energies

Article

Wind Energy Potential in Pakistan: A Feasibility Study in Sindh Province

Rafiq Asghar [1], Zahid Ullah [2], Babar Azeem [3], Sheraz Aslam [4,*], Muhammad Harris Hashmi [5], Ehtsham Rasool [5], Bilawal Shaker [5], Muhammad Junaid Anwar [5] and Kainat Mustafa [6,*]

1 Faculty of Electrical & Electronics Engineering, Universiti Malaysia Pahang (UMP), Pekan 26600, Pahang, Malaysia
2 Department of Electrical Engineering, UMT Lahore Sialkot Campus, Sialkot 51310, Pakistan
3 Department of Electrical Energy and Mobility System, Carinthia University of Applied Sciences, 9524 Villach, Austria
4 Department of Electrical Engineering, Computer Engineering, and Informatics, Cyprus University of Technology, 3036 Limassol, Cyprus
5 Department of Computer Science, University of Alabama at Birmingham, Birmingham, AL 35294, USA
6 Department of Computer Science, Virtual University of Pakistan, Lahore 54000, Pakistan
* Correspondence: sheraz.aslam@cut.ac.cy (S.A.); kainatmustafa@yahoo.com (K.M.)

Abstract: The environment and the economy are negatively impacted by conventional energy sources, such as coal, gasoline, and other fossil fuels. Pakistan's reliance on these resources has resulted in a catastrophic energy crisis. This has driven the government to make critical decisions such as early retail closures, power outages for the industrial sector, and an increase to two days a week vacations. Wind energy, accessible and affordable, will become a viable option for meeting Pakistan's present and future energy demands. Approximately 3% of Pakistan's land can produce nearly 132 GW of power with an installed capacity of 5 MW per km^2. In this study, four zones (Karachi, Thatta, Badin, and Jamshoro) in Sindh province are assessed for the feasibility of wind energy generation. The installed capacity, generator types, and detailed specifications are provided for each zone. Moreover, the wind mapping of Pakistan is presented considering the four potential zones. The zones are analyzed using annual wind speed and power output considering wind data measured at 50 m height over one year. The higher mean speed is recorded at Jamshoro compared to other zones. The analysis indicates that all four sites are suitable for large-scale wind power generation due to their energy potential.

Keywords: wind energy; wind turbine generators; wind mapping; Sindh case; wind energy integration

check for updates

Citation: Asghar, R.; Ullah, Z.; Azeem, B.; Aslam, S.; Hashmi, M.H.; Rasool, E.; Shaker, B.; Anwar, M.J.; Mustafa, K. Wind Energy Potential in Pakistan: A Feasibility Study in Sindh Province. *Energies* **2022**, *15*, 8333. https://doi.org/10.3390/en15228333

Academic Editors: Qingan Li, Junlei Wang, Dongran Song, Mohamed Talaat, Mingzhu Tang and Xiaojiao Chen

Received: 13 October 2022
Accepted: 3 November 2022
Published: 8 November 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Electric power is a fundamental human need and plays a crucial role in every country's social and economic growth [1]. In most developing countries, non-renewable energy resources, such as coal and fossil fuels, are mainly used to generate electrical power, which has numerous repercussions for the ecosystem, human well-being, and government expenditure. Moreover, resource constraints, production challenges, market price volatility, and thermal-power plant management issues place fossil fuels at the forefront of global-level policy [2]. Consequently, the energy deficit is apparent if new energy sources are not discovered and the current source of energy generation is not modified. Over the past few decades, researchers have continuously developed novel solutions for addressing future energy needs and reducing reliance on fossil fuels [3]. Several countries have initiated the creation of a more environmentally sustainable and less harmful energy infrastructure that could meet the rapidly growing energy demands [4]. Integrating renewable energy sources into the energy mix would reduce the adverse effects on the environment and the healthcare expenses associated with economic growth while reducing debt and stabilizing energy prices in the long run [5]. Hence, there has been a lot of emphasis on developing renewable energy globally. Wind and solar energy may be the most sustainable options when considering ecosystem health, human well-being, and resource availability [6]. In 2016, wind energy generated more than 487 GW of power, a 16% increase over 2015 [7], while offshore wind energy capacity increased by 4.5 GW.

The energy supply in Pakistan is highly dependent on thermal power generation, which accounts for 60 percent of total energy. Any price surge in the foreign petroleum and natural gas market substantially impacts power generation in Pakistan, which could make circular debt issues much more crucial [8,9]. Due to its reliance on thermal resources, the country has recently experienced a severe energy crisis, resulting in widespread load shedding and the near suspension of daily activity. This has driven the Government of Pakistan (GOP) to make crucial decisions such as the early closure of malls, power reduction for the industrial sector, and two days of vacation a week that significantly influenced academia, industry, and business [10–12]. Another worst scenario for the GOP is the most significant Green House Gas (GHG) emissions from the energy sector, roughly 48. Sixty-two million tons and consuming almost 14.19 Mtoe of fossil fuels [13,14]. The detail of GHG emissions percentage from various sectors in Pakistan is shown in Figure 1. The Intergovernmental Panel on Climate Change (IPCC) has recently confirmed that human activities in South Asia are responsible for a 90 percent rise in GHG emissions [3,15]. Temperatures in South Asia are anticipated to rise by an average of 3.3 °C by the end of the century, with Pakistan and India experiencing more significant rises than the average [3]. Pakistan is particularly vulnerable to the impacts of climate change due to its economic dependence on agribusiness and natural resources [16]. Wheat production in Pakistan is projected to decrease by 6–7 percent with a 1 °C temperature increase [17,18]. At the same time, cash crops such as mangoes and cotton would be badly impacted by a temperature increase of even less magnitude.

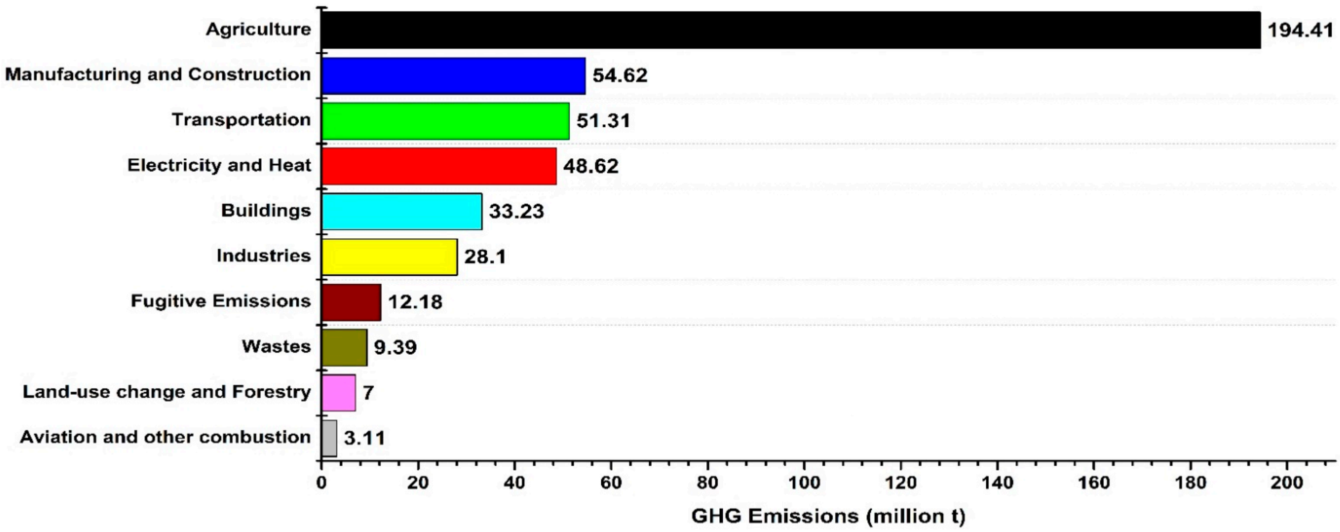

Figure 1. GHG Emissions by Various Sectors [19].

Additionally, human settlements in coastal regions are particularly vulnerable to the impacts of climate change. Several coastal settlements and villages risk entirely submerging by increasing sea levels and rainfall in some areas [20]. Therefore, to overcome the challenges mentioned above, the energy sector needs to transform from thermal-based power generation into renewable and environmentally sustainable alternatives. The essential requirement for this transition is the support and financing from the local and international stakeholders that will facilitate the GOP to take advantage of rapidly advancing renewable energy technology. Pakistan Meteorological Department (PMD) has performed a preliminary assessment of wind energy and developed a map indicating that the optimum potential for harvesting wind energy exists at 50 m, with a total capacity of about

300,000 MW [21–23]. The GOP also promised to mitigate the effects of climate change and environmental damage by increasing the percentage of renewable energy to about 30% by the end of 2030 during a Green Grids Initiative (GGI) conference on climate change [24]. However, despite the availability of technical data, the potential to capture renewable energy, particularly wind energy, in Pakistan has not been thoroughly explored [25]. There was just a 200 MW increase in total wind energy output in 2018, and no new projects were completed after that year.

In contrast, neighboring countries such as India and China witnessed a spectacular increase of 4.7 GW and 144.2 GW within the same time frame. Constructing wind farms in coastal Sindh and Baluchistan would decrease energy shortfalls and drastically reduce import oil expenses by roughly USD12 billion annually [3,20]. Consequently, it is vital to monitor the transitional challenges and design a more positive and effective strategy for optimizing the wind energy potential in the country.

This paper explains a detailed description of the energy production and wind potential scenario in different regions of Pakistan. For this purpose, fourteen possible sites have been identified and divided into four different zones. One-year wind speed data were collected for 30 m and 50 m heights of these proposed zones. These wind speed data are classified into seven classes: poor (0–5.1 m/s) to superb (8.2–11.0 m/s). Goldwind wind turbines GW 140/3 MW and GW 136/4.2 MW were analyzed for power generation from these four zones. Based on the analysis, it is estimated that GW 140/3 MW can extract 130 GWh from Zones 1–3. Similarly, Zone 4 can produce 43.6 GWh of electricity from a single GW 140/3 MW. Hence, this paper highlights wind energy as a potential resource that can be tapped immediately to overcome the current energy crises and warrants energy security.

The remainder of our paper is arranged as follows: Section 2 reviews the wind energy conversion system. The geographical features and generation capacity of Pakistan are comprehensively discussed in Section 3. Section 4 provides a discussion of the results. Section 5 discusses wind energy integration into the power system, while Section 6 concludes the paper with a summary and future directions.

2. Wind Energy Conversion System (WECS)

A WECS is a complex framework that integrates various aerodynamic, automotive, structural, and computational technologies [26,27]. The WECS framework employs a turbine to convert the wind's kinetic energy into mechanical energy that may be used to power generators or produce electricity [28,29]. The mechanical power generated by the Wind Turbines (WTs) can be calculated using the following equations:

$$\frac{dm}{dt} = \rho A \frac{dx}{dt} \tag{1}$$

$$\frac{dK.E}{dt} = \frac{1}{2}\rho A\, V^3 \tag{2}$$

$$P_m = \frac{1}{2}\rho A V^3 Cp\ (\lambda, \alpha) \tag{3}$$

where A, ρ, α are the WTs' swept area, air density, and pitch angle. Considering the WT structure, the tip speed λ and power coefficient Cp are critical determinants that evaluate and influence the power extracted by a WT. The λ can be described as the ratio of the turbine's tangent speed to the actual wind speed, whereas the Cp is the ratio of the true power generated to the maximum wind power available at the blades [30].

$$\lambda = \frac{\omega R}{V} \tag{4}$$

$$C_p(\lambda, \alpha) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\alpha - 5\right)e^{-\frac{21}{\lambda_i}} + 0.0068\lambda \tag{5}$$

where

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\alpha} - \frac{0.035}{\alpha^3 + 1}$$

The estimated potential power efficiency of a WT is 0.593, which indicates that the currently available WT can extract only 59.3 percent of the wind power. This 0.593 factor is called the Betz's or Lanchester limit [31]. Therefore, it is important to calibrate the speed at the turbine's shaft to achieve the maximum tip speed and power coefficient to maximize active power generation.

A turbine's annual power density ($P_{Density}$) is the amount of wind energy produced by the turbine divided by the area of the turbine in a given wind zone and is expressed as [32]:

$$P_{Density} = \frac{P_{ave}}{\pi R} \tag{6}$$

where P_{ave} is the average power. In contrast to rated power P_{rated}, average power is an important metric for determining energy in a given period, which may affect the cost-effective viability of a wind power generation system. Electrical power output P_e may be calculated in terms of rate power as follows:

$$P_e = \begin{cases} 0 & V_{cut-in} > V_\omega \\ P_{rated} \frac{V^k{}_{cut-in} - V^k{}_\omega}{V^k{}_{rated} - V^k{}_{cut-in}} & V_{rated} \geq V_\omega \geq V_{cut-in} \\ P_{rated} & V_f \geq V_\omega \geq V_{rated} \\ 0 & V_\omega > V_f \end{cases} \tag{7}$$

where V_ω, V_f, V_{cut-in}, and k are the maximum speed, cut-in speed, cut-out speed, and shape factor, respectively. The normal range for the k is anywhere between 1 and 3. A low value implies a broad range of wind speeds around the average, while a high value suggests a narrow range of wind speeds [33]. Similarly, average power can be determined from the following equation:

$$P_{ave} = P_{rated} \frac{e^{-(V_{cut-in}/C)^k} - e^{-(V_{rated}/C)^k}}{(V_{rated}/C)^k - (V_{cut-in}/C)^k} - \frac{1}{e^{(V_{cut-in}/C)^k}} \tag{8}$$

where C is the Weibull factor.

2.1. Wind Turbine Generator (WTG) Technology

The generator design of wind turbines is a determining factor, and there is no consensus among researchers and industries on the optimal WTGs [34,35]. The primary criteria for WTGs are significant torque and power density, minimal mechanical components, high accuracy, simple construction, high dependability, and adaptability to varying wind patterns. In addition, generators must operate under challenging conditions despite failures, and the commercial acceptability of any generator technology is closely related to its power conversion system's relative availability and cost [36]. Two primary classes of WTGs can be used for different wind energy applications, for instance, Direct Current (DC) and Alternating Current (AC) (synchronous and asynchronous) generators. Table 1 shows these two types of WTGs and their detailed performance. Table 2 also lists the most popular manufacturers of wind turbines and their power ranges. In principle, they may operate at either constant or variable speeds; however, due to the fluctuating nature of wind power, it is preferable to operate the WTGs at variable speeds, which reduces the mechanical stress on the propellers and drivetrain components.

Table 1. Comparison between various WTGs.

Parameters	DC Generators	Synchronous Generator				Asynchronous Generator	
		Electromagnetic	PM	Reluctance	HTS	FISG	DFIG
Efficiency	Low	High	Highest	Moderate	Highest	Low	High
Outlay	Low	Moderate	Highest	Moderate	Highest	Low	Moderate
Dependability	Fair	High	Highest	Highest	Moderate	Moderate	High
Controllability	Inferior	Better	Better	Better	Best	Better	Better
Speed	Constant	Variable	Variable	Variable	Variable	Variable	Variable
Fault response	Lower	Moderate	Moderate	Moderate	High	Lower	Moderate
Converter size	Full	Full	Full	Full	Full	Not Required	20–30%
Grid-Provision Ability	Lower	Moderate	Highest	Moderate	High	Lower	High
Mass saving	Lower	Moderate	Highest	Lower	Highest	Lower	Moderate
Power supply	Direct Grid Connection	Total	Total	Total	Total	Direct Grid Connection	Partial
Maximum Power	Low	Moderate	High	Low	Moderate	Low	High
Active–reactive power	No	Separate	Separate	Separate	Separate	Dependent	Separate
Voltage fluctuation	High	Low	Low	Moderate	Very Low	High	Low
Application	Domestic/Small-Scale wind application	Small–Medium Wind Application	Small–Medium Wind Application	Developing Phase	Developing Phase	Small-Scale wind applications	Medium–Large Wind Application

Table 2. Large wind turbine generators in the market.

Name	Manufacturer	Country	Rotor Dia. (m)	Swift Area (m^2)	Rated Power (MW)	Generator Types	On/Offshore	Status
Acciona	Acciona Energy S.A.	Spain	70–148	3848–17,203	1.5–3.3	Asyn	Yes/No	Active
Adwen	Adwen Offshore, S. L	Spain	116–180	10,568–25,447	5.0–8.0	Syn, Asyn	Yes/Yes	Active
AMSC	American Superconductor	America	82–190	5281–28,353	1.65–10.0	Syn, Asyn	Yes/Yes	Active
Bard	BARD Holding	Germany	122	11,690	5.28–6.5	Syn, Asyn	Yes/Yes	Active
Dongfang	Dongfang Electric Co.	China	70–185	3848–26,880	1.5–10.0	Syn	Yes/Yes	Active
Envision	Envision Energy	China	70.6–161	3915–20,358	1.5–5.0	Asyn	Yes/No	Active
Fuhrlander	Fuhrländer AG	Germany	12.8–132	130–13,685	0.02–3.0	Syn, Asyn	Yes/No	Inactive
GE	GE Renewable Energy	America	46–220	1662–38,000	0.6–14.0	Syn, Asyn	Yes/Yes	Active
HITACHI	Hitachi, Ltd.	Japan	80–136	4978–14,540	2.0–5.2	Syn, Asyn	Yes/Yes	Active
MingYang	MingYang Smart Energy	China	77.1–242	4369–46,000	1.5–16.0	Syn, Asyn	Yes/Yes	Active
Mitsubishi	Mitsubishi Power, Ltd.	Japan	25–167	490.9–21,900	0.25–7.0	Syn, Asyn	Yes/Yes	Active
Nordex	Nordex SE	Germany	17–163	227–20,867	0.6–5.0	Syn, Asyn	Yes/Yes	Active
REpower	REpower Systems	Germany	48.4–152	1840–18,146	0.6–6.15	Syn, Asyn	Yes/Yes	Inactive
Siemens	Siemens Wind Power A/S	Denmark	62–154	3020–18,600	1.3–7.0	Syn, Asyn	Yes/Yes	Inactive
Siemens Gamesa	Siemens Energy AG	Spain	114–222	10,207–39,000	2.1–14.0	Syn, Asyn	Yes/Yes	Active
Unison	Unison Co., Ltd.	Korea	50–146.3	1963–16,812	0.75–4.2	Syn	Yes/No	Active
Vestas	Vestas Wind Systems	Denmark	10–236	78.5–43,742	0.2–15.0	Syn, Asyn	Yes/Yes	Active
W2E	Wind to Energy GmbH	Germany	116–215	10,568–36,305	2.0–9.0	Syn, Asyn	Yes/Yes	Active
Windtec	American Superconductor	America	80–190	-	2.0–10.0	Syn, Asyn	Yes/Yes	Active

2.1.1. DC Generators

Traditional DC machines have output coils that rotate in a magnetic field to provide the appropriate magnetic flux, with the primary winding at the stator and the armature winding at the rotor [34]. The magnetic field that controls the power is either permanent or electromagnetic and is obtained directly from the rotor through carbon brushes. Normally, when the machine is electrically powered, it runs according to the shunt-wound generator concept [37]. There are several DC generators, but the permanent Magnet DC (PMDC) or the Dynamo are the most prevalent for wind applications. For the PMDC generator's output terminals to deliver power, the armature-generated current must flow through a slip ring and carbon brush [38]. PMDC generators are a viable option for small-scale wind energy systems due to their reliability, ability to operate at low rotational speeds, and high performance. These generators can produce power even in low-wind situations owing to their low cut-in speed. Moreover, PMDC generators react rapidly to any variations in wind speed due to their uniform stator field. These generators are compact and more efficient than other types because they lack field windings and field coil losses. Figure 2 shows a PMDC wind-generating system that contains a turbine, a DC generator, an inverter's circuit, a step-up transformer, and a grid. A virtual DC machine (VDCM) control and an improved VDCM control with differential compensations for the converter are presented [39,40], which may increase damping with varying wind speed and load. The major drawback of DC generators for high-energy applications is that the maintenance and operation of brushes and controllers are expensive [41]. In addition, they needed fully fledged converters to connect to the electrical grid. Consequently, these generators are often used in low-energy applications where the load is relatively close to the turbine, in high-temperature applications, or in rechargeable batteries [42].

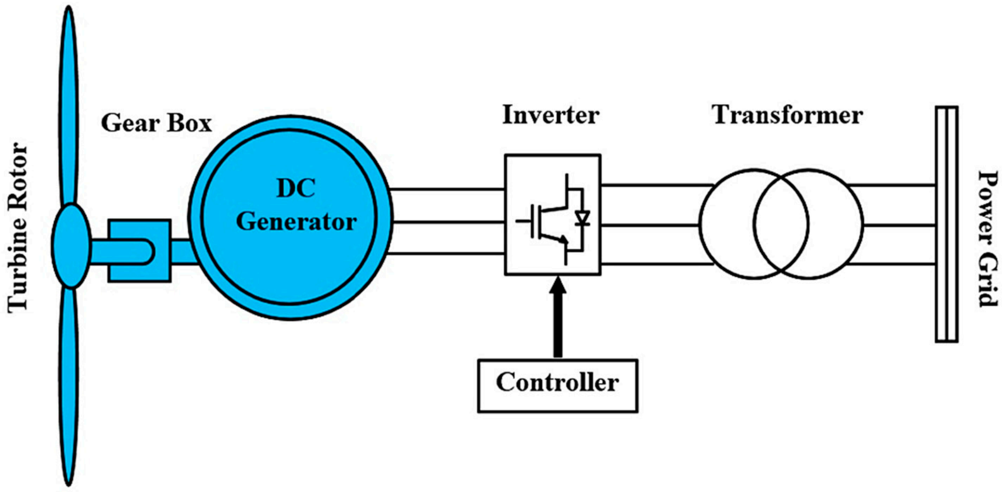

Figure 2. DC generator layout for wind energy systems [34].

2.1.2. AC Synchronous Generators

Since the early stages of WTs' development, significant efforts have been made to use three-phase SGs. The SG is simply a synchronized electromechanical device consisting of a Rotating Magnetic Field (RMF) on the rotor and a static stator with several coils delivering the generated output [43]. The rotor winding is energized electromagnetically by an auxiliary DC supply connected across the rotor-circuit windings or by permanent magnets attached [44]. When the turbine rotates the rotor, the stator generates three-phase electricity, which is then transferred to the electrical grid through inverters and transformers. SGs are an established technology since their capacity to produce electricity has been thoroughly investigated and utilized for decades [45]. They play an essential role in both power generation and specific driving applications. In recent years, the Permanent Magnet Synchronous Generator (PMSG) has become more prevalent in wind turbines due to its better reliability, lower maintenance costs, and compact size [46]. The absence of a commutator, slip-ring, and brush in the PMSG makes the machine more robust, economical, and straightforward. Figure 3 depicts a wind turbine employing PMSGs with an AC/DC/AC converter. The Machine Side Converter (MSC), linked between the PMSG and a DC-Link capacitor, controls the maximum power tracking. Similarly, the Grid Side Converter (GSC), connected to the power grid and the DC-Link capacitor, maintains a constant DC-link voltage for reliable operation. Different control strategies for variable speed operation of WTs with PMSG have been proposed. These include linear control, Proportional Integral (PI) control [47], Proportional Integral Derivative (PID) control [48], and non-linear control, such as Sliding Mode Control (SMC) [30] and Model Predictive

Control (MPC) [49]. These controllers' performance is demonstrated using simulation results for various wind speeds.

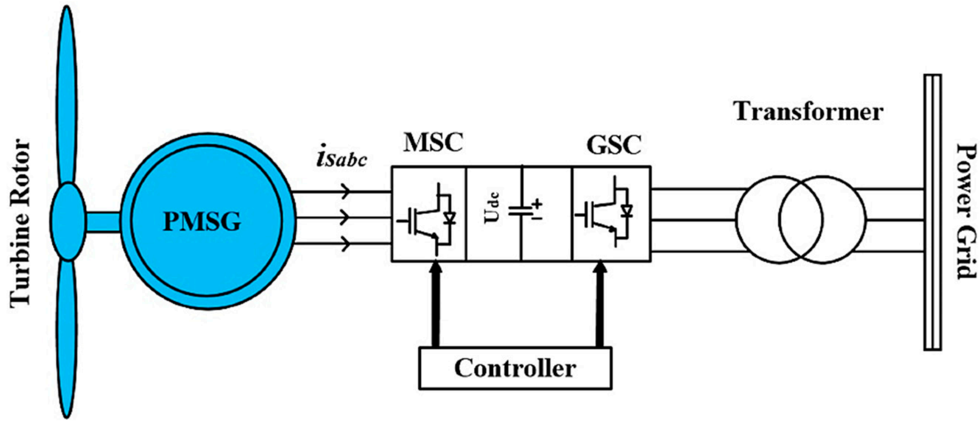

Figure 3. PMSG-based wind turbine.

Even though PM removes field winding, flux through the rotor cannot be adjusted, and it can only attain maximum efficiency under certain conditions, such as a certain wind speed [43]. In addition, demagnetization generated by a too high current or temperature and the extravagant cost of permanent magnets are additional disadvantages of these generators. PMSGs cannot produce power with consistent frequency; hence, they must always be coupled to the grid through converters [50,51]. Modern PMSGs are desirable for direct drive applications because they may eliminate complex gearbox systems, which are the root cause of most WTs failures. The High-Temperature Superconducting (HTS) generator is another type of SG with a stator core, HTS field circuit, rotor core, rotor cooling mechanism, external chiller, electromagnetic shielding, and casing [52]. In mechanical design, the stator, rotor, refrigeration, and transmission configuration may be particularly difficult for maintaining HTS coils under ambient temperatures. Superconducting coils can transport ten times the current of copper wire despite their low electrical resistance and conduction loss [53]. Since superconductors may improve current density and, thus, reduce weight and dimension even more, they are an excellent choice for use in WTG excitation circuits because of their ability to minimize energy losses drastically.

2.1.3. AC Asynchronous Generators

Induction Generators (IGs) are generally compact, durable, and cost-effective, with a significant damping capacity that enables them to withstand rotor speed variations and external transmission disturbances [54,55]. These generators are ideal for residential and industrial wind power applications since their electrical sizes range from a few horsepower to several megawatts. There are two main types of IGs: Fixed Speed Induction Generators (FSIGs) with squirrel cage rotors and Doubly-Fed Induction Generators (DFIGs) with wound rotors. These generators need reactive power adjustment, such as a capacitor bank or bidirectional converter, since they consume reactive power from the utility. Before the 1990s, most wind turbine manufacturers produced FSIGs directly connected to the grid through a transformer [56]. The main advantage of the FSIG is that it does not need a voltage regulator or a complex microprocessor, has a straightforward design, and has relatively low operating and maintenance costs [55]. While FSIGs dominated the market for many years, variable speed generators have replaced them in most applications.

FSIG has certain downsides, including the fact that the blades may not be in the optimal operating position for a range of scenarios and the inability to produce energy quickly, owing to the blades' pitch angle being the only variable. In addition, FSIGs have intrinsic issues such as low energy conversion, inflexibility in allowing grid voltage regulation, inherent power fluctuations, and mechanical stress concerns resulting from high wind speeds [55]. These generators have been found to cause catastrophic failures and subsequent maintenance, and since the voltage level is unregulated, reactive power must be delivered separately. As a result, FSIGs can only operate within a minimal and well-defined constant speed range. The extensive deployment of DFIGs has dominated the wind turbine market; nowadays, more than 85 percent of operational wind turbines utilize DFIG owing to its lower startup cost, compact size, and voltage control assistance [7,57]. The stator is linked to the power grid through a transformer, whereas the rotor is coupled with PWM converters, which control the rotor circuit current, frequency, and phase angle. As illustrated in Figure 4, the Rotor Side Converter (RSC) that connects the DFIG and the DC-Link capacitor guarantees that the rotor speed remains constant irrespective of wind speed. Similarly, coupled to the power grid and the DC-Link capacitor, the GSC maintains a constant DC-Link voltage while supporting the grid voltage with reactive power independent of wind speed variations [7]. Variable speed operation of WTs with DFIG has been achieved by using different control strategies. These include fuzzy PI [58], backstepping [59], SMC [7], MPC [60], robust [61], and so on, and the simulation results demonstrate the operation of these controllers for a broad range of wind speeds. Due to their wide-operating slip range, such generators are helpful in many ways. These include higher efficiency, reduced compressive stresses, and more stable voltage control. In addition, DFIG's fractional-rated converter resulted in lower converter prices, less power consumption, enhanced performance, and lower noise output [55]. Despite these advantages, magnetic circuits rely on a constant supply of reactive power from the system or local passive components, which makes them vulnerable to voltage fluctuations. Furthermore, there is no effective control over operating voltage or prolonged fault current, and the damping effect may cause rotor power loss.

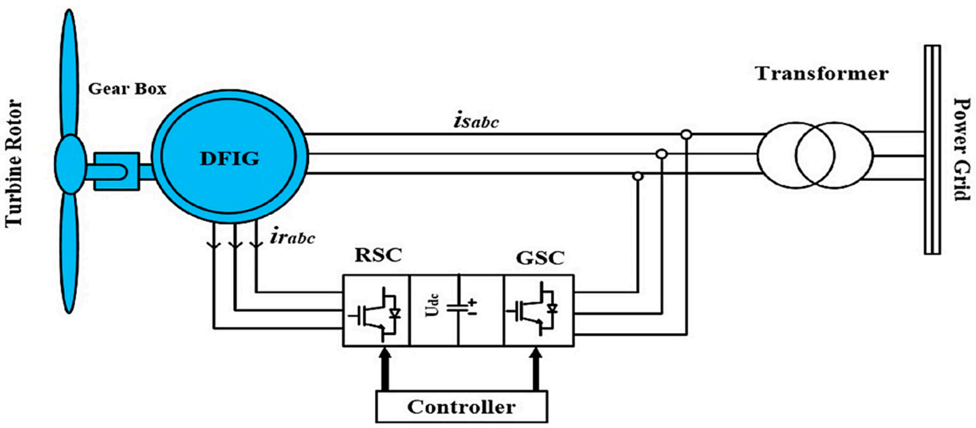

Figure 4. DFIGs-based wind turbine.

3. Geographical Features and Generation Capacity of Pakistan

The Islamic Republic of Pakistan is situated between (24.50, 36.75) latitudes north and (61, 75.5) longitudes east. The country is separated from Central Asia and the Middle East by hilly terrain. Pakistan is a semi-industrialized market with a Gross Domestic Product (GDP) per capita of USD1562, supported by the prominent textile, food processing, and agricultural sectors [62]. The World Bank ranks Pakistan's economy as the 67th best in the world in terms of exports and its labor market as the 10th biggest in the world [63]. Moreover, Pakistan is the world's 36th biggest country, with 881,913 square kilometers, and is home to five provinces: Sindh, Baluchistan, Punjab, Khyber Pakhtunkhawa (KPK), and Gilgit-Baltistan. There are four seasons in Pakistan: (1) a chilly, dry winter from November to February; (2) a hot, dry spring from March to May; (3) the late spring stormy season, or southwest rainfall period, from June to August; (4) the monsoon season's retreat in September and October [64]. Rainfall can fluctuate dramatically yearly, and flood and drought cycles are not unusual. Pakistan is home to the biggest mountain ranges in the world, including the Karakorum, Himalaya, and Hindukush, as well as the northern uplands of KPK and the northern tribal territories [65]. The Punjab province is almost plain, and five of the country's primary and important rivers run through it. The Thar Desert, also known as the Lower Indus Valley, is a large desert area in the southern part of Pakistan's Sindh province that extends into neighboring India. Baluchistan, along with the mountainous regions, is the most barren part of the country.

Energy is the backbone of all economies and is often described as the driving force behind national progress and prosperity [66]. Economic progress, human well-being, and a higher living level depend on an adequate and affordable electricity supply. The state's socioeconomic growth and international viability depend on supplying reliable, adequate electricity at reasonable prices to all consumers. In a developing country such as Pakistan, energy consumption is quite high and has been steadily rising since independence. Pakistan's total power generation was about 60 MW in 1947, when the country gained independence, for its 31.5 million people [67]. By the end of the 1970s, it had risen to 1.3 GW, thanks to the building of various power plants. After the 1980s, electricity output grew to about 3 GW; ten years later, it reached around 7 GW. Pakistan's installed power-generating capacity rose 65 percent in six years, from 23,337 MW in 2014 to 38,719 MW in June 2020 [68]. Figures 5 and 6 depict Pakistan's total installed generating capacity and the proportion of all generating sources during the last six years. The results show that the energy generated by thermal resources is quite significant, but wind and solar energy have the least value. During this time, 14.3 GW of power was added to the total generating capacity, with over 77% coming from conventional energy sources and just 6.7% from wind and solar. In addition, the capacity of public thermal power plants has remained almost unchanged, although the thermal power output of independent power producers has increased by 9.2 GW. As a result of these power increases from independent power producers, the present circular debt issue in the electrical sector has expanded to over Rs2.5 trillion. It is expected to reach Rs4.0 trillion by 2025 if it continues to expand at the same pace [69,70]. Hence, there is an urgent need for power sector reform and an increase in the use of renewable energy sources such as wind and solar. The Government of Pakistan (GOP) has recently promoted the use of indigenous, eco-friendly renewable energy sources. Numerous attempts have been made to stimulate the long-term growth of the renewable energy sector and capitalize on these resources' potential while determining the optimal strategy for profiting from lowering alternative energy prices. The Ministry of Energy, in consultation with other relevant parties, developed the renewable energy policy ARE-2019, which the government then approved in August 2020 [71]. This policy aims to provide a stable environment in which the proportion of renewable energy in Pakistan may steadily rise. In addition, this policy is intended to promote energy security, financial benefits, the protection of natural resources, long-term growth, and economic equality by using locally available resources. The GOP has initiated ten large hydropower projects, which will be completed by 2028, to enhance the renewable energy share [72]. Aside from major renewable energy projects, small-scale micro and mini projects for lighting, pumping systems, and power production are promoted in northern regions and the Chitral district [73]. These small-scale initiatives will produce power ranging from 30 kW to 800 kW and reduce 80 kilotons of CO_2e. Although these efforts will be favorable in the long run, in the short and medium term, wind energy is a more practical choice than hydro projects owing to the shorter time between pre-construction and commissioning [74]. Wind and solar energy also have lower per-kilowatt installation costs than hydro and other renewable energy sources, as shown in Figure 7 [75]. Wind and solar energy installation costs have decreased dramatically since 2016, and this trend is expected to continue in subsequent years as cumulative deployment increases. Private enterprises in Pakistan have initiated some wind energy projects. However, this would not fulfil the country's current energy demand of 41.5 GW [76,77]. Due to low public engagement and a reluctance to issue Power Purchase Agreements (PPAs) for new solar and wind projects, the country's huge potential remains unexplored. This potential can be exploited through close collaboration between public and private sector organizations. In the present scenario, large-scale capacity projects such as Muppandal and Jaisalmer wind farms [78,79] in a neighboring country would swiftly alleviate the country's energy crisis. Such large-scale projects are now integral to our medium- to long-term energy pricing schemes. This would not only alleviate the burden of oil expenses, which has resulted in the closure of 14 power plants with a combined capacity of 7 GW [77], but would also provide electricity to 70% of the remote population. These large-scale projects can be implemented through effective regulatory frameworks that are more competitive than those of neighboring nations and beneficial to both public and private firms. Since without offering benefits such as incentives and streamlining the financing plan, it would be difficult to attract private enterprises for participating in large-scale projects.

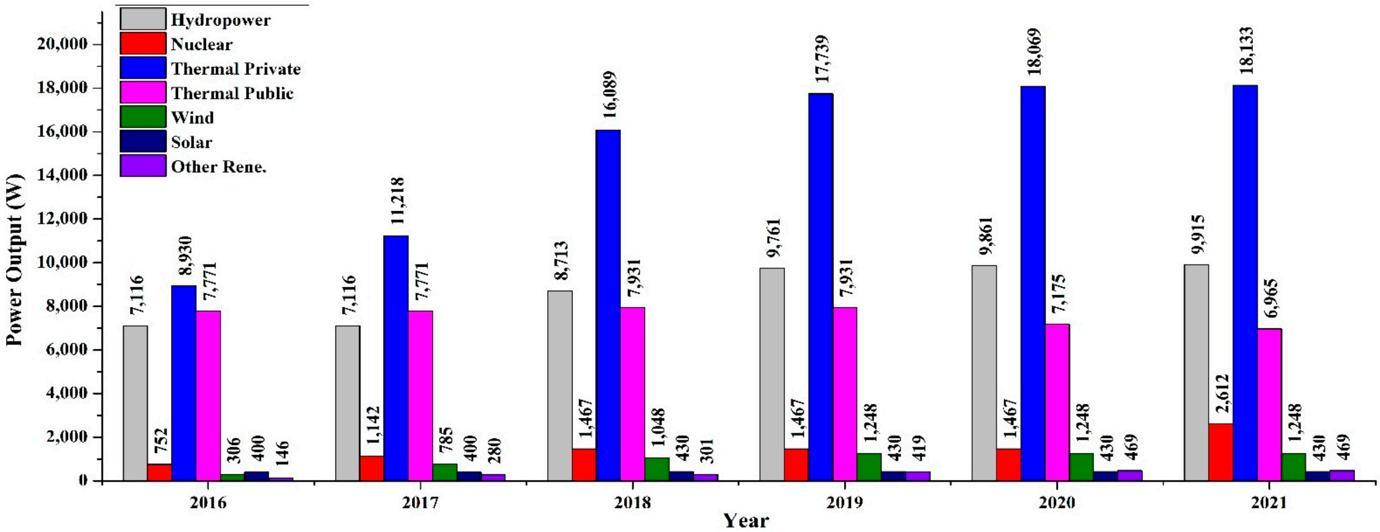

Figure 5. Installed Generation Capacity of Pakistan.

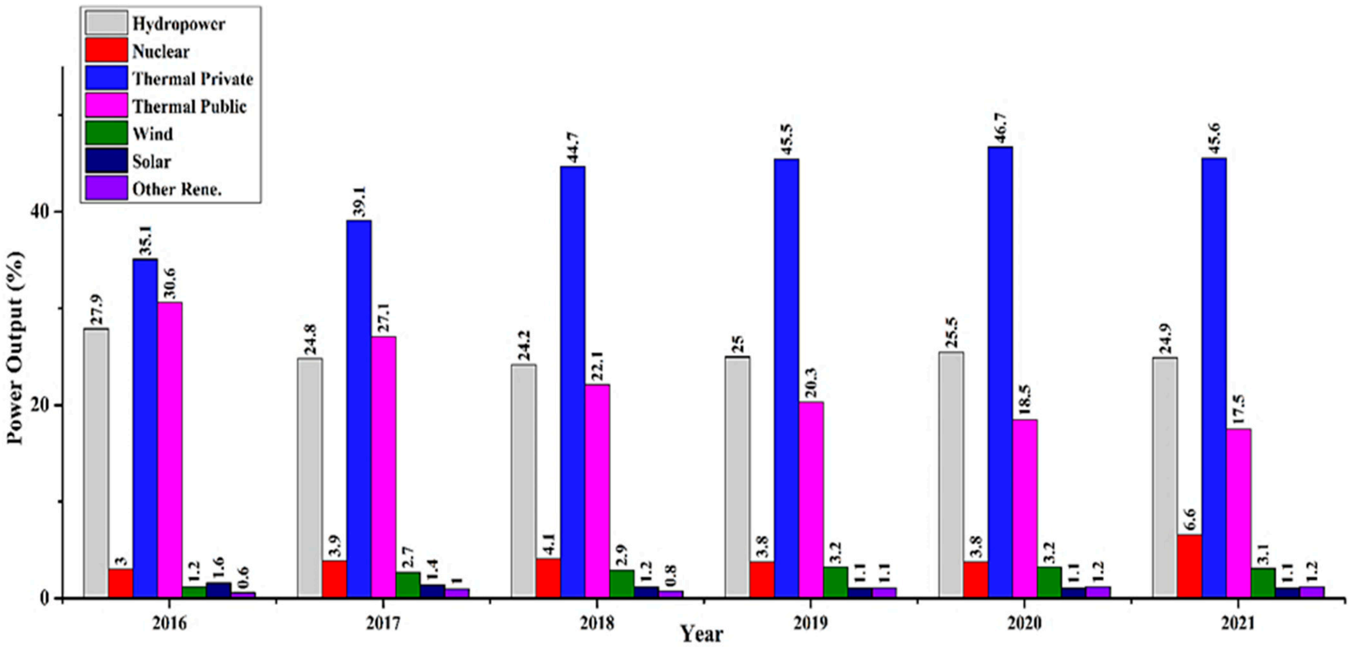

Figure 6. Percentage Installed Capacity of Pakistan.

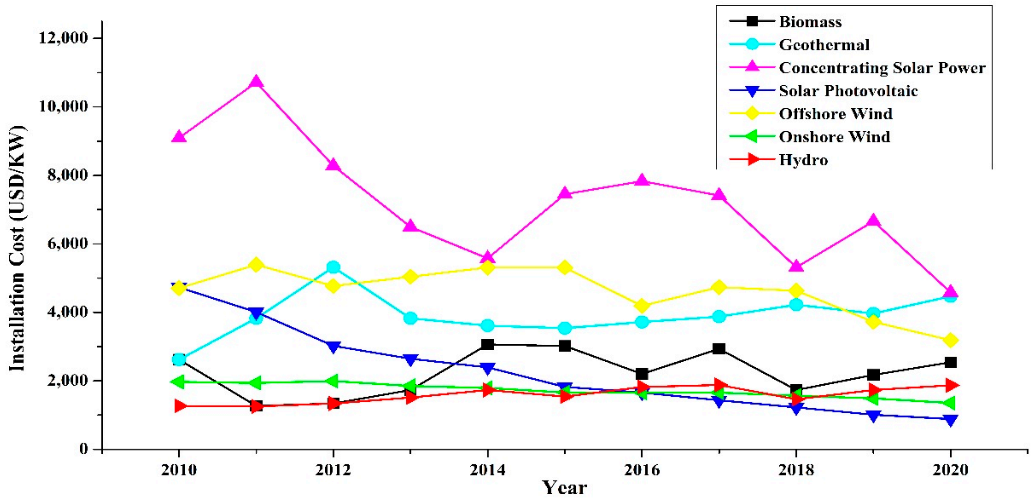

Figure 7. Installation Cost of various renewable energy [75].

Wind Mapping of Pakistan

The GOP is determined to construct wind energy projects across the country to meet a substantial portion of the nation's electrical demands using environmentally friendly technologies. According to the Alternative Energy Development Board (AEDB) and PMD assessments, coastal Sindh and Baluchistan, as well as some northern regions, had significant wind energy potential [80]. According to these estimations, the districts of Thatta, Karachi, Jamshoro, and Badin in Sindh province, as well as the districts of Gwadar and Makran Coastlines in Balochistan province, have suitable locations for wind energy construction, deployment, and operation. Another study discovered that Pakistan could produce 3200 GW from clean energy sources, including 340 GW from wind, 2900 GW from solar, 50 GW from hydropower, 3.1 GW from micro hydro, 1.8 GW from bagasse energy conversion, and 0.5 GW from wastes [81,82]. NREL has As per research reported by National Renewable Energy Laboratory (NREL), Pakistan has a total wind energy potential of approximately 132 GW [83]. Table 3 summarizes NERL's analysis of Pakistan's wind energy potential at 50 m altitude for classes 4 to 7. According to the Table, around 3% of the land can produce nearly 132 GW of power with an installed capacity of 5 MW per km^2. In these estimates, more than 6 percent of Pakistan's land, classified as Class 3, or moderate, and suitable for wind energy generation, is omitted. As a result, these estimates may be refined further using advanced modelling and analytic techniques to generate complete wind resource maps for Pakistan. Apart from low-wind and metropolitan regions, 40 to 35 per cent of Sindh and Baluchistan's coastlines could be assessed for wind energy production [81]. The theoretical production capacity of wind energy has been estimated to reach 123 GW, assuming a density factor of 5.40 MW/km^2. The annual wind power generation along Pakistan's coastlines is expected to be 212 TWh or 2.15 times the nation's combined conventional power output. NREL has further evaluated the coastlines of Sindh and Balochistan, and various viable sites for wind energy have been identified, as seen in Table 4 [84]. Data from 47 wind observation sites were gathered and analyzed for the coastlines of Sindh and Balochistan [83]. The analyses indicate that a wind corridor extending from Hyderabad to Keti Bandar and Quetta to Gwadar has considerable potential for power production. In addition to reducing energy shortages, constructing wind energy projects in the Jhimpir, Gharo, and Keti Bandar corridors would alleviate the burden of $12 billion in annual oil imports. According to Table 5, the GOP has currently captured 1235 MW of wind power from this corridor. This corridor may produce consistent power from June to September when the southwest monsoon passes through Pakistan. The Indian government has built multiple wind farms along this wind corridor, extending into Rajasthan state. Rajasthan is one of India's leading states for harnessing wind energy to generate power, with a capacity of 18.7 GW [85,86]. 4.3 GW of wind power capacity has been commissioned from 15 separate projects in Rajasthan, with Suzlon and Enercon accounting for around 68 percent of the total capacity.

Table 3. Analysis of Pakistan's wind power capacity at 50 m [83].

Resource Potential	Wind Speed at 50 m (m/s)	Wind Power Class	Covered Area (km/s)	Output Power (W/m^2)	Area Percentage	Total Output Power (GW)
Good	6.9–7.4	4	18,106	400–500	2.05	90.53
Excellent	7.4–7.8	5	5218	500–600	0.59	26.09
Outstanding	7.8–8.6	6	2495	600–800	0.28	12.48
Superb	>8.6	7	543	>800	0.06	2.72
Total			26,362		2.98	131.82

Table 4. Wind Potential of Pakistan [84].

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

Table 5. Wind Power facilities in Pakistan.

Project	Company	Location	District	(MW)	Status	Cost ($)	Completed
Jhimpir Wind Energy Project	Burj Capital	Jhimpir	Thatta	49.7	Active	134 million	2013
Jhimpir Wind Power Plant	Morlu Enerji	Jhimpir	Thatta	56.4	Active	143 million	2013
FFC Energy Ltd.	Fauji Fertilizer Company	Jhimpir	Thatta	49.5	Active	134 million	2013
Three Gorges First Wind Farm	China Three Gorges Corporation	Jhimpir	Thatta	49.5	Active	125 million	2014
Foundation Wind Energy–II	Fauji Foundation	Gharo	Thatta	50	Active	127 million	2014
Foundation Wind Energy–I	Fauji Foundation	Gharo	Thatta	50	Active	128 million	2015
Sapphire Wind Power	Sapphire Group	Gharo	Thatta	52.8	Active	127.7 million	2015
Yunus Energy	Lucky Cement Limited	Jhimpir	Thatta	50	Active	110.2 million	2016
Metro Wind Power	Infraco Asia Development Pvt Ltd.	Jhimpir	Thatta	50	Active	136 million	2016
Tenaga Generai Ltd.	Tenaga Generasi Limited	Gharo	Thatta	49.5	Active	117 million	2016
Gul Ahmed Wind Power	Gul Ahmed Energy Limited	Jhimpir	Thatta	50	Active	131 million	2016
Master Wind Energy	Master Group of Industries	Jhimpir	Thatta	52.8	Active	125 million	2016
Tapal Wind Energy	Tapal Group and Akhtar Group	Jhimpir	Thatta	30	Active	-	2016
Hydro-China Dawood Power	Hydrochina Corporation	Gharo	Thatta	49.5	Active	115 million	2017
Sachal Energy Wind Farm	Arif Habib Group	Jhimpir	Thatta	49.5	Active	134 million	2017
United Energy Pakistan	United Energy Group	Jhimpir	Thatta	99	Active	250 million	2017
Hawa Energy Ltd.	Hawa Energy and JS Group	Jhimpir	Thatta	49.6	Active	130.2 million	2018
Artistic Energy Pvt Ltd.	General Electric and Artistic Milliners	Jhimpir	Thatta	49.5	Active	120 million	2018
Three Gorges Second Wind Farm	China Three Gorges Corporation	Jhimpir	Thatta	49.6	Active	113.1 million	2018
Three Gorges Third Wind Farm	China Three Gorges Corporation	Jhimpir	Thatta	49.6	Active	113 million	2018
Tricon Boston Corporation	General Electric and Tricon Boston	Jhimpir	Thatta	148.8	Active	342 million	2018
Zephyr Power Ltd.	CDC Group PLC	Gharo	Thatta	50	Active	103.3 million	2019

4. Results and Discussion

In this paper, we examine and assess the wind patterns and potential of Karachi, Thatta, Badin, and Jamshoro, all located in Sindh's southern region, as shown in Figure 8. A seasonal and monthly wind speed trend analysis is performed for each zone. One-year wind speed data were collected for 30 m and 50 m heights. Accordingly, these sites were divided into different classes, as shown in Table 6, specified by NREL for heights of 30 m and 50 m. Data collected from all zones were analyzed to determine the amount of electricity generated by GW 140/3 MW and GW 136/4.2 MW. We use these generators because they are a low cut-in and rated speed, which makes them ideal for use at the proposed sites.

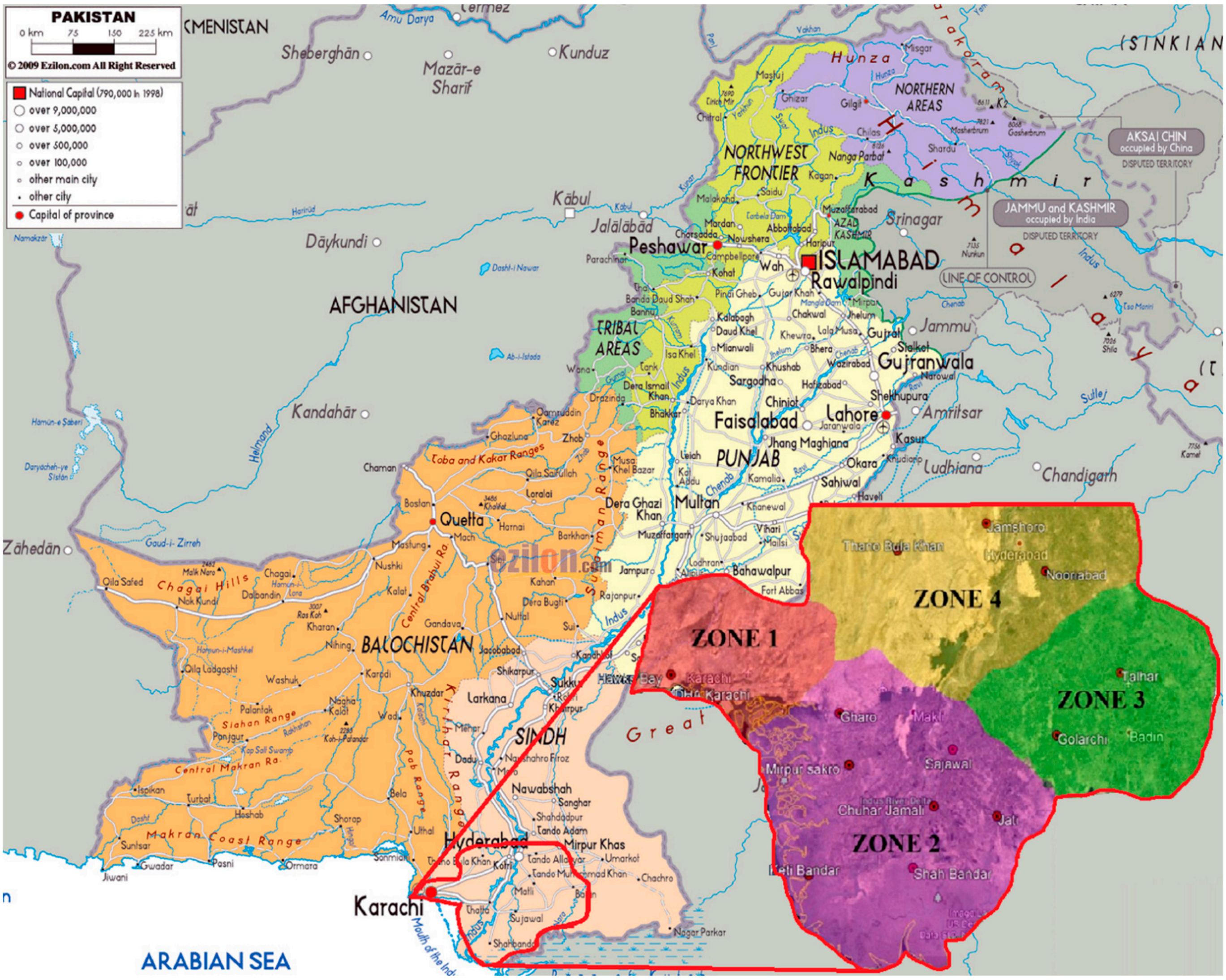

Figure 8. Analysis of four different zones in Pakistan.

Table 6. Classification of four zones based on wind speed.

Zone	District	Region	30 m			50 m			Class (30 m)	Class (50 m)
			Low	Average	High	Low	Average	High		
1	Karachi	DHA Karachi	2.9	5.0	7.4	3.6	5.9	9.0	1	2
		Hawks Bay	2.8	5.1	6.8	3.2	5.4	7.1	1	2
2	Thatta	Chuhar Jamali	2.9	4.6	7.4	3.9	5.8	8.0	1	2
		Gharo	3.0	5.9	9.1	3.8	6.6	9.4	2	3
		Jati	3.5	5.4	8.5	4.4	6.4	9.1	2	3
		Keti Bandar	4.1	6.1	9.1	4.4	7.0	10.2	2	4
		Mirpur sakro	2.8	5.2	9.2	3.6	6.4	10.7	1	3
		Sajawal	3.0	5.0	7.7	4.2	6.6	9.7	1	3
		Shah Bandar	3.8	5.8	8.9	4.5	6.5	9.6	2	3
3	Badin	Golarchi	3.2	5.1	7.5	4.3	6.7	9.4	1	3
		Talhar	2.0	4.6	7.3	2.7	6.3	10.3	1	3
4	Jamshoro	Jamshoro	3.7	6.9	11.6	5.0	8.5	13.9	4	6
		Nooriabad	3.5	6.4	9.7	4.2	7.0	10.6	3	4
		Thano Bula Khan	2.1	4.7	8.7	2.7	5.5	9.8	1	2

(1) Zone 1—Karachi

At the height of 50 m, the average wind speed at the Defense Housing Authority (DHA) Karachi and Hawke's Bay was 5.9 and 5.4 m/s, respectively. During the monsoon season, the highest average wind speed for DHA Karachi and Hawke's Bay occurred in July. The maximum speed recorded for DHA Karachi is 9.0 m/s, while the maximum speed recorded for Hawke's Bay was 7.1 m/s, as shown in Figure 9. In November, DHA Karachi and Hawke's Bay experienced minimal wind speeds of 3.6 and 3.2 m/s, respectively. Therefore, the Goldwind GW 140/3 MW, rated at 3.0 MW MW at a wind speed of 10.5 m/s, is the most suitable WTG for these conditions. It has a low cut-in speed of 2.5 m/s and can operate in harsh climatic conditions with a cut-out speed of 20 m/s. This turbine uses a PMSG with a rotor diameter of 140 m. At a height of 50 m, the average wind speed from January to October is above 5.7–6.3 m/s, which is ideal for these types of turbines. Figure 10 depicts the monthly wind-generated power outputs at DHA Karachi and Hawke's Bay. In Zone 1, a single GW 140/3 MW generator is expected to produce 3.2 GWh in July, with the lowest output of 0.45 GWh in November. Zone 1 winds have a higher potential in the summer (May to August) than in the winter (November to January). A single 3 MW wind turbine in Zone 1 produces 18.1 GWh of electricity per year, which may significantly contribute to narrowing the supply–demand imbalance in Karachi.

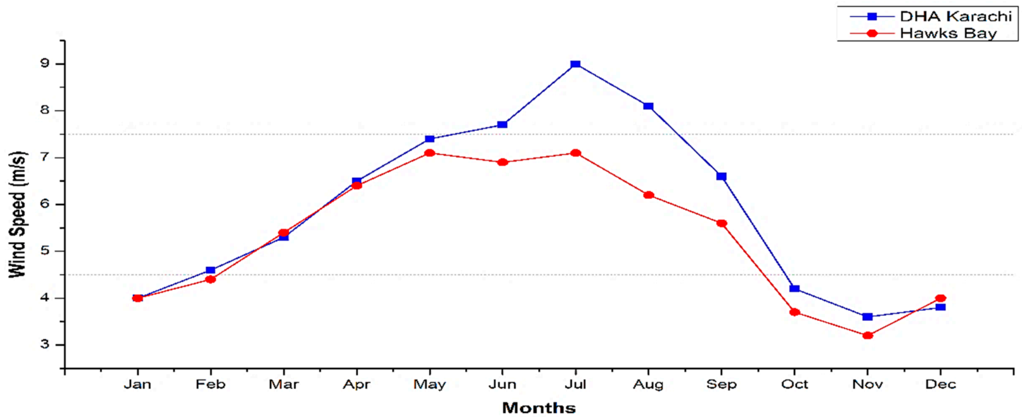

Figure 9. Annual Wind Speed for Zone 1 (Karachi).

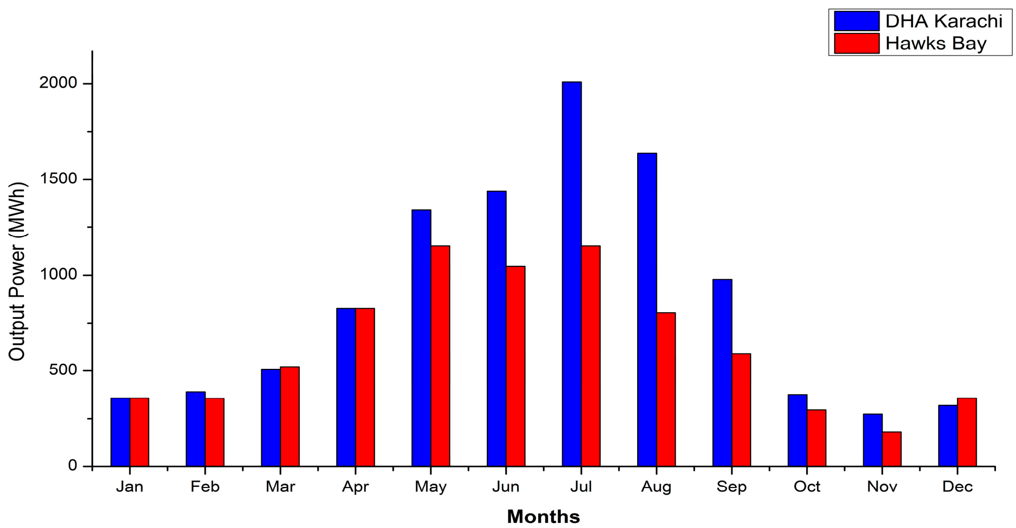

Figure 10. Power output in MWh for Zone 1 (Karachi).

(2) Zone 2—Thatta

There are six regions in Zone 2: Chuhar Jamali; Gharo; Jati; Keti Bandar; Mirpur Sakro; Sajawal; and Shah Bandar. Chuhar Jamali is classified as class 2, while the other six are all classified as class 3. Figure 11 shows that Chuhar Jamali has the lowest average wind speed of 5.8 m/s in Zone 2, while Keti Bandar has the highest average of 7.1 m/s. Similarly, Gharo and Mirpur Sakro have the lowest and highest monthly wind speeds, with 3.8 m/s and 10.7 m/s, respectively. Goldwind GW 140/3 MW was also selected for Zone 2 due to its low cut-in and rated speed. At a hub height of 50 m, Figure 12 shows monthly MWh production estimates for Zone 2 of the specified wind turbine. It is estimated that Chuhar Jamali, Gharo, Jati, Keti Bandar, Mirpur Sakro, Sajawal, and Shah Bandar produce 9.8 GWh, 13.3 GWh, 11.2 GWh, 14.3 GWh, 11.5 GWh, 13.1 GWh, and 12.0 GWh, respectively. Most of the power is generated during the summer, between April and September, with the highest output in July. In this way, Zone 2 can meet the peak power demand in Sindh province, which occurs between April and September. Consequently, anticipated power may resolve the energy shortage concerns in these regions that negatively impact human living conditions.

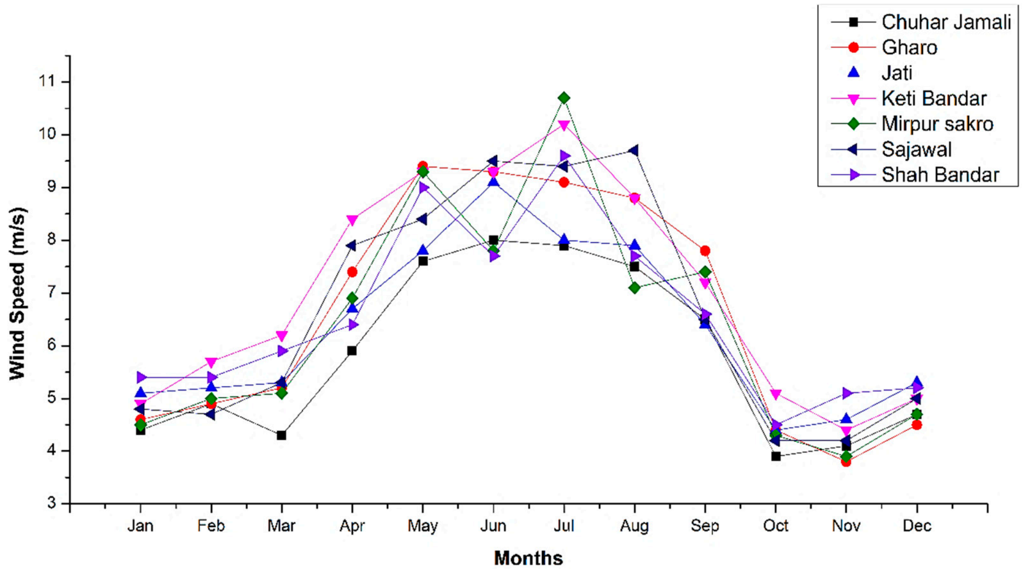

Figure 11. Annual Wind Speed for Zone 2 (Thatta).

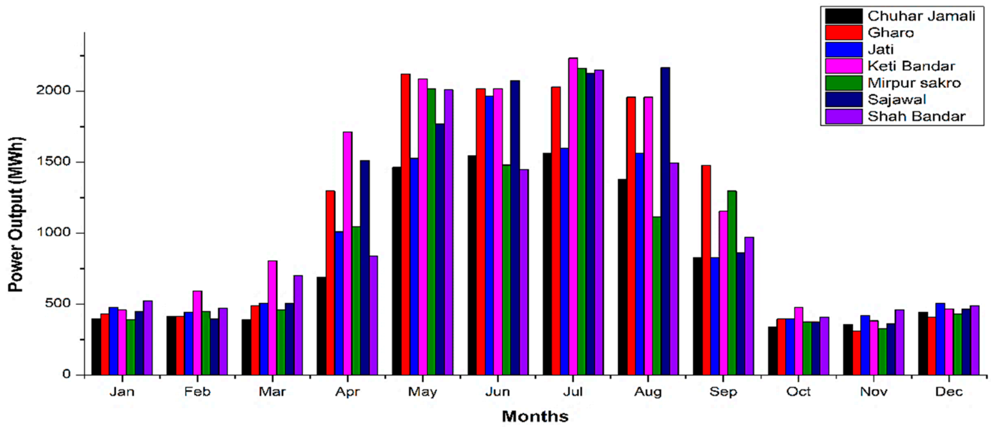

Figure 12. Power output in MWh for Zone 2 (Thatta).

(3) Zone 3—Badin

Zone 3 consists of two regions, Golarchi and Talhar, which are classified as class 3 according to their average wind speed. At 50 m in altitude, the average wind speed was 6.7 m/s in Golarchi and 6.3 m/s in Talhar. The maximum speed in Talhar in June reached 10.3 m/s, but in Golarchi in June and July, the maximum speed remained at 9.4 m/s. A comparison of the wind speeds in the two regions is shown in Figure 13. GW 140/3 MW is the most practical wind turbine at these wind speeds, generating 3 MW of rated electricity when the wind speed is between 10.5 and 11.0 m/s. The monthly electric power generated at Zone 3 is shown in Figure 14. The peak production of 2.2 GWh is estimated at Talhar in May with a single 140/3 MW wind generator, and the lowest output of 57.6 MWh is estimated in November. The peak production of 2.16 GWh is estimated in Talhar in June with a single GW 140/3 MW wind generator, and the lowest output of 36 MWh is estimated in November at Talhar.

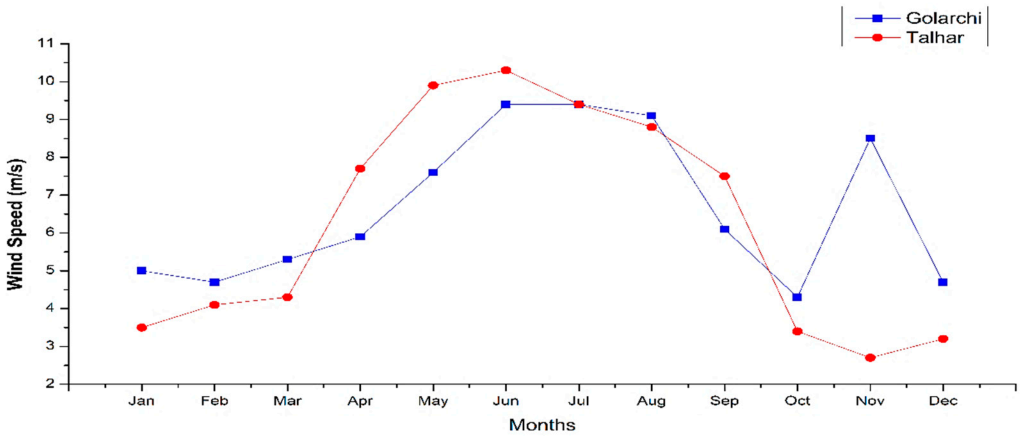

Figure 13. Annual Wind Speed for Zone 3 (Badin).

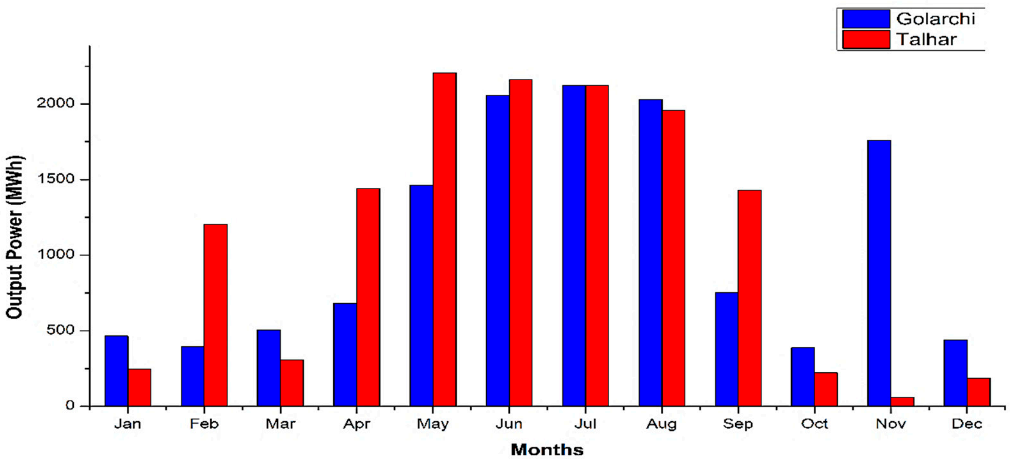

Figure 14. Power output in MWh for Zone 3 (Badin).

Similarly, Golarchi's peak production was estimated to be 2.12 GWh in July, and its lowest production was 386 MWh in October. Zone 3 is estimated to produce 26.6 GWh annually from a single GW 140/3 MW WTG. Even while monthly power density estimates imply that the power density is below the marginal threshold during the winter, this is countered by high numbers throughout the summer, notably in May and September.

(4) Zone 4—Jamshoro

This zone consists of three regions: Jamshoro; Nooriabad; and Thano Bula Khan. As a result of their wind speed, Jamshoro has been classified as a class 6 wind area, Nooriabad as a class 4, and Thano Bula Khan as a class 2. As shown in Figure 15, Jamshoro, Nooriabad, and Thano Bula Khan recorded the highest wind speeds at 13.9, 10.6, and 9.8 m/s, respectively, while the lowest winds were observed at 5, 4.2, and 2.7 m/s. In this zone, we chose the GW 136/4.2 MW wind turbine because its lower cut-in speed makes it a viable option for Thano Bula Khan due to its higher yield. This turbine has a cut-in speed of 2.5 m/s and can produce 4.2 MW at a rated speed of 11.5 m/s, which is a good option for Jamshoro. It has a rotor diameter of 136 m and employs PMSG technology. The output power from this zone using a single GW 136/4.2 MW is shown in Figure 16. It is estimated that Jamshoro, Nooriabad, and Thano Bula Khan can produce 19.7 GWh, 14.9 GWh, and 8.9 GWh, respectively, with a GW136/4.2 MW WTG. The highest power production is estimated at 3.04 GWh for Jamshoro between June and August, while Nooriabad and Thano Bula Khan can produce 2.9 and 2.5 GWh, respectively, during June and July. According to this pattern, Zone 4 and the surrounding region are potential sites for constructing large, economically feasible wind farms.

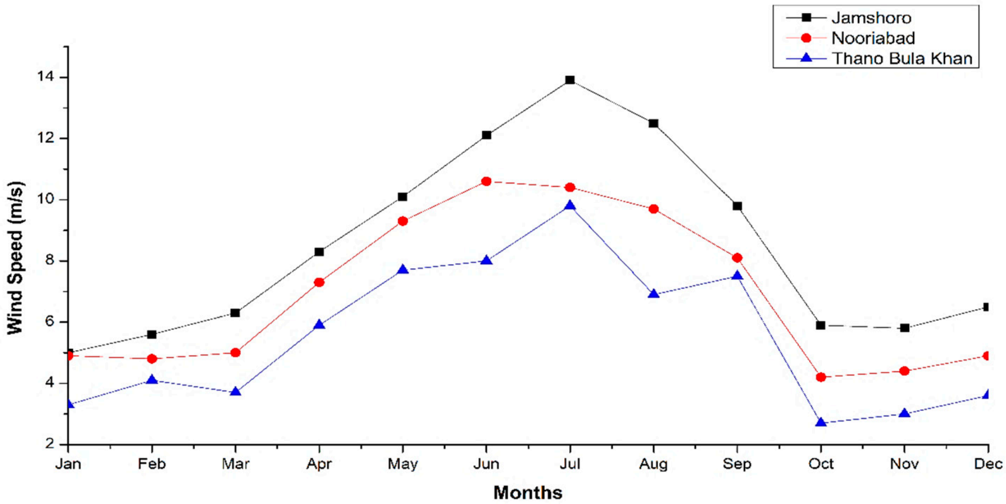

Figure 15. Annual Wind Speed for Zone 4 (Jamshoro).

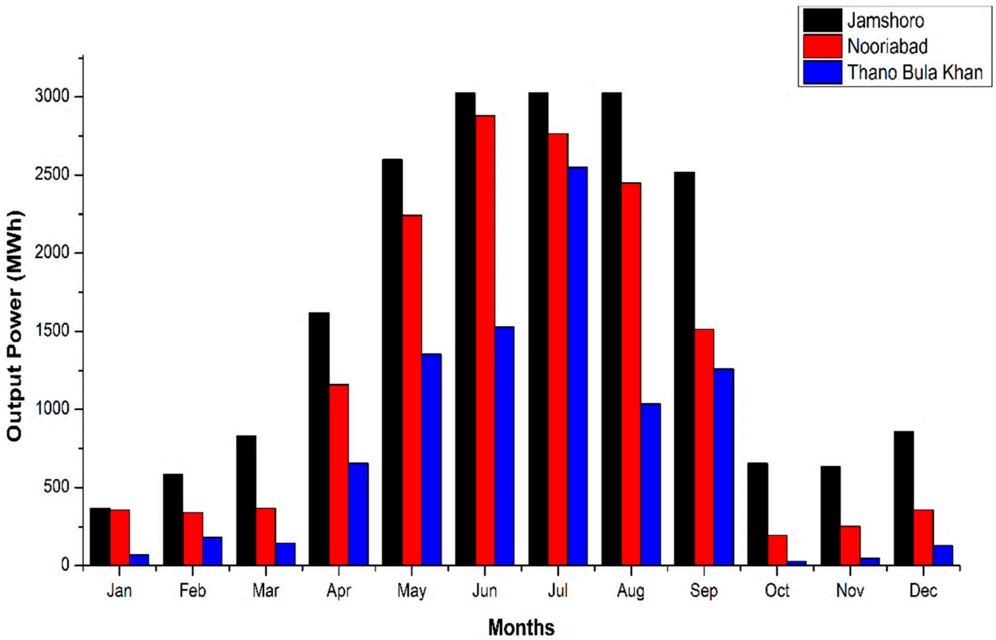

Figure 16. Power output in MWh for Zone 4 (Jamshoro).

Figure 17 displays a proposed wind turbine's yearly power production capacity for all four zones. The annual production of all four zones from a single wind turbine generator is estimated to be 173.5 GWh. Zone 2 Thatta is predicted to have a peak output of 85.26 GWh, while Zone 1 Karachi is expected to have the lowest generation of 18.09 GWh. Similarly, a single wind turbine at Jamshoro and Badin can generate 43.58 GWh and 26.59 GWh yearly.

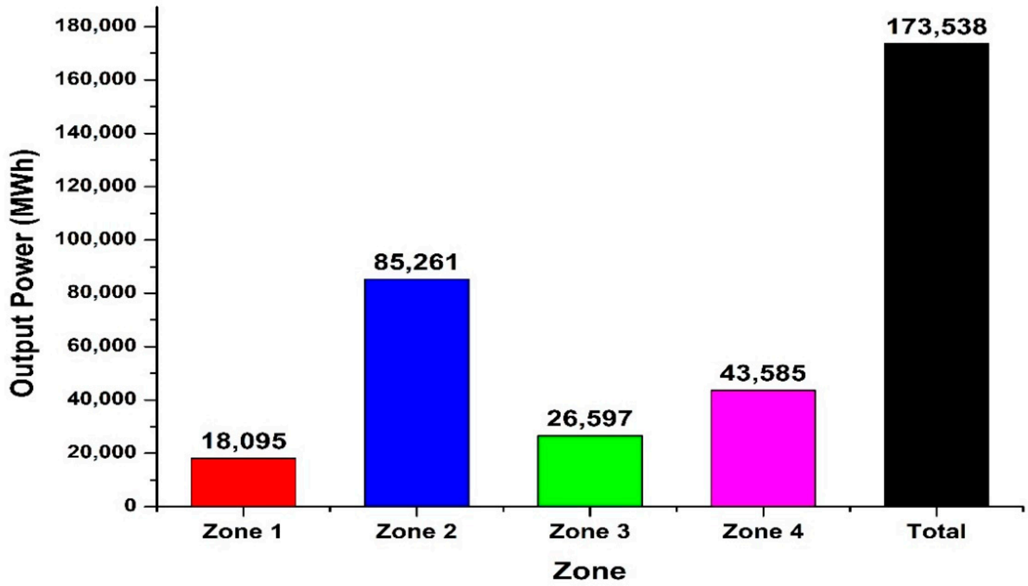

Figure 17. Power output in MWh for all zones.

5. Wind Energy Integration into the Power System

Environmental preservation is critical in saving the globe from environmental calamities by achieving the goal of a low-carbon society. The solution is optimizing the energy mix by integrating wind energy into the power grid and reducing reliance on traditional energy sources. Significant adjustments must be made to adapt wind energy power into the current grid system, primarily designed for conventional energy sources. Since wind energy fluctuates and is unpredictable, grid stations must contend with the challenges of high transmission and battery storage systems. Figure 18 displays a detailed power system layout for incorporating wind energy. The WTs employ the various generators outlined in Section 2 to transform the wind's kinetic energy into electrical energy. The AC power is then converted to DC, allowing the battery to store power that may be utilized during peak hours, mitigating the intermittent nature of wind energy. Dc supply may also power High Voltage DC (HVDC) transmission systems. Next, a DC-to-AC converter is installed at the utility grid facility to convert HVDC to AC voltage at a steady frequency. Filters may reduce the harmonic distortion in the voltage waveform during the power conversion, and Voltage Source Converters (VSC) are installed at the grid station.

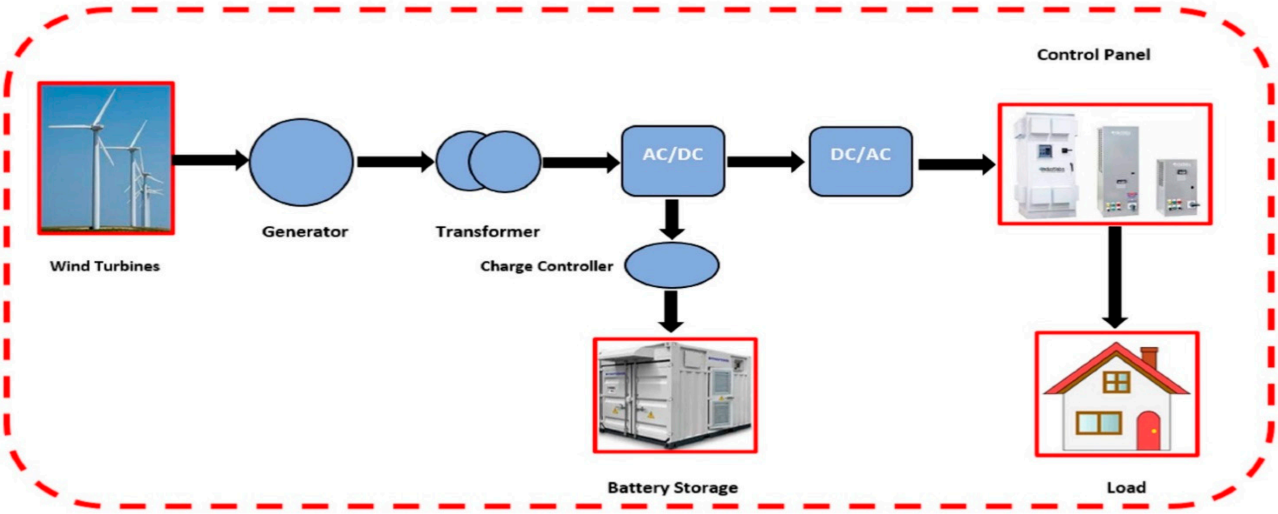

Figure 18. Wind energy integration into the power system.

Pakistan's electricity grid is relatively outdated and has not been appropriately modified to use wind energy efficiently. Due to poor conductive materials and ineffective distribution and transmission systems, up to 25–30% of the total power is lost. Furthermore, the country's inadequate power infrastructure has resulted in significant energy losses due to harmonics generated by grid station switchgear, as well as voltage and frequency fluctuations. Putting significant volumes of wind power into the electrical grid would disrupt the whole system. Since wind energy is intermittent, a method for storing excess energy that may be released when there is a high electricity demand must be devised. Such battery storage systems will put an additional burden on the already fragile electricity grid and grid station switchgear. Consequently, the GOP must renovate or develop new transmission facilities to connect areas with significant wind energy to those with high power demand to efficiently capture wind energy.

6. Conclusions

Pakistan's energy supply relies heavily on thermal power production, which accounts for 60% of total energy. Any increase in the price of imported oil and natural gas significantly impacts power production in Pakistan, potentially making circular debt concerns even more critical. The country has experienced a severe energy crisis over the past decade, resulting in widespread load shedding and the near suspension of daily activities. Wind energy is an alternative option that could meet future energy needs while addressing the country's energy imbalance. Consequently, this paper presents the assessment of wind energy potential along the coastlines of Sindh province. Four zones were selected for the case study: Karachi, Thatta, Badin, and Jamshoro, and the specifications and required energy forecast for each zone were reviewed. The results were analyzed for one-year wind speed data for 30 m and 50 m heights. The findings demonstrate that average wind speeds exceed 5.6 m/s in all zones, with Zone 4 having the most practicable locations with average wind speeds reaching 7 m/s. Furthermore, with an average wind speed of 5.6 m/s, Zone 1 is considered the least feasible region for wind farms. To produce power, Zones 1, 2, and 3 each utilize a Goldwind wind turbine (GW140/3 MW), whereas Zone 4 uses a GW136/4.2 MW. Using a single GW140/3 MW WTG, Zone 1, 2, and 3 may generate 18.09 GWh, 85.26 GWh, and 26.59 GWh, respectively. Similarly, employing a single GW136/4.2 MW WTG, Zone 4 may generate 43.58 GWh. Hence, the analysis indicates that all four sites are suitable for large-scale wind power generation due to their energy potential. Such development is expected to reduce GHG emissions while significantly improving Pakistan's economic prospects by reducing dependency on fossil fuels and creating employment opportunities. Achieving these goals requires effective measures, subsidies, technical skills, and significant political and financial commitments.

Future research might investigate the power capture from wind energy at 90 m height over one year. Furthermore, Pakistan may be compared to the European Union, which has significantly more modern wind-energy infrastructure. Different generators will be employed in these zones to study wind energy output compared to Goldwind generators.

Author Contributions: Conceptualization, R.A., Z.U. and B.A.; Data curation, B.A., M.H.H., E.R. and B.S.; Formal analysis, E.R., M.J.A. and S.A.; Investigation, R.A., Z.U. and M.H.H.; Methodology, R.A. and B.A.; Project administration, S.A., K.M. and Z.U.; Resources, S.A. and K.M.; Software, R.A., E.R. and B.S.; Supervision, Z.U.; Validation, R.A., Z.U., M.H.H. and M.J.A.; Visualization, B.A. and E.R.; Writing—original draft, R.A., Z.U., B.A., M.H.H. and M.J.A.; Writing—review and editing, E.R., B.S. and S.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Da Silveira Bezerra, P.B.; Callegari, C.L.; Ribas, A.; Lucena, A.F.P.; Portugal-Pereira, J.; Koberle, A.; Szklo, A.; Schaeffer, R. The Power of Light: Socio-Economic and Environmental Implications of a Rural Electrification Program in Brazil. *Environ. Res. Lett.* **2017**, *12*, 095004. [CrossRef]
2. Martins, F.; Felgueiras, C.; Smitkova, M.; Caetano, N. Analysis of Fossil Fuel Energy Consumption and Environmental Impacts in European Countries. *Energies* **2019**, *12*, 964. [CrossRef]
3. Asghar, R.; Rehman, F.; Ullah, Z.; Qamar, A.; Ullah, K.; Iqbal, K.; Aman, A.; Nawaz, A.A. Electric Vehicles and Key Adaptation Challenges and Prospects in Pakistan: A Comprehensive Review. *J. Clean. Prod.* **2021**, *278*, 123375. [CrossRef]
4. Ullah, Z.; Asghar, R.; Khan, I.; Ullah, K.; Waseem, A.; Wahab, F.; Haider, A.; Ali, S.M.; Jan, K.U. Renewable Energy Resources Penetration within Smart Grid: An Overview. In Proceedings of the 2020 International Conference on Electrical, Communication, and Computer Engineering (ICECCE), Istanbul, Turkey, 12–13 June 2020. [CrossRef]
5. Dinç, D.T.; Akdoğan, E.C. Renewable Energy Production, Energy Consumption and Sustainable Economic Growth in Turkey: A VECM Approach. *Sustainability* **2019**, *11*, 1273. [CrossRef]
6. Ahmadi, A.; Tiruta-Barna, L.; Benetto, E.; Capitanescu, F.; Marvuglia, A. On the Importance of Integrating Alternative Renewable Energy Resources and Their Life Cycle Networks in the Eco-Design of Conventional Drinking Water Plants. *J. Clean. Prod.* **2016**, *135*, 872–883. [CrossRef]
7. Asghar, R.; Rehman, F.; Ullah, Z.; Aman, A.; Iqbal, K.; Nawaz, A.A. Modified Switch Type Fault Current Limiter for Low-Voltage Ride-through Enhancement and Reactive Power Support of DFIG-WT under Grid Faults. *IET Renew. Power Gener.* **2020**, *14*, 1481–1490. [CrossRef]
8. Mirza, I.A.; Khali, M.S. Renewable Energy in Pakistan: Opportunities and Challenges. *Sci. Vis.* **2011**, *16*, 13–20.
9. Hulio, Z.H.; Jiang, W.; Chandio, G.S. Power Policies, Challenges, and Recommendations of Renewable Resource Assessment in Pakistan. *Energy Explor. Exploit.* **2022**, *40*, 947–976. [CrossRef]
10. Ayaz Akhbar Energy Crisis: Markets, Shopping Malls to Close by 9pm in Islamabad. Available online: https://www.geo.tv/latest/423187-electricity-crisis-markets-shopping-malls-to-close-by-9pm-in-islamabad (accessed on 28 July 2022).
11. The Straits Times Facing "Severe" Energy Crisis, Pakistan Reverts to Five-Day Work Week. Available online: https://www.straitstimes.com/asia/south-asia/facing-severe-energy-crisis-pakistan-reverts-to-five-day-work-week (accessed on 28 July 2022).
12. Azeem, K.; Nadeem, W.; Zia, A.; Shehzad, S.; Anwar, Z. Impact of CNG Crisis on Student's Academic Life. *J. Educ. Pract.* **2017**, *8*, 81–90.
13. Hydrocarbon Development Institute of Pakistan Pakistan Energy Yearbook. 2020. Available online: https://www.hdip.com.pk/energy-yearbook.php (accessed on 28 July 2022).
14. Mir, K.A.; Purohit, P.; Mehmood, S. Sectoral Assessment of Greenhouse Gas Emissions in Pakistan. *Environ. Sci. Pollut. Res. Int.* **2017**, *24*, 27345–27355. [CrossRef]
15. IPCC. The IPCC's Fifth Assessment Report: What's in it for South Asia? *Intergov. Panel Clim. Chang.* **2014**, 70–79. Available online: http://cdkn.org/wp-content/uploads/2014/04/J1731_CDKN_FifthAssesmentReport_WEB.pdf. (accessed on 28 July 2022).
16. Mustafa, Z. Climate Change and Its Impact with Special Focus in Pakistan. *Pakistan Eng. Congr. Symp.* **2011**, *33*, 100–116.
17. Syed, A.; Raza, T.; Bhatti, T.T.; Eash, N.S. Climate Impacts on the Agricultural Sector of Pakistan: Risks and Solutions. *Environ. Chall.* **2022**, *6*, 100433. [CrossRef]
18. Shaheen, N.; Jahandad, A.; Goheer, M.A.; Ahmad, Q.A. Future Changes in Growing Degree Days of Wheat Crop in Pakistan as Simulated in CORDEX South Asia Experiments. *APN Sci. Bull.* **2020**, *10*, 82–89. [CrossRef]
19. Hannah Ritchie; Max Roser Pakistan: CO_2 Country Profile-Our World in Data. Available online: https://ourworldindata.org/co2/country/pakistan (accessed on 31 October 2022).
20. Chaudhry, Q.U.Z. Climate Change Profile of Pakistan Climate Change Profi Le of Pakistan. *Asian Dev. Bank* **2017**, 30–35. [CrossRef]
21. Mirza, I.A.; Khan, N.A.; Memon, N. Development of Benchmark Wind Speed for Gharo and Jhimpir, Pakistan. *Renew. Energy* **2010**, *35*, 576–582. [CrossRef]
22. Baloch, M.H.; Kaloi, G.S.; Memon, Z.A. Current Scenario of the Wind Energy in Pakistan Challenges and Future Perspectives: A Case Study. *Energy Rep.* **2016**, *2*, 201–210. [CrossRef]
23. Hulio, Z.H.; Jiang, W.; Rehman, S. Technical and Economic Assessment of Wind Power Potential of Nooriabad, Pakistan. *Energy Sustain. Soc.* **2017**, *7*, 35. [CrossRef]
24. Mushahid Hussain Pakistan's Battle Against Climate Change. Available online: https://www.ipsnews.net/2019/04/pakistans-battle-climate-change/ (accessed on 28 July 2022).
25. SAARC Energy Centre. *Deployment of Electric Road Mass Transportation in South Asia*; SAARC Energy Centre: Islamabad, Pakistan, 2017.
26. Shoaib, M.; Siddiqui, I.; Rehman, S.; Khan, S.; Alhems, L.M. Assessment of Wind Energy Potential Using Wind Energy Conversion System. *J. Clean. Prod.* **2019**, *216*, 346–360. [CrossRef]
27. Majout, B.; El Alami, H.; Salime, H.; Zine Laabidine, N.; El Mourabit, Y.; Motahhir, S.; Bouderbala, M.; Karim, M.; Bossoufi, B. A Review on Popular Control Applications in Wind Energy Conversion System Based on Permanent Magnet Generator PMSG. *Energies* **2022**, *15*, 6238. [CrossRef]

28. Tiwari, R.; Babu, N.R. Recent Developments of Control Strategies for Wind Energy Conversion System. *Renew. Sustain. Energy Rev.* **2016**, *66*, 268–285. [CrossRef]
29. Kala, H.; Sandhu, K.S. Effect of Change in Power Coefficient on the Performance of Wind Turbines with Different Dimensions. In Proceedings of the 2016 International Conference on Microelectronics, Computing and Communications (MicroCom), Durgapur, India, 23–25 January 2016. [CrossRef]
30. Majout, B.; Bossoufi, B.; Bouderbala, M.; Masud, M.; Al-Amri, J.F.; Taoussi, M.; El Mahfoud, M.; Motahhir, S.; Karim, M. Improvement of PMSG-Based Wind Energy Conversion System Using Developed Sliding Mode Control. *Energies* **2022**, *15*, 1625. [CrossRef]
31. De Lellis, M.; Reginatto, R.; Saraiva, R.; Trofino, A. The Betz Limit Applied to Airborne Wind Energy. *Renew. Energy* **2018**, *127*, 32–40. [CrossRef]
32. Baloch, M.H.; Abro, S.A.; Kaloi, G.S.; Mirjat, N.H.; Tahir, S.; Nadeem, M.H.; Gul, M.; Memon, Z.A.; Kumar, M. A Research on Electricity Generation from Wind Corridors of Pakistan (Two Provinces): A Technical Proposal for Remote Zones. *Sustainability* **2017**, *9*, 1611. [CrossRef]
33. Daoudi, M.; Abdelaziz, A.S.M.; Mohammed, E.; Elmostapha, E. Analysis of Wind Speed Data and Wind Energy Potential Using Weibull Distribution in Zagora, Morocco. *Int. J. Renew. Energy Dev.* **2019**, *8*, 267–273. [CrossRef]
34. Cao, W.; Xie, Y.; Tan, Z. Wind Turbine Generator Technologies. *Adv. Wind Power* **2012**, *1*, 177–204. [CrossRef]
35. Chaudhuri, A.; Datta, R.; Kumar, M.P.; Davim, J.P.; Pramanik, S. Energy Conversion Strategies for Wind Energy System: Electrical, Mechanical and Material Aspects. *Materials* **2022**, *15*, 1232. [CrossRef]
36. Lebsir, A.; Bin Tunisi, A.; Mangel, H.; Bin Buzayd, M.E.H. Electric Generators Fitted to Wind Turbine Systems: An Up-to-Date Comparative Study. *J. Electr. Syst.* **2015**, *11*, 281–295.
37. Manwell, J.F.; Mcgowan, J.G.; Rogers, A.L. *Wind Energy Explain: Theory, Design and Application*, 2nd ed.; John Wiley & Sons Ltd: Chichester, UK, 2009; pp. 23–87. ISBN 978-1-119-99436-7.
38. Alternative Energy Permanent Magnet DC Generator for Wind Turbine Machines. Available online: https://www.alternative-energy-tutorials.com/wind-energy/pmdc-generator.html (accessed on 29 July 2022).
39. Huanga, D.; Fan, S.; Fan, B. Virtual DC Generator Control Strategy for Load DC-DC Converter. In Proceedings of the 2015 International Symposium on Computers & Informatics, Beijing, China, 17–18 January 2015; Volume 13, pp. 1359–1368. [CrossRef]
40. Zhi, N.; Ding, Y.; Du, L. Virtual DC Generator Control Strategy Based on Differential Compensation. In Proceedings of the 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA, 29 September–3 October 2019; pp. 1454–1458. [CrossRef]
41. Kavya, P.; Bharathi, A.V.; Apparao, A. Investigation on Usage of Brush Less DC Generator in Wind Farm Application. *Int. J. Pure Appl. Math.* **2017**, *115*, 513–517.
42. Ruviaro, M.; Rüncos, F.; Sadowski, N.; Borges, I.M. Analysis and Test Results of a Brushless Doubly Fed Induction Machine with Rotary Transformer. *IEEE Trans. Ind. Electron.* **2012**, *59*, 2670–2677. [CrossRef]
43. Yassin, H.M.; Abdel-Wahab, R.R.; Hanafy, H.H. Active and Reactive Power Control for Dual Excited Synchronous Generator in Wind Applications. *IEEE Access* **2022**, *10*, 29172–29182. [CrossRef]
44. Goudarzi, N.; Zhu, W.D. A Review on the Development of Wind Turbine Generators across the World. *Int. J. Dyn. Control* **2013**, *1*, 192–202. [CrossRef]
45. De Freitas, T.R.S.; Menegáz, P.J.M.; Simonetti, D.S.L. Rectifier Topologies for Permanent Magnet Synchronous Generator on Wind Energy Conversion Systems: A Review. *Renew. Sustain. Energy Rev.* **2016**, *54*, 1334–1344. [CrossRef]
46. Potgieter, J.H.J.; Kamper, M.J. Design of New Concept Direct Grid-Connected Slip-Synchronous Permanent-Magnet Wind Generator. *IEEE Trans. Ind. Appl.* **2012**, *48*, 913–922. [CrossRef]
47. Kim, Y.S.; Chung, I.Y.; Moon, S. Il Tuning of the PI Controller Parameters of a PMSG Wind Turbine to Improve Control Performance under Various Wind Speeds. *Energies* **2015**, *8*, 1406–1425. [CrossRef]
48. Yang, B.; Shu, H.; Qiu, D.; Zhu, D. Optimal Passive PID Controller of PMSG for Maximum Power Point Tracking via Interactive Teaching-Learning Optimizer. In Proceedings of the 2018 37th Chinese Control Conference (CCC), Wuhan, China, 25–27 July 2018; pp. 7644–7649. [CrossRef]
49. Youssef, A.R.; Mohamed, E.E.M.; Ali, A.I.M. Model Predictive Control for Grid-Tie Wind-Energy Conversion System Based PMSG. In Proceedings of the 2018 International Conference on Innovative Trends in Computer Engineering (ITCE), Aswan, Egypt, 19–21 February 2018; pp. 467–472. [CrossRef]
50. Bakbak, A.; Canseven, H.T.; Altintas, M.; Ayaz, M.; Mese, E. Maximizing Energy Extraction from Direct Grid Coupled Permanent Magnet Synchronous Generators. In Proceedings of the 2021 IEEE Applied Power Electronics Conference and Exposition (APEC), Phoenix, AZ, USA, 14–17 June 2021; pp. 981–988. [CrossRef]
51. Rasool, E.; Liaquat, M.; Bhatti, A.I.; Mehmood, A. Cooperative Adaptive Cruise Control with Fuel Efficiency Using PMP Technique. In Proceedings of the 2019 5th International Conference on Control, Automation and Robotics (ICCAR), Beijing, China, 19–22 April 2019; pp. 396–400. [CrossRef]
52. Terao, Y.; Sekino, M.; Ohsaki, H. Electromagnetic Design of 10 MW Class Fully Superconducting Wind Turbine Generators. *IEEE Trans. Appl. Supercond.* **2012**, *22*, 5201904. [CrossRef]
53. Asghar, R. Fault Current Limiters Types, Operations and Its Limitations. *Int. J. Sci. Eng. Res.* **2018**, *9*, 1020–1027.
54. Zou, Y. Induction Generator in Wind Power Systems. *Induction Mot.-Appl. Control Fault Diagn.* **2015**, 4–35. [CrossRef]

55. Chen, H.; Zuo, Y.; Chau, K.T.; Zhao, W.; Lee, C.H.T. Modern Electric Machines and Drives for Wind Power Generation: A Review of Opportunities and Challenges. *IET Renew. Power Gener.* **2021**, *15*, 1864–1887. [CrossRef]
56. Saini, S. Review of Doubly Fed Induction Generator Used in Wind Power Generation. *Int. J. Environ. Sci. Dev. Monit.* **2013**, *4*, 53–56.
57. Mehdipour, C.; Hajizadeh, A.; Mehdipour, I. Dynamic Modeling and Control of DFIG-Based Wind Turbines under Balanced Network Conditions. *Int. J. Electr. Power Energy Syst.* **2016**, *83*, 560–569. [CrossRef]
58. Liu, S.; Han, Y.; Du, C.; Li, S.; Zhang, H. Fuzzy PI Control for Grid-Side Converter of DFIG-Based Wind Turbine System. In Proceedings of the 2021 40th Chinese Control Conference (CCC), Shanghai, China, 26–28 July 2021; pp. 5788–5793. [CrossRef]
59. Mensou, S.; Essadki, A.; Minka, I.; Nasser, T.; Idrissi, B.B. Backstepping Controller for a Variable Wind Speed Energy Conversion System Based on a DFIG. In Proceedings of the 2017 International Renewable and Sustainable Energy Conference (IRSEC), Tangier, Morocco, 4–7 December 2017. [CrossRef]
60. Asghar, R.; Ali, A.; Rehman, F.; Ullah, R.; Ullah, K.; Ullah, Z.; Sarwar, M.A.; Khan, B. Load Frequency Control for EVs Based Smart Grid System Using PID and MPC. In Proceedings of the 2020 3rd International Conference on Computing, Mathematics and Engineering Technologies (iCoMET), Sukkur, Pakistan, 29–30 January 2020. [CrossRef]
61. Khan, I.; Zeb, K.; Uddin, W.; Ishfaq, M.; Ul Islam, S.; Jan, K.U. Robust Control Design for DFIG Based Wind Turbine under Voltage Sags. In Proceedings of the 2020 3rd International Conference on Computing, Mathematics and Engineering Technologies (iCoMET), Sukkur, Pakistan, 29–30 January 2020. [CrossRef]
62. Wikipedia Pakistan-Wikipedia. Available online: https://en.wikipedia.org/wiki/Pakistan (accessed on 31 July 2022).
63. World Bank Exports of Goods and Services (Current US$) | Data. Available online: https://data.worldbank.org/indicator/NE.EXP.GNFS.CD?most_recent_value_desc=true (accessed on 31 July 2022).
64. Manaky Seasons in Pakistan | Climate Change in Pakistan. Available online: https://manaky.com/almanak/seasons-in-pakistan (accessed on 24 May 2022).
65. Raheem, A.; Abbasi, S.A.; Memon, A.; Samo, S.R.; Taufiq-Yap, Y.H.; Danquah, M.K.; Harun, R. Renewable Energy Deployment to Combat Energy Crisis in Pakistan. *Energy. Sustain. Soc.* **2016**, *6*, 16. [CrossRef]
66. Luo, B.; Khan, A.A.; Ali, M.A.S.; Yu, J. An Evaluation of Influencing Factors and Public Attitudes for the Adoption of Biogas System in Rural Communities to Overcome Energy Crisis: A Case Study of Pakistan. *Sci. Total Environ.* **2021**, *778*, 146208. [CrossRef] [PubMed]
67. Raza, M.A.; Khatri, K.L.; Ul Haque, M.I.; Shahid, M.; Rafique, K.; Waseer, T.A. Holistic and Scientific Approach to the Development of Sustainable Energy Policy Framework for Energy Security in Pakistan. *Energy Rep.* **2022**, *8*, 4282–4302. [CrossRef]
68. NEPRA State of Industry Report 2020. *Stat. Data About Energy Electr. Sect.* **2021**, *15*, 80–97.
69. Israr Khan Circular Debt at Rs2.467tr Threatens Power Sector Sustainability. Available online: https://www.thenews.com.pk/print/964747-circular-debt-at-rs2-467tr-threatens-power-sector-sustainability (accessed on 31 July 2022).
70. Asian Development Bank. *Proposed Programmatic Approach and Policy-Based Loan for Subprogram 2 Islamic Republic of Pakistan: Energy Sector Reforms and Financial Sustainability*; 2021; pp. 1–7. Available online: https://www.adb.org/sites/default/files/project-documents/53165/53165-002-rrp-en.pdf (accessed on 22 November 2021).
71. AEDB. *Alternative and Renewable Energy Policy 2019*; AEDB: Islamabad, Pakistan, 2021.
72. The Express Tribune Construction of 10 Dams Will Ensure Food Security in Country: PM. Available online: https://tribune.com.pk/story/2300648/construction-of-10-dams-will-ensure-food-security-in-country-pm (accessed on 31 July 2022).
73. GOP. *Community-Based Renewable Energy Development in the Northern Areas and Chitral (NAC), Pakistan*; GOP: Islamabad, Pakistan, 2019.
74. Heneghan, B.; Boyne, K. Life-Cycle of an Onshore Wind Farm. Irsih Wind Energy Association (IWEA). 2019, 1–20. Available online: https://windenergyireland.com/images/files/iwea-onshore-wind-farm-report.pdf (accessed on 1 May 2019).
75. IRENA Renewable Power Generation Costs in 2020. Available online: https://irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020 (accessed on 1 August 2022).
76. Wikipedia Electricity Sector in Pakistan. Available online: https://en.wikipedia.org/wiki/Electricity_sector_in_Pakistan#cite_note-8 (accessed on 1 August 2022).
77. Haris, Z.; Eric, Y. Fuel Shortages Hit Nearly a Quarter of Pakistan's Operational Power Plants. Available online: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/072022-fuel-shortages-hit-nearly-a-quarter-of-pakistans-operational-power-plants (accessed on 1 August 2022).
78. Manoj, V.; Swathi, A.; Rao, V.T. A PROMETHEE Based Multi Criteria Decision Making Analysis for Selection of Optimum Site Location for Wind Energy Project. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1033*, 012035. [CrossRef]
79. Tabassum, Z.; Shastry, C.B.S. Renewable Energy Generation-Solar and Wind, Challenges and Policies Adopted in Karnataka, India. In Proceedings of the 2021 Fourth International Conference on Microelectronics, Signals & Systems (ICMSS), Kollam, India, 18–19 November 2021. [CrossRef]
80. Sumair, M.; Aized, T.; Gardezi, S.A.R.; Bhutta, M.M.A.; Rehman, S.M.S.; ur Rehman, S.U. Comparison of Three Probability Distributions and Techno-Economic Analysis of Wind Energy Production along the Coastal Belt of Pakistan. *Energy Explor. Exploit.* **2020**, *39*, 2191–2213. [CrossRef]
81. Harijan, K.; Uqaili, M.A.; Memon, M.; Mirza, U.K. Forecasting the Diffusion of Wind Power in Pakistan. *Energy* **2011**, *36*, 6068–6073. [CrossRef]

82. Habib, S.; Muhammad Javed Iqbal, K.; Amir, S.; Naseer, H.M.; Akhtar, N.; Ur Rehman, W.; Irfan Khan, M. Renewable Energy Potential in Pakistan and Barriers to Its Development for Overcoming Power Crisis. *Soc. Bus. Manag.* **2021**, *27*, 6836–6846. [CrossRef]
83. Elliott, D. *South Asia Regional Initiative for Energy Cooperation and development (SARI-Energy): Wind Resource Assessment and Mapping for Afghanistan and Pakistan*; National Renewable Energy Laboratory: Golden, CO, USA. Available online: https://nawabi.de/power/wind/afgpak_wind_nrel.pdf (accessed on 21 May 2007).
84. Shami, S.H.; Ahmad, J.; Zafar, R.; Haris, M.; Bashir, S. Evaluating Wind Energy Potential in Pakistan's Three Provinces, with Proposal for Integration into National Power Grid. *Renew. Sustain. Energy Rev.* **2016**, *53*, 408–421. [CrossRef]
85. RajRAS. Power Resources of Rajasthan. Available online: https://www.rajras.in/rajasthan/economy/infrastructure/power/ (accessed on 1 August 2022).
86. Wind Power Profile of Rajasthan; Jaipur, India, 2019. Available online: https://www.indianwindpower.com/pdf/Rajasthan-State-Wind-Power-Profile.pdf (accessed on 30 June 2019).