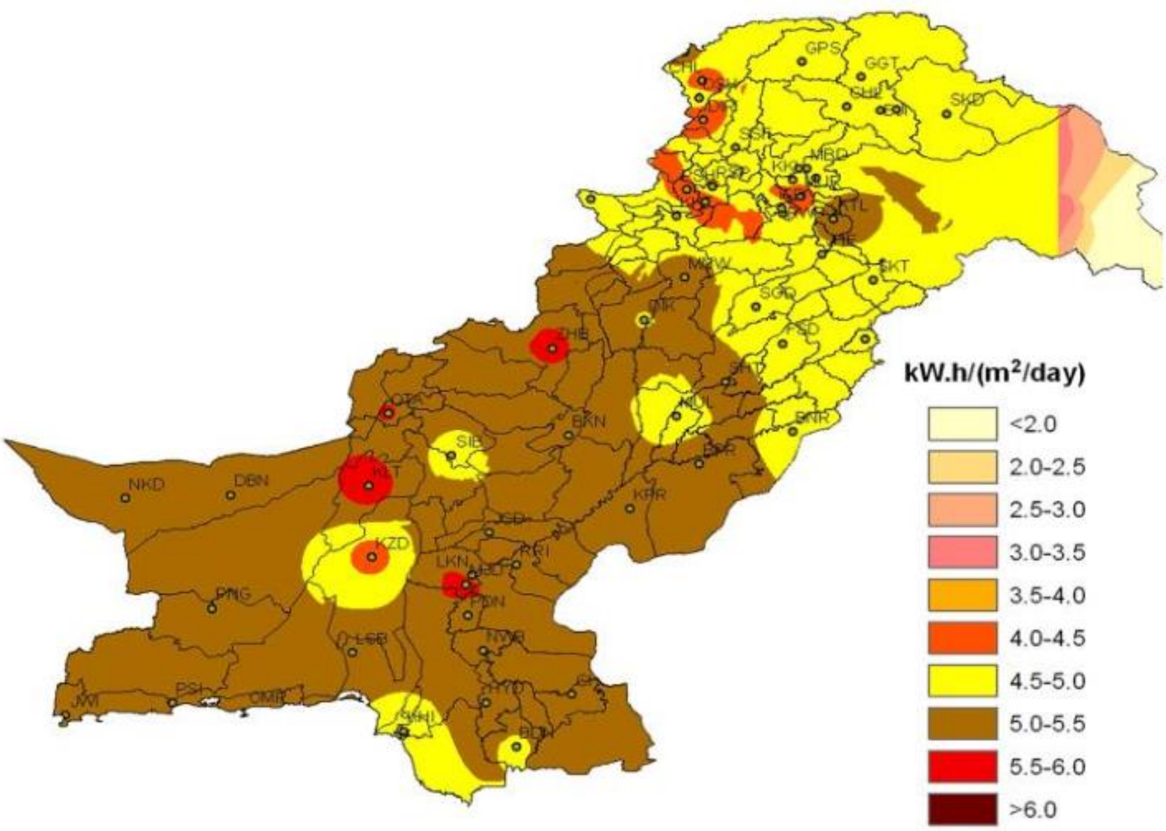

Figure 2: Solar Irradiation Map of Pakistan [27].

Pakistan is endowed with significant solar energy potential, with several regions of the country offering high levels of solar irradiance that make them ideal for large-scale solar farm installations. Among the most promising areas are the southern and southwestern provinces of the country, including **Sindh, Balochistan**, and parts of **Punjab** and **Khyber Pakhtunkhwa. Sindh** is particularly noteworthy, with the **Thar Desert** standing out as one of the most optimal regions for solar energy generation. This desert area receives an average solar radiation of 5.5 to 7.0 kWh/m²/day, making it an ideal location for solar power generation [28]. The **Nawabshah** region in Sindh, along with areas around **Thatta** and **Badin,** also exhibits strong solar potential due to its high solar irradiance, which ranges from 5.0 to 6.5 kWh/m²/day. Moving westward, **Balochistan** has vast areas, particularly around **Quetta, Chagai**, and **Lasbela,** which receive consistently high levels of solar radiation [29]. These regions enjoy solar irradiance of about 5.0 to 7.5 kWh/m²/day, and their relatively flat terrain and low population density further enhance their viability for large-scale solar energy projects**. Punjab**, specifically in its southern districts such as **Dera Ghazi Khan, Multan,** and **Bahawalpur,** also presents good solar potential. These areas benefit from average solar radiation levels of 5.5 to 6.0 kWh/m²/day [30]. The **Cholistan Desert,** in particular, is a hotspot for solar development due to its clear skies and minimal cloud cover, making it an attractive location for solar farms. Additionally, parts of **Khyber Pakhtunkhwa** in areas like **Peshawar** and **Swat Valley** offer considerable solar irradiance, with daily averages ranging from 5.0 to 6.0 kWh/m². The **Salt**

Range in **Punjab** also presents a promising site due to its high solar exposure and the relatively low levels of air pollution in the area [31]. These regions, with their optimal climatic conditions and solar radiation values, are critical to unlocking the full potential of solar energy in Pakistan, and with the right infrastructure and policy support, could significantly contribute to the country's renewable energy goals. For these sites to be harnessed effectively, it is essential that local and national authorities prioritize the development of solar infrastructure, including grid connections and storage solutions, to ensure the efficient distribution and use of the generated power.

Wind Potential of Pakistan

The Government of Pakistan is determined to build wind energy projects all over the country so that environmentally friendly technologies can meet a big part of the country's electricity needs. The Alternative Energy Development Board (AEDB) and PMD studies indicate that coastal Sindh and Baluchistan as well as certain northern areas have significant wind energy potential [32]. These estimates indicate that the districts of Gwadar and Makran Coastlines in Balochistan province, as well as Thatta, Karachi, Jamshoro, and Badin in Sindh province, have appropriate sites for wind energy development, deployment, and operation. A different research found that Pakistan could generate 3200 GW from renewable energy, such as 0.5 GW from wastes, 3.1 GW from micro hydropower, 340 GW from wind, 2900 GW from solar, and 50 GW from hydropower [33]. NREL possesses Pakistan has a potential for wind energy of around 132 GW overall, according to study published by the National Renewable Energy Laboratory (NREL). The wind energy potential of Pakistan at 50 meters above sea level for classes 4 through 7 is given by NERL in Table 1.

Table 1: A survey of Pakistan's 50-meter wind power capability

Resource Potential	Wind Power Class	Wind Speed at 50 m (m/s)	Covered Area (km/s)	Output Power (W/m²)	Area (%)	Total Output Power (GW)
Good	4	6.9-7.4	18,106	400–500	2.05	90.53
Excellent	5	7.4-7.8	5218	500–600	0.59	26.09
Outstanding	6	7.8-8.6	2495	600–800	0.28	12.48
Superb	7	>8.6	543	>800	0.06	2.72
Total			26,362		2.98	131.82

The Table shows that with an installed capacity of 5 MW per km2, almost 3% of the land can generate approximately132 GW of power. These estimates exclude more than 6% of Pakistan's land, categorized as Class 3, or moderate, which is suitable for the generation of wind energy. These approximations may be

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improved even more by applying modern modelling and analytical methods to produce comprehensive wind resource maps for Pakistan. 40 to 35 percent of Sindh and Baluchistan's coasts might be evaluated for wind energy generation, excluding low-wind and urban areas [34]. The potential wind energy production capacity is calculated at 123 GW, based on a density factor of 5.40 MW/km^2. It is anticipated that Pakistan's coasts would generate 212 TWh of wind power annually, which is 2.15 times the country's total production of conventional electricity. NREL has conducted a comprehensive assessment of the coasts of Sindh and Balochistan, identifying many suitable locations for wind energy, as shown in Table 2 [35].

Table 2: Wind Energy Potential of Pakistan [35]

Wind Class	Description	Wind Speed (m/s)	Power Density (W/s^2)
1	Superb	Greater than 8.6	Greater than 800
2	Outstanding	7.8–8.6	600–800
3	Excellent	7.4–7.8	500–600
4	Good	6.9-7.4	400–500
5	Moderate	6.2–6.9	300–400
6	Marginal	5.4–6.2	200–300
7	Poor	0–5.4	0–200

For Sindh and Balochistan's coasts, information was collected and examined from 47 wind observation locations [36]. According to the assessments, a wind corridor stretching from Hyderabad to Keti Bandar and Quetta to Gwadar has significant power generation potential. In addition to mitigating energy shortages, the establishing of wind energy projects in the Jhimpir, Gharo, and Keti Bandar corridors will relieve the $12 billion yearly expenditure on oil imports. Table 3 indicates that the GOP has currently acquired 1235 MW of wind power from this corridor.

Table 3: Pakistan's wind power plants [37]

Project	Company	Location	District	(MW)	Status	Cost ($)
Jhimpir Wind Energy Project	Burj Capital	Jhimpir	Thatta	49.7	Active	134 million
Three Gorges First Wind Farm	China Three Gorges Corporation	Jhimpir	Thatta	49.5	Active	125 million
Foundation Wind Energy–II	Fauji Foundation	Gharo	Thatta	50	Active	127 million

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Artistic Energy Pvt Ltd.	General Electric and Artistic Milliners	Jhimpir	Thatta	49.5	Active	120 million
Three Gorges Second Wind Farm	China Three Gorges Corporation	Jhimpir	Thatta	49.6	Active	113.1 million
Master Wind Energy	Master Group of Industries	Jhimpir	Thatta	52.8	Active	125 million
Jhimpir Wind Power Plant	Morlu Enerji	Jhimpir	Thatta	56.4	Active	143 million
Sachal Energy Wind Farm	Arif Habib Group	Jhimpir	Thatta	49.5	Active	134 million
United Energy Pakistan	United Energy Group	Jhimpir	Thatta	99	Active	250 million
FFC Energy Ltd.	Fauji Fertilizer Company	Jhimpir	Thatta	49.5	Active	134 million
Foundation Wind Energy–I	Fauji Foundation	Gharo	Thatta	50	Active	128 million
Sapphire Wind Power	Sapphire Group	Gharo	Thatta	52.8	Active	127.7 million
Yunus Energy	Lucky Cement Limited	Jhimpir	Thatta	50	Active	110.2 million
Metro Wind Power	Infraco Asia Development Pvt Ltd.	Jhimpir	Thatta	50	Active	136 million
Hawa Energy Ltd.	Hawa Energy and JS Group	Jhimpir	Thatta	49.6	Active	130.2 million
Three Gorges Third Wind Farm	China Three Gorges Corporation	Jhimpir	Thatta	49.6	Active	113 million
Tenaga Generai Ltd.	Tenaga Generasi Limited	Gharo	Thatta	49.5	Active	117 million
Gul Ahmed Wind Power	Gul Ahmed Energy Limited	Jhimpir	Thatta	50	Active	131 million
Tapal Wind Energy	Tapal Group and Akhtar Group	Jhimpir	Thatta	30	Active	136 million
Hydro-China Dawood Power	Hydrochina Corporation	Gharo	Thatta	49.5	Active	115 million
Tricon Boston Corporation	General Electric and Tricon Boston	Jhimpir	Thatta	148.8	Active	342 million

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Zephyr Power Ltd.	CDC Group PLC	Gharo	Thatta	50	Active	103.3 million

This corridor has the potential to generate reliable electricity from June to September during the southwest monsoon in Pakistan. Many wind farms have been constructed by the Indian government along this wind corridor, which extends into the state of Rajasthan. Rajasthan is one of India's leading states for harnessing wind energy to generate power, with a capacity of 18.7 GW [38]. Fifteen different projects in Rajasthan have commissioned 4.3 GW of wind power capacity, with around 68 percent of the total capacity coming from Suzlon and Enercon.

Potential of wind energy in southern Region of Sindh

In this paper, we analyse and evaluate the wind patterns and potential of Karachi, Thatta, Badin, and Jamshoro, situated in the southern part of Sindh, as seen in Figure 3. An examination of seasonal and monthly wind speed trends is conducted for each zone.

Figure 3: An examination of four separate zones of Sindh

Zone 1_ Karachi

The average wind speed at the Defense Housing Authority (DHA) Karachi and Hawke's Bay was 5.9 and 5.4 m/s, respectively, at a height of 50 m [39]. The month of July had the greatest average wind speed for DHA Karachi and Hawke's Bay during the monsoon season. As shown in Figure 4, the highest speed recorded for DHA Karachi was 9.0 m/s, whereas the highest speed recorded for Hawke's Bay was 7.1 m/s.

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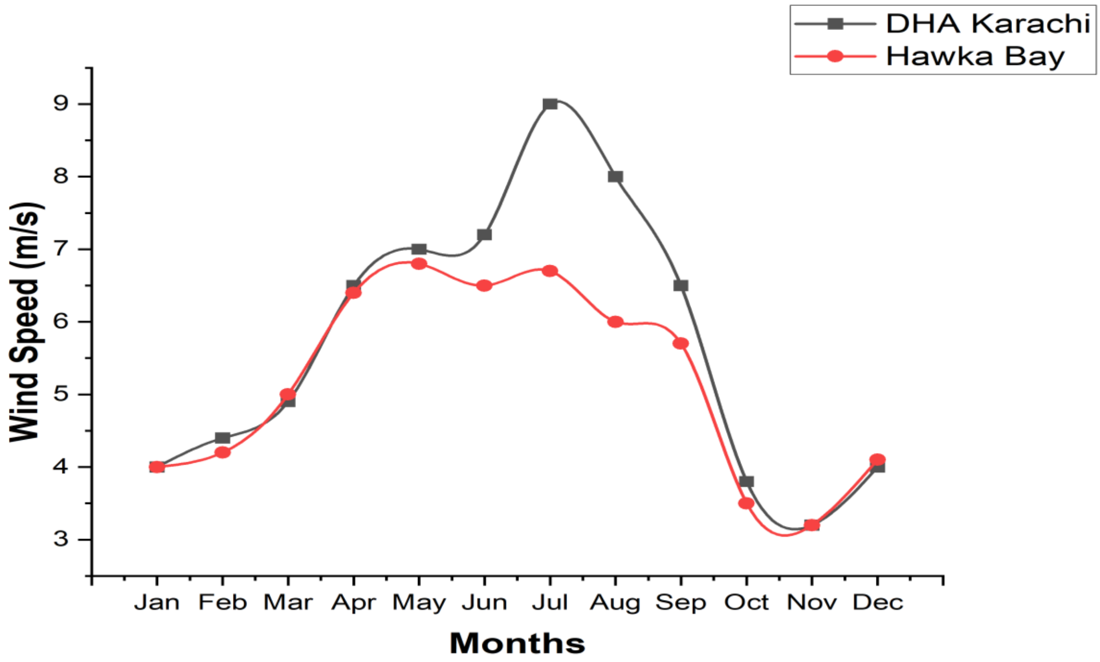

Figure 4: Yearly Wind Velocity for Zone 1 (Karachi)

The lowest wind speeds recorded in November were 3.6 m/s in DHA Karachi and 3.2 m/s in Hawke's Bay. Consequently, the Goldwind GW 140/3 MW, with a capacity of 3.0 MW at a wind speed of 10.5 m/s, is the most suitable wind turbine generator for these circumstances [40]. It can function in harsh conditions because to its low cut-in speed of 2.5 m/s and high cut-out speed of 20 m/s. This turbine employs a Permanent Magnet Synchronous Generator (PMSG) with a rotor diameter of 140 meters. At the height of 50 meters, the mean wind velocity from January to October exceeds 5.7–6.3 m/s, which is optimal for these turbine designs. In Zone 1, the lowest production of 0.45 GWh was in November, while the highest production of 3.2 GWh was anticipated in July from a single GW 140/3 MW unit. Winds in Zone 1 have more potential during the summer months (May to August) compared to the winter months (November to January). A single 3 MW wind turbine in Zone 1 generates 18.1 GWh of power each year, which might help to close the supply-demand gap in Karachi.

Zone 2_ Thatta

Zone 2 is divided into six regions: Shah Bandar, Mirpur Sakro, Chuhar Jamali, Gharo, Jati, Keti Bandar, and Sajawal. The other six are all categorized as class 3, with Chuhar Jamali falling into class 2. Chuhar Jamali has the lowest average wind speed in Zone 2, at 5.8 m/s, Although Keti Bandar has the greatest average speed of 7.1 meters per second [41]. Gharo and Mirpur Sakro, on the other hand, have the lowest and greatest monthly wind speeds, with 3.8 meters per second and 10.7 meters per second, respectively, as shown in Figure 5.

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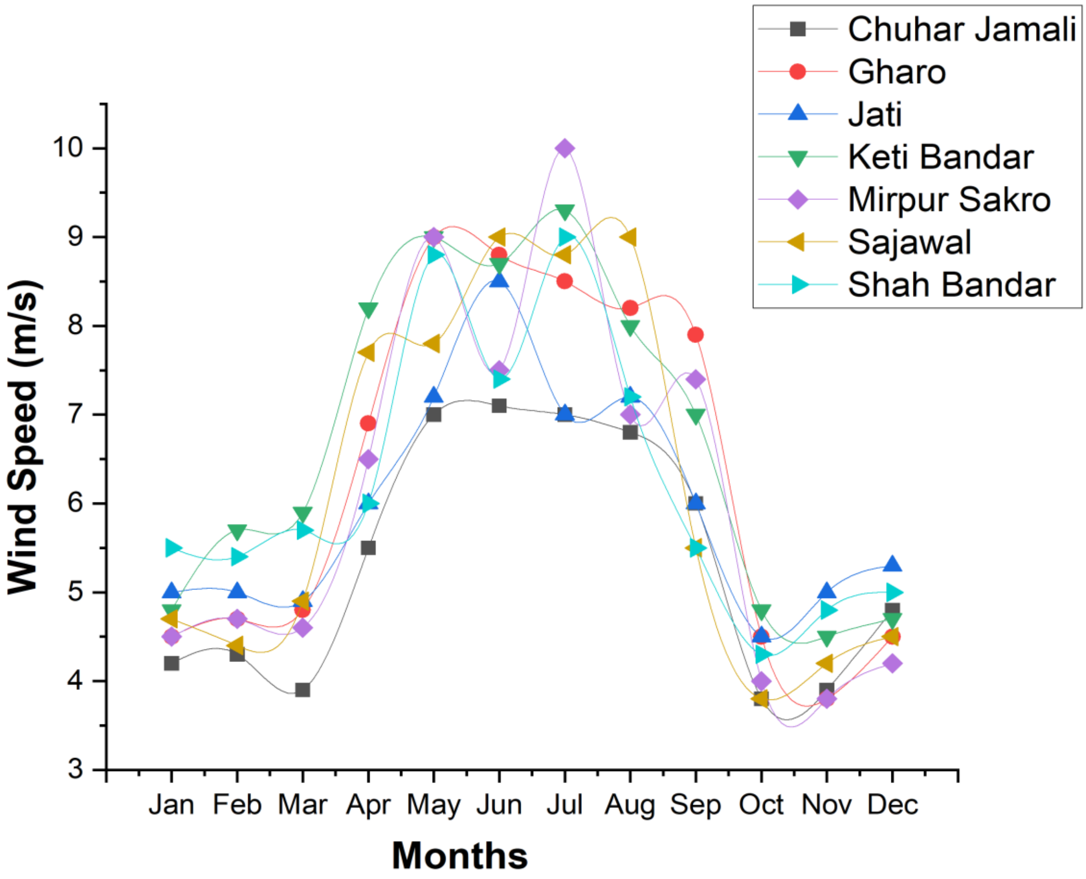

Figure 5: Yearly Wind Velocity for Zone 2 (Thatta).

The Goldwind GW 140/3 MW was chosen for Zone 2 because of its low cut-in and rated speeds [89]. Chuhar Jamali, Gharo, Jati, Keti Bandar, Mirpur Sakro, Sajawal, and Shah Bandar are predicted to generate 9.8 GWh, 13.3 GWh, 11.2 GWh, 14.3 GWh, 11.5 GWh, 13.1 GWh, and 12.0 GWh, respectively [42]. The majority of electricity is produced throughout the summer months, namely from April to September, peaking in July. This allows Zone 2 to handle the highest demand for electricity in Sindh province, which occurs in the months of April through September. Thus, projected energy may alleviate the energy deficit issues in these areas that adversely affect human living standards.

Zone 3_ Badin

Zone 3 comprises two areas, Golarchi and Talhar, categorized as class 3 based on their average wind velocity. At a height of 50 meters, the mean wind velocity was 6.7 m/s in Golarchi and 6.3 m/s in Talhar [43]. In June, the greatest speed in Talhar reached 10.3 m/s, but in Golarchi, the maximum speed stayed at 9.4 m/s for both June and July. Figure 6 illustrates a comparison of wind speeds between the two areas.

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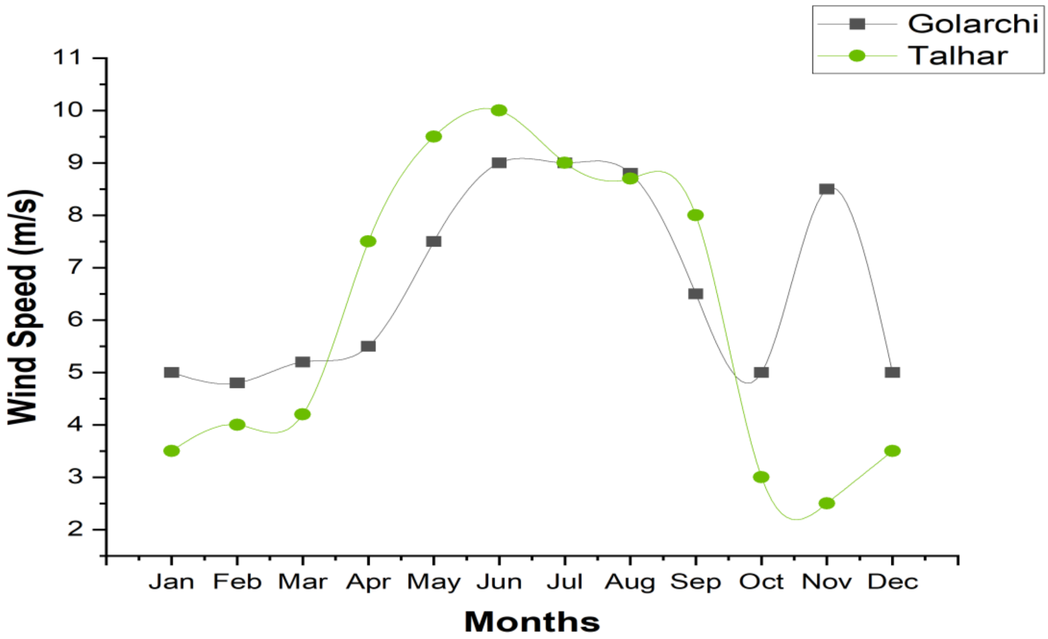

Figure 6: Yearly Wind Velocity for Zone 3 (Badin)

The GW 140/3 MW is the most efficient wind turbine at these wind velocities, producing 3 MW of rated energy when the wind speed ranges from 10.5 to 11.0 m/s [44]. The maximum output of 2.2 GWh is projected at Talhar in May with a solitary 140/3 MW wind turbine, while the minimum production of 57.6 MWh is anticipated in November. The maximum production of 2.16 GWh is projected at Talhar in June with a single GW 140/3 MW wind turbine, while the minimum output of 36 MWh is anticipated in November in Talhar. On the other hand, Golarchi's maximum output was calculated at 2.12 GWh in July, while its minimum production was 386 MWh in October. Zone 3 is projected to generate 26.6 GWh per year from a single GW 140/3 MW wind turbine generator. Although monthly power density estimates suggest that power density remains below the marginal threshold in winter, this is offset by elevated levels throughout the summer, particularly between May and September.

Zone 4_ Jamshoro

Jamshoro, Nooriabad, and Thano Bula Khan are the three areas that make up this zone. Due to high wind speed, Jamshoro has been designated as a class 6 wind location, Nooriabad as a class 4, and Thano Bula Khan as a class 2. Figure 7 illustrates that Jamshoro, Nooriabad, and Thano Bula Khan saw the maximum wind speeds of 13.9, 10.6, and 9.8 m/s, respectively, while the lowest wind speeds recorded were 5, 4.2, and 2.7 m/s.

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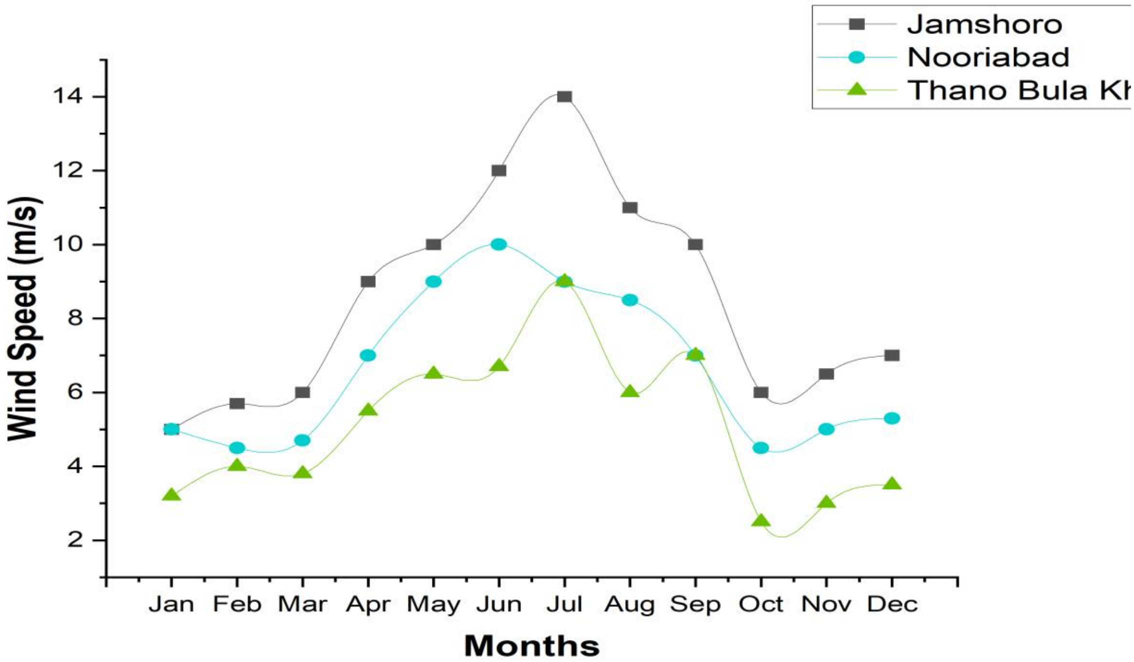

Figure 7: Yearly Wind Velocity for Zone 4 (Jamshoro)

We selected the GW 136/4.2 MW wind turbine for this area owing to its reduced cut-in speed, which enhances its viability for Thano Bula Khan by increasing energy production. This turbine can make 4.2 MW at a rated speed of 11.5 m/s and has a cut-in speed of 2.5 m/s [45]. It is a good choice for Jamshoro. It has a rotor diameter of 136 meters and utilizes Permanent Magnet Synchronous Generator (PMSG) technology [46]. According to estimates, with a GW136/4.2 MW WTG, Thano Bula Khan can generate 8.9 GWh, Jamshoro 19.7 GWh, and Nooriabad 14.9 GWh. From June to August, Jamshoro is expected to generate the largest amount of electricity at 3.04 GWh, followed by Nooriabad at 2.9 GWh and Thano Bula Khan at 2.5 GWh. Based on this trend, Zone 4 and its vicinity are viable locations for the establishment of large, economically viable wind farms.

Power Output of all Zones

The annual power output capacity of a planned wind turbine for each of the four zones is shown in Figure 8. The yearly output of all four zones from a single wind turbine generator is projected to reach 173.5 GWh. Zone 2 Thatta is anticipated to achieve a maximum production of 85.26 GWh, while Zone 1 Karachi is projected to provide the lowest generation at 18.09 GWh [47]. The annual generation capacities of 43.58 GWh and 26.59 GWh, respectively, may be achieved by a single wind turbine in Jamshoro and Badin.

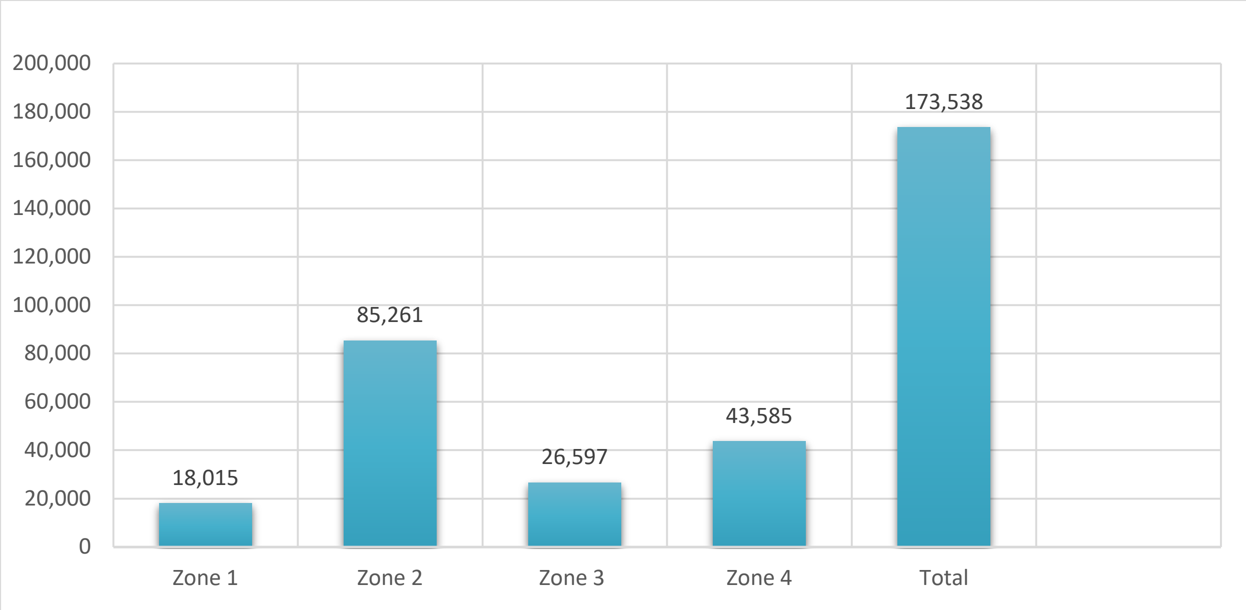

Figure 8: Power output in MWh for all zones.

Wind potential in Southern Balochistan

Balochistan is situated in the southern part of Pakistan. This is one of the most potential locations for wind energy development in the country. Balochistan wind energy potential is projected to be approximately 50,000 MW [48]. The Jeevani and Gwadar areas in Balochistan situated near the coastal strip are the most notable wind corridors. These sites have regular wind speeds of more than 7 m/s, making them suitable for wind energy harvesting. In 2017, a 50MW wind power plant was established and become operational in Jeevani [49]. The **Lasbela** district is another area with high wind potential due to its location near the coast and consistent wind patterns. Several wind energy projects are already operational in Balochistan, such as the **Jeevani Wind Power Project** and **Gwadar Wind Power Project.** The Sindh-Balochistan Wind Corridor, which covers from the south of Sindh to the north of Balochistan, has been highlighted as a key area for future wind farm development.

Discussion

This study has analyzed the optimal sites for wind and solar energy generation in Pakistan, focusing on their potential for sustainable power generation. The results of the analysis demonstrate that Pakistan is endowed with significant renewable energy resources, particularly in the form of wind and solar energy, which, if harnessed efficiently, could play a pivotal role in the country's transition towards sustainable energy.

Solar Energy Potential

The geographical distribution of solar energy potential in Pakistan reveals that areas in Sindh, Balochistan, and the southern regions of Punjab have the highest solar irradiance levels, making them the most suitable for large-scale solar farm installations. The Thar Desert, which stretches across Sindh and parts of Rajasthan in India, emerges as a prime location for solar power generation, with average solar radiation levels of 5.5 to 7.0 kWh/m²/day. The Cholistan Desert and the southern regions of Punjab, such as Multan, Bahawalpur, and Dera Ghazi Khan, also show considerable solar potential, with solar irradiance levels in the range of 5.5 to 6.0 kWh/m²/day. These areas have the added advantage of low cloud cover and minimal rainfall, ensuring higher sunshine hours throughout the year, which is critical for maximizing energy generation from solar farms.

Despite the promising potential, the large-scale deployment of solar energy in Pakistan faces several challenges. While the technological advancements in photovoltaic (PV) systems have made solar energy more affordable, issues related to infrastructure development, such as the lack of grid connectivity and energy storage solutions, continue to impede the growth of the solar industry. Additionally, the government's historical focus on thermal and hydroelectric power generation has led to limited policy support for solar energy, though this has started to shift with the introduction of various renewable energy policies and initiatives under the China-Pakistan Economic Corridor (CPEC). As these policies evolve, it is crucial for the government to ensure that adequate incentives are provided for private sector investment in solar energy and the development of necessary infrastructure.

Wind Energy Potential

In terms of wind energy, Pakistan's coastal regions, particularly the Sindh province, hold significant promise for large-scale wind power generation. The Thatta and Gwadar regions, along with the Indus Delta area, have been identified as optimal locations for wind farms, with wind speeds exceeding 6.5 m/s at 80 meters above ground level. These areas experience consistent wind patterns, particularly during the monsoon season, making them ideal for the deployment of wind turbines. The Jhimpir Wind Corridor in Sindh is already home to one of the country's most developed wind farms, with a total installed capacity of over 100 MW, demonstrating the feasibility of wind energy in Pakistan. Furthermore, the proximity of these wind-rich areas to major load centers, such as Karachi, offers an additional advantage in terms of reducing transmission losses and improving grid stability.

However, the wind energy sector in Pakistan faces similar challenges to the solar sector. One of the key issues is the lack of an integrated national grid that can efficiently transport wind power from remote regions to urban centers. Furthermore, the intermittency of wind energy requires the development of energy storage technologies and backup systems to ensure a stable and reliable supply of electricity. Another challenge is the need for a comprehensive wind resource mapping and further studies to identify and validate additional potential wind sites, particularly in regions with fluctuating wind speeds or complex terrain.

Future Work

The findings of this study offer valuable insights into the optimal sites for wind and solar energy generation in Pakistan. However, several areas require further investigation to enhance the understanding and application of renewable energy potential in the country. Future work should focus on refining solar and wind resource mapping, including high-resolution geographic data and more detailed assessments of seasonal variations in energy generation potential. Additionally, it would be beneficial to conduct long-term studies on the economic feasibility of integrating solar and wind energy systems at the national level, considering factors such as capital costs, return on investment, and maintenance requirements. Further research could also explore the development of hybrid systems that combine solar, wind, and energy storage technologies. These systems could address issues related to intermittency and grid stability, ensuring a continuous and reliable energy supply even during periods of low solar or wind output. A key area of future work would involve exploring the integration of advanced energy storage solutions, such as lithium-ion batteries, pumped hydro storage, and compressed air energy storage, which could significantly improve the grid's reliability and flexibility.

Moreover, policy frameworks that support the efficient deployment of renewable energy technologies need to be further developed. Future studies could focus on understanding the role of government policies, regulatory frameworks, and financial incentives in accelerating the transition to renewable energy in Pakistan. This could include analyzing the effectiveness of existing policies and recommending changes to attract more private-sector investments in renewable energy projects. Lastly, the social and environmental impacts of large-scale solar and wind farm developments need to be studied in greater detail. Research into the social acceptability of these projects, including land acquisition processes and community engagement, will be critical to ensuring that renewable energy initiatives benefit both the environment and the local populations. Assessing the long-term environmental impacts, such as the effects on local wildlife and ecosystems, should also be prioritized. By addressing these areas of future work, researchers and policymakers can better equip Pakistan to harness its full renewable energy potential, advancing the country toward a more sustainable, clean, and energy-secure future.

Conclusion

This study highlights Pakistan's significant potential for wind and solar energy, particularly in regions like **Sindh, Balochistan,** and southern **Punjab**. By harnessing these resources, the country can reduce its reliance on fossil fuels, mitigate climate change, and enhance energy security. However, challenges such as inadequate infrastructure, grid connectivity, and limited policy support hinder the large-scale development of renewable energy projects. The complementary nature of wind and solar energy offers a promising solution for ensuring a reliable power supply throughout the year. To fully realize this potential, Pakistan needs to invest in infrastructure, energy storage, and favorable policy frameworks. Moreover, ongoing research, community engagement, and environmental assessments will be essential for the sustainable development of these resources. In conclusion, Pakistan's wind and solar energy resources present a tremendous opportunity for a cleaner, more sustainable energy future. Addressing the existing challenges through collaborative efforts and innovation will pave the way for a greener energy transition in the country.

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