TECHNO-ECONOMIC ANALYSIS OF WIND ENERGY POTENTIAL OF SPECIFIC SITES IN PAKISTAN

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Islamabad, Pakistan
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A thesis submitted in partial fulfillment of the requirement for the degree of Master of Science in Environmental Engineering

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2023

APPROVAL CERTIFICATE

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"Techno-Economic Analysis of Wind Energy Potential of Specific Sites in Pakistan"

Submitted by

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I declare that that this research work titled**"Techno-Economic Analysis of Wind Energy Potential of Specific Sites in Pakistan"** is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources has been properly acknowledged/referred.

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DEDICATION

Dedicated to my exceptional parents and adored siblings whose tremendous support and cooperation led me to this wonderful accomplishment.

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I am thankful to my Creator Allah Subhana-Wattala to have guided me throughout this work at every step and for every new thought which You setup in my mind to improve it. Indeed, I could have done nothing without Your priceless help and guidance. Whosoever helped me throughout the course of my thesis, whether my parents or any other individual, was Your will, so indeed none be worthy of praise but You.

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Aimen Umer

TABLE OF CONTENTS

LIST OF ABBREVIATION

AboveGround Level	AGL
Analytical Hierarchy Process	AHP
AlternativeEnergyDevelopmentBoard	AEDB
AtmosphericDataAssimilationSystem	ADAS
DenmarkTechnicalUniversity	DTU
EnergySectorManagementAssistanceProgram	ESMAP
ECMWF Reanalysis Dataset	ERA
FifthAssessmentReport	AR5
Giga-Watt	GW
GoddardEarthObservingSystem	GEOS
GreenhouseGas	GHG
GrossDomesticProduct	GDP
IntergovernmentalPanel onClimateChange	IPCC
InternationalElectrotechnicalCommission	IEC
InternationalOrganizationforStandardization	ISO
Kilo-Watt	KW
Levelized Cost of Electricity	LCOE
Mega-Watt	MW
Modern-EraRetrospectiveanalysisforResearchand Applications	MERRA
NationalAeronauticsand SpaceAdmiration	NASA
NationalCenterforAtmosphericResearch	NCAR
NationalCentersforEnvironmentalPrediction	NCEP
NationalElectricPower RegulatoryAuthority	NEPRA
PakistanMeteorologicalDepartment	PMD
RootMean SquareErrors	RMSE
SurfacemeteorologyandSolarEnergy	SSE
System Advisory Model	SAM
SynthesisReport	SYR

Tera-Watt	TW
TheWorldBank	WB
UnitedStatesAgencyforInternationalDevelopment	USAID
WeatherResourceandForecasting	WRF
WindPower Density	WPD

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Wind energy is one of the most abundant and viable renewable energy resource options worldwide which can be used as alternative to fossil fuel, but spatial distribution and variability makes it difficult to utilize. In this study wind resource availability and electricity generation potential of wind resource was computed. For this purpose, Era-5 reanalysis dataset was utilized to develop the wind resource map of Pakistan. Geospatial and site suitability analysis has been conducted to find the most appropriate side for wind farm. Weights showing the degree of importance of each criterion were calculated via the analytic hierarchy process method and integrated to the model. During this process geographical data was collected and processed using GIS for finding the best wind resource site and restricted regions were developed by overlaying the maps on each other. In this study six main criteria were considered which includes different factors i.e., elevation, slope, land use, proximity to road, urban expansion, and proximity to transmissions lines. Results showed that the most suitable site for wind energy farm is in the District of Sindh, Jamshoro. After finding the most appropriate site techno economic analysis was conducted using SAM. Empirical model was designed to study the long-term feasibility of the wind farm. Results indicate that annual energy production of about 193,592,672 can be generated form this site which in return can reduce the carbon emissions of about 8219944 equivalent kg of CO_2 emissions. Moreover, a positive net present value, levelized cost of electricity around 4.39¢/kWh, and payback period of approximately 9.7 years justify the economic viability of the proposed wind farm design at Jamshoro region. This study will serve as a valuable reference for similar wind profile site locations in neighboring countries as well. Moreover, this study presents long-term economic feasibility with site specific analysis which can provide prospects for investment in sustainable energy development and increase its utilization in developing countries.

CHAPER 1

1. INTRODUCTION

1.1 Background

Energy, especially in the form of electricity, has become one of the primary necessities for the success of a nation (Odoi-Yorke et al., 2023). Socioeconomic development of a country largely dependent on the energy resources of the country. Apart from this, the revolution in the industrial sector, the well-being and prosperity of the people also depend on energy resources (Zafar et al., 2018). An effective and robust energy profile of a country can tell how well a country is equipped to meet energy demands in future (Jamshidi et al., 2021). Conventionally, fossil fuels are being used to meet the energy requirements, however due to drastic change in climate and depletion of environment the primary energy resources are insufficient to encounter the ever-growing demands of energy usage (N. Ahmed et al., 2021). Moreover, the use of fossil fuel not only contributes to greenhouse gas (GHG) emissions and climate change, but also has an influence on economies and populations as these resources are used up. With rising energy demand, CO_2 emissions rose by over 2 billion tons in 2021, the highest increase recorded ever and even offsetting the drop-in pandemic activity seen in 2020. For CO2 emission, coal shares the 40% emissions followed by natural gas. The demand of electricity is fulfilled by use of coal and oil; however, the developing countries are facing serious prices burdens. Thus, these countries are in need of sustainable, economical and renewable resources to provide affordable electricity to the people. Therefore, the usage of renewable resources is imperative.

1.2 Global Renewable Energy Scenario

Renewable energy has significant implications for society both worldwide and in underdeveloped countries, in addition to lessening its harmful environmental effects. The potential global capacity for the expansion of renewable energy is, theoretically, greater than the projected future energy consumption for the year 2030. In 2020, 29% of the world's electricity came from renewable sources, an increase of 2% from the year before, with hydropower and wind energy accounting for the greatest percentages. By the end of 2021, an additional 8% of renewable energy is anticipated. Without China, only 22% of the world's investments in renewable capacity were made in 2020. Fig. 1 represents the share of electricity produced from different renewable sources worldwide. Wind and Solar energy are the two most economical and feasible energy sources as compared to conventional energy (N. Ahmed et al., 2021). Wind energy is considered to be the most suitable renewable energy source mainly due to the simple infrastructure and ease of installation, long-life of wind turbines, and lower cost of energy generation (Rafique et al., 2018a). Keeping in view of the future energy scenario, the utilization of wind energy will play an important role in meeting energy demands.

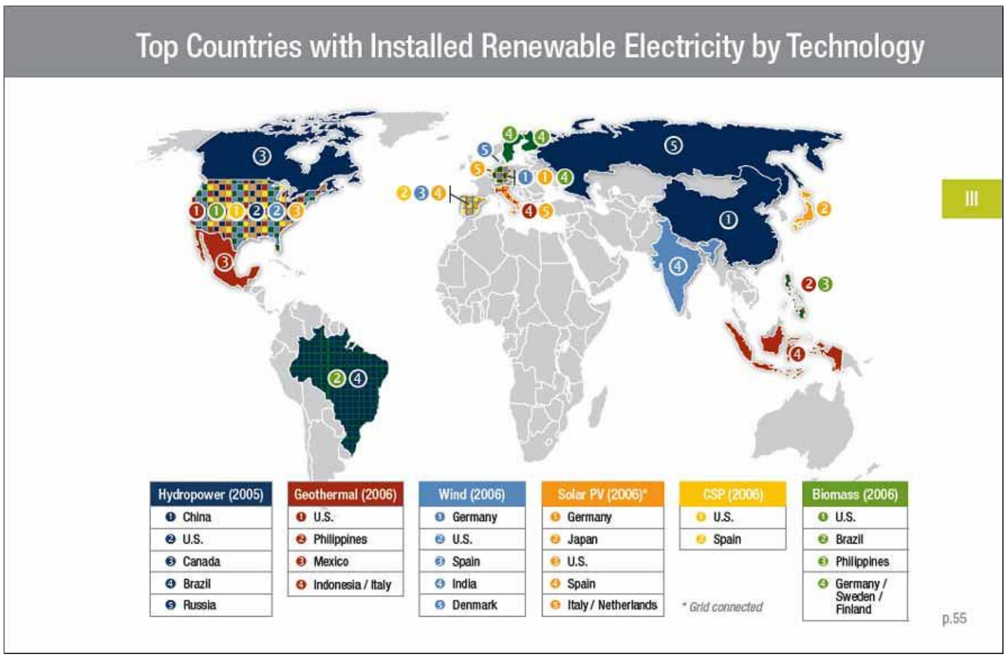


Figure 1. Electricity Generation Worldwide

1.3 Renewable Resources in Developing Countries

The developing countries such as Pakistan, India, and Iran continuously require energy to develop in this modern industrial era. In past decade (2010-2020), electricity demand of Pakistan was around 14, 375 MW, however it will reach around 30,000 MW at the end of 2030. India and Iran also have the same increasing trend of electricity demand with peak values of around 1,90,198 MW for India and 57,681 MW for Iran (Khan et al., 2023a). From Fig. 2, it is clearly seen that these countries mutually share the common region of northern coast of Arabian sea and have vast resources of wind throughout the year. Moreover, these countries have planned industrial development in this region which will eventually increase the energy demand in the near future. Thus, the use of wind resources from these countries in the coastal region will provide clean development prospects in future.

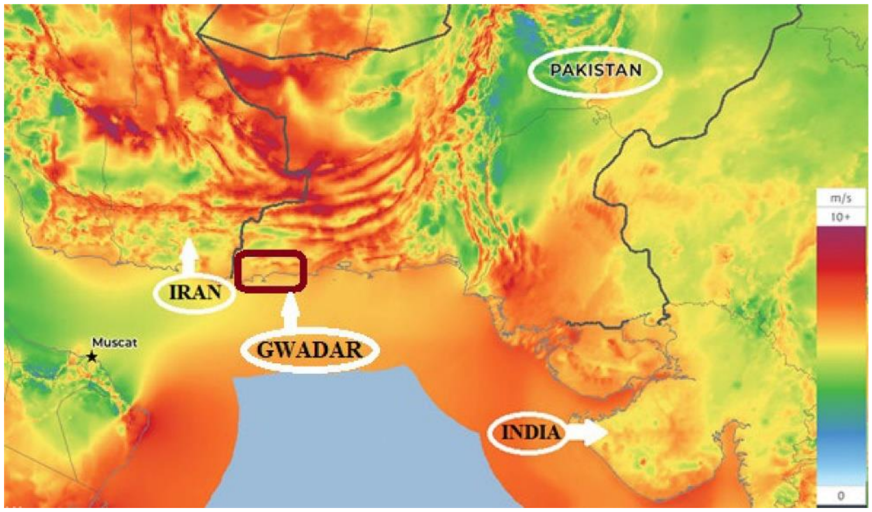


Figure 2. Map of Coastal Region of Arabian Sea

1.4 Wind Power in Pakistan

Pakistan being one of the developing countries, is facing the serious energy crises and 5 percent energy demand is added every year with growing population. According to a survey report, roughly around 51 million people in Pakistan have no access to electricity. This has become a major problem for the government as most of the country`s electricity demand is streaming through fossil fuels. The fluctuations in global oil prices have further added to the problems of government (Khan et al., 2023a). The government has been establishing plans and policies to form an energy sector to use wind energy as a clean and sustainable energy source. For that purpose, the private sectors were motivated to invest in this area by relaxing the energy policy back in 2006. According to this plan, the Alternative Energy Development Board (AEDB) was tasked to add renewable energy to the national energy mix up to 5 percent by 2030. Thus, in past few years, renewable technologies have grown in Pakistan due to regulatory amendments, encouragements, and investor friendly policies of the government. About 1200 MW was added from renewable resources into the energy mix of the country during the period from 2015 to 2018. Individually, it comprised of 600 MW from wind energy, 400 MW from photovoltaic solar energy, 160 MW from biomass, and 50 MW from small hydropower plants (Khan et al., 2023a).

Pakistan is lacking in generating good quality wind data for researchers and institutes having interest of working in this sector. Although Pakistan Meteorological Department (PMD) masts have been used to record wind characteristic data, such as wind speed and direction, under a large-scale project of wind mast installation completed in 2002, there have been reports of flaws in the installation of these masts, and the use of locally calibrated sensors and data loggers has further decreased the reliability of the recorded wind data. In 2007, AEDB and PMD worked with USAID to create a meso-scale wind map of Pakistan displaying the expected wind speed at 50 metres above ground level (AGL). Following the creation of a wind map, analysis carried out by PMD in 2004 and later in 2007 revealed the existence of a wind corridor in Pakistan's south. Recently, in collaboration with the AEDB, a project to map renewable energy resources was launched with funding from the World Bank's Energy Sector Management Assistance Programme (ESMAP). Under this initiative by the World Bank and AEDB, 12 localities in Pakistan had wind towers built in 2016. These wind masts offer unrivalled data quality.

1.5 Problem Statement

Rapid growth in population has led to an increase in urbanization which eventually poses high risk to the environment. The reason for that is the excessive use of fossil fuels. Due to the excessive use of fossil fuels, the emission of greenhouse gases increased in the environment and results in climate change. Pakistan is a developing country and to meet the energy demands spends billions of dollars to utilize fossil fuel for that purpose, which in return put serious burden to the Pakistan economy. On the flip side, Pakistan is rich in renewable energy resources and can produce excessive energy from these resources. One of the renewable energy resources is wind energy which is still in developing phase and have the sufficient ability to provide sustainability to the energy sector of Pakistan. In this study, a GIS based approach is used to check the feasibility and potential of wind energy. To analyze the wind energy potential, different databases from GIS were used such as wind speed, topography, urban areas and special activities. Moreover, the technoeconomic analysis was also performed by estimating the wind energy output of specific areas and by adding the installation cost. Besides benefiting the decision makers for the sector in Pakistan, the results obtained in the study are also important for the development of the wind power sector in other developing countries.

1.6 Research Objectives

The main focus of this study was to select such suitable sites in Pakistan where the wind energy can be generated. Suitable wind data is used for this purpose. Moreover, the technoeconomic analysis was also performed to analyze the cost effectiveness of these wind parks. Based on this following research objectives are designed for this study

- Selection of Sites for the development of Wind parks in Pakistan
- Techno-economic analysis of wind power plants

CHAPTER 2

2. LITERATURE REVIEW

Numerous studies on site selection for wind energy have been conducted. In (Aukitino et al., 2017), researchers looked at the characteristics of the wind of Kiribati, including speed, temperature, and direction. They utilized parameters of Weibull and discovered that moment method (MM) was the most precise technique. In (Katinas et al., 2017a) the evaluation of Lithuania's wind power potential is done. To evaluate the wind resource, the authors employed the Weibull probability distribution function. In an additional investigation project, the power potential and wind characteristics of Nooriabad in Pakistan were examined (Hulio et al., 2017). Five approaches were used to attain the correctness of the Weibull parameters in this study.

The authors employed the probability function of Weibull to estimate the Chad wind resource which is situated in North-Central Africa, at 10-meter height (Soulouknga et al., 2018). The significance of regional wind energy potential development is demonstrated by the current research that has been published. Here are a few of the regional studies that have been discussed and which demonstrate the development of wind energy. The Iranian province of Kaman's Shahabad City wind potential was evaluated by the authors (Mostafaeipour et al., 2011a). The author in (Mostafaeipour, 2010a) evaluated the wind power potential at ten, twenty, and forty meters in the Iranian region of Yazd. Iran's resource potential was also assessed in order to determine another evaluation. Tehran, the capital of Iran, was the area under consideration. On the eleven-year wind speed data derived in (Keyhani et al., 2010). The Iranian city of Zarinah's wind energy potential was researched in (Mohammadi &Mostafaeipour, 2013a), the wind resource research at Binalood was evaluated at a height of 10, 30, and 40 m in (Mostafaeipour et al., 2013), and the wind resource assessment study at Semnan Province was carried out in (Mirhosseini et al., 2011).

The wind energy potential of Iran's Lotak and Shandol was investigated by Teimourian in (Teimourian et al., 2019). The authors found that for the generation of power at minimum price, the sites are best after taking into account measurements of wind made at ten, thirty and forty meters above ground using wind measurement intervals of 10 minutes. Turkmenistan's wind resources have been evaluated by Bahrami and Arian. The author evaluated the wind energy potential of 18 distinct places and concluded that energy can be produced for the least amount of money (Bahrami, Teimourian, Okoye, & Khosravi, 2019a). In a second piece of research, Brahami Arian and colleagues looked at 17 distinct Uzbek regions' potential for wind energy. The author determined that Buhari Ak Bajtal, Kungrad, and Nukus are the areas with the highest yearly wind power density, capacity factor, and energy density (Bahrami, Teimourian, Okoye, & Shiri, 2019).

Shahrbabak, in the Iranian province of Kaman, the feasibility assessment for wind energy is presented (Mostafaeipour et al., 2011b). The author concluded that the location is ideal for the development of a small wind energy farm by using the two-parameter Weibull distribution function for wind analysis and wind power density for energy generation. (Baseer et al., 2015) shows the wind assessment of Jubail, a city in Saudi Arabia, utilizing 24-hour data from wind measurements taken at three distinct heights. The Weibull distribution function was employed by the authors. Similarly, in another study conducted in the previously mentioned Jubail region, the authors measured the wind at seven different places and used the maximum probability, least-squares regression, and WAsP methods to analyze the k and c Weibull parameters (Baseer, Meyer, et al., 2017).

The research gives a technical and economical assessment of a wind farm of 100MW in Gwadar area of Pakistan, which is strategically and economically significant due to its exceptional location on the Arabian Sea shore. This location has been the subject of several feasibility studies; however, this study makes use of hourly wind data collected on-site, the latest financial data, and an optimized wind farm design configuration. For the purpose of evaluating the long-term economic viability of wind farms, empirical relationships are given (Khan et al., 2023b). This study (Kazmi et al., 2022) shows the assessment of the techno-economic impact of massive wind farms connected to inadequate transmission networks in Pakistan, taking into account the inter-farm wake effect, reactive power loss, and correcting utilizing a variety of voltage-ampere reactive (VAR) devices. The active power deficit caused by the wake effect was partially addressed in this study by elevating the hub height by 20 m, which helped to recover the active power deficit to 48% and lessen the impacts of upstream wind farms.

The authors in (Baseer, Rehman, et al., 2017) utilized the multicriteria decision approach (MCDA) and geographic information system (GIS) to choose the optimal location for a wind power project. In (Bassyouni et al., 2015) the evaluation of the wind parameters of Jeddah, Saudi Arabia is performed. Similar studies of wind resource evaluation for Yanbu, a Saudi Arabian industrial city, for seven distinct stations in the Eastern Province of Saudi Arabia, and for Lidar-based wind measurements are done in (Rehman, 2004), (Rehman et al., 2012), and (Rehman et al., 2018). Additional research on wind potential is done in Saudi Arabia have been conducted to evaluate the potential of wind energy considering various wind turbines (Al-Abbadi, 2005), (Rafique et al., 2018b).

A crucial element in harnessing wind energy is the site's current potential wind speed. According to reports, wind speeds between 3 and 25 m/s are ideal for turning wind into electricity. Additionally, the occurrences of effective wind speeds show the rate of energy resources that are readily accessible. In a study (Li & Li, 2005) the seasonal and nocturnal figures are used from Canada's Waterloo to estimate the value of wind energy.

Like this, (Dahmouni et al., 2011) evaluated the wind power potential at Tunisia's Borj Cedria at heights of 10, 20, and 30 m, projecting the wind energy density by analyzing seasonal wind speeds. Additionally, (Bidaoui et al., 2019) evaluated the wind energy potential of five cities in northern Morocco, including Tangier, Tetuan, Al Hoceima, Nador, and Larach. To research the energy sector, the wind characteristics of Port Said in Egypt (Lashin& Shata, 2012) were employed. The energy flux approach was employed by the authors. For Tindouf in (Himri et al., 2012), which considered the eight-year data, and for the Timimoun area of Algeria in (Himri et al., 2016), measured wind speed data were employed.

In (Mohammadi &Mostafaeipour, 2013b) the author determine the Iranian city of Zarrineh’s energy potential of wind. He finds the most accurate way of computing wind the difference in power between the standard deviation approach and the method of power density is another goal of this research. In this study data on wind speed obtained in Zarrineh between 2004 and

2009 are chosen as sample data to assess the performance. Analysis was done on the wind speed data recorded at 10 meters every three hours. At a height of 10 meters, the measured yearly mean wind speed and mean wind power are 4.07 m/s and 161.44 W/m2, respectively. The power density methodology has been shown to be the best way of evaluating potential of wind energy based on hourly, monthly, seasonal, and yearly values.

In a study (Urišić&Mikulović, 2012) an analysis is done of the South Banat region's wind energy resources. Measurements of the wind parameters taken at the location of the village of Bavanite served as the basis for the studies. The information was gathered between 2009 and 2010 at heights of 10, 40, 50, and 60 m. The direction of wind, power density, average speed of wind, , and the other parameters like k and c of the Weibull distribution were all examined statistically using the observed data. An examination of the turbulence of wind at the site of measurement is carried out on the basis of established standard deviation of the wind speed. A mathematical technique for estimating the vertical wind speed profile has been devised and is based on the sum of least squares method.

The 3 functions of probability density such as Lognormalare, 2-parameter Weibull, and Logistic, were used to simulate the distribution of wind speeds utilizing data collected over the most recent three years, from 2009 to 2011, at the location of Inner Mongolia in China (Wu et al., 2013). To choose the optimal function, the effectiveness of the three is compared. The Weibull function is one of the most useful methods for characterizing the distribution of wind speed in many situations since it is one of the most favorable distributions. Although the 18 methods of differential evolution performances and 3 particle swarm optimization algorithms are compared in order to estimate the shape parameter in the Weibull function, the best-performing algorithm is ultimately chosen in order to identify the ideal shape parameter and produce the most accurate shape parameter estimation results.

This study aims to evaluate the Gharo site's wind conditions and potential for producing wind energy (Hulio, 2021). Calculations of the wind power density, yearly energy yield, and capacity factors at 10, 30, and 50 m have been made using the site's wind parameters. To precisely calculate the wind power at the location, the distribution of wind frequency, including seasonal and percentage distribution of seasonal frequency, has been studied. Three distinct heights are used to calculate the coefficient of variation. Additionally, a cost analysis per kWh of energy has been done.

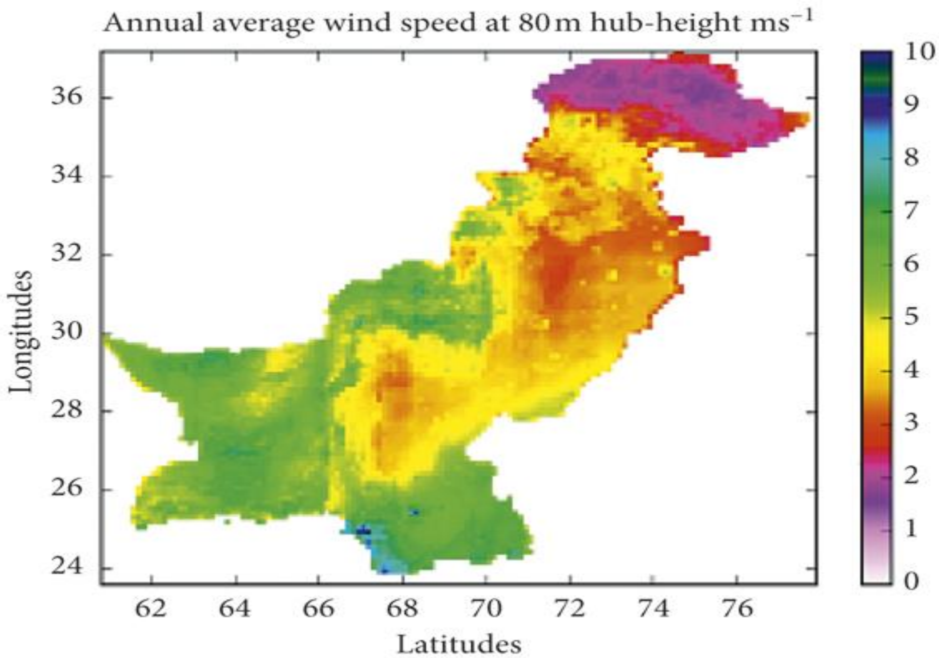


Figure 3. Geospatial Wind Resource Estimation in Pakistan (Hulio, 2021)

Thisorea's Youngman, a proposed site for the offshore wind farm that will be built in 2019 (Lee et al., 2013), this research sought to evaluate offshore wind power generation potential. Since October 2010, the HEMOSU-1 offshore meteorological tower, which was erected for this purpose, has been gathering wind and other meteorological data. The observed data fit well to Weibull models with properly calculated parameters after the Weibull model was fitted to the frequency distribution of the data. Due to the high wind speeds and steady wind direction from the northwest Siberian high, winter was found to be the ideal season for harvesting wind energy.

In (Irwanto et al., 2014) the examination of the wind speed characteristics at Chuping and Kangar in Perlis, Malaysia is presented. The parameters include mean wind speeds on a daily, monthly, and annual basis. In order to examine the characteristics of wind speed and determine the potential for wind power generation, the Weibull distribution function is used. This article presents and analyzes wind power and energy as functions of tower height. The findings indicate that the mean wind speed in Chuping between 2005 and 2009 was 1.12 m/s, while the average wind speed at Kangar between 2012 and 2013 was 2.50 m/s. According to an analysis of the Weibull distribution function, the wind speed and density of probabilities at Chuping are 0.97 m/s and 73%, respectively, whereas at Kangar they are 2.5 m/s and 45%.

For optimal use, a location's wind power potential must be evaluated. In the (Chandel et al., 2014) study, the evaluation of the potential of wind resource of the western Himalayan India named Himachal Pradesh is done to identify potential sites and offer guidance to policymakers for utilizing the potential of wind of the area for mechanical applications and generation of wind power. Using wind data for the years 2008 to 2012, the Wind Energy Pattern Factor (WEPF) approach is used to evaluate the wind potential of 12 locations representing various terrains and climatic zones. For these sites, Weibull and cumulative wind distributions, Weibull parameters, and Wind Power Density (WPD) are calculated. In the area, summertime sees the highest daily mean wind speeds, while wintertime sees the lowest.

The study's (A. S. Ahmed, 2012) goal is to demonstrate that there is enough wind potential in Egypt's vast deep south to support the operation of wind turbines there. However, it provides a generalized approximation profile that is helpful for the building of wind parks in this area. First-time publication and analysis of the calculation's input data. The standard deviation, coefficient of variation, and monthly Weibull parameters have all been statistically examined. The wind speed is constant and blows over the area of Egypt in 2 primary regions, NNWand N, with extended frequencies duration ranging from 67-87 percent during the course of the year. And its average speed of wind is ranging from 6.8–7.9 m/s at the three stations, according to a comparison of the rose diagrams. Two distinct methodologies were utilized to assess the wind energy density at 10 m height per month.

The authors of the study (Shami et al., 2016) investigate the data of three provinces named Sindh, Khyber Pakhtun, and Balochistanwind speed. Punjab, the 4th province, has relatively little potential for wind energy and is therefore not taken into consideration. In order to use Jiwani as a case study, Pakistan Meteorological Department (PMD) provided data of wind speed for this instance location in Balochistan. The study aims to determine the extent to which wind energy can be captured in the 3 provinces. Then Jiwani is the main focus because of its anticipated specific power density for wind turbine sizing. Finally, the incorporation of wind energy production (from breezy areas) into the national power grid is proposed.

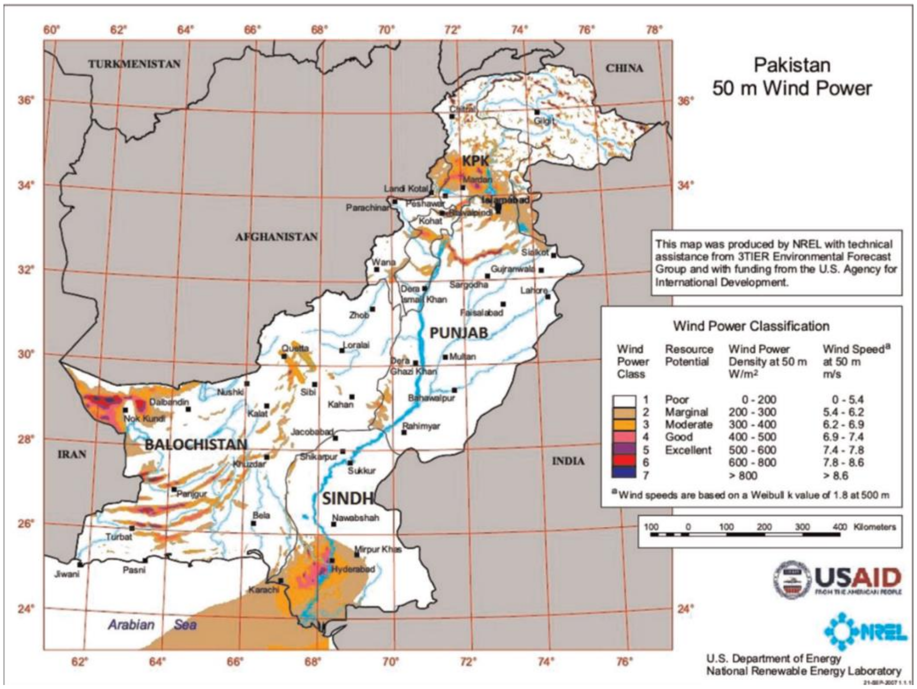


Figure 4. Pakistan Wind Map (Hulio, 2021)

The Weibull distribution approach is used to examine Bangladesh's potential for wind energy in the study (Azad et al., 2015). The information was gathered from the variously situated Meteorological Departments of Bangladesh. Weibull parameters were determined using three different Weibull distribution methods, and they were confirmed using various widely known statistical tools. The effective statistical tools to rate the methodology employed in this study are chi-square error, relative percentage error and analysis of variance, etc. By using the effective least square method with the least amount of error, the analysis found the windy spot with the greatest potential.

The wind direction and speed data were collected by the authors in the study (Valencia Ochoa et al., 2019) using a meteorological station in Puerto Bolivar, department of La Guajira, in the far north of Colombia. Its coordinates are 12°11′N 71°55′W. The data shown was gathered using a temperature sensor, a barometric pressure sensor, and a wind speed and direction sensor. These measurements were made at the weather station's highest position, which is 10 meters above the ground. The meteorological station has gathered hourly frequency data for the past 20 years (1993-2013). A mathematical model was developed to estimate the Julian averages for missing data, allowing frequency histograms and 4 other types of probability distributions to be computed for this data.

The study (Hulio et al., 2019) aims to evaluate the Hawke's Bay site's wind potential and wind characteristics. Calculations of the power density of wind, yearly energy, and capacity factors at thirty, sixty, and eighty meters have been made using the site's wind parameters. The Weibull parameters are determined using one of 5 different methods for example empirical,graphical approaches, energy pattern, and maximum likelihood modified maximum likelihood, The root means square error and coefficient of correlation values between the data collected and the estimations are used to determine the accuracy of the five approaches. The results of all methods were found to be best fits. Additionally, a cost analysis per kWh of energy has been done.

The study (Katinas et al., 2017b) presents the wind power density in particular regions and investigates the use of Weibull probability distribution approaches. Eight different methods have been used to examine the reliability of determining the shape k and scale c parameters for the Weibull probability density function. Root means square error, chi-square test, determination coefficient, and relative error were calculated to evaluate the method's reliability. Measurements of wind properties have been made throughout Lithuania's coastal and interior regions.

Using HOMER and RETScreen, the study (Salehin et al., 2016) presents a modeling framework for analyzing renewable energy systems, with a focus on power systems producing electricity. HOMER was used to optimize cost, electricity sharing, and energy system components. Following that, the HOMER results, together with other acceptable inputs, were used as input in RETScreen for a comprehensive project evaluation with an energy scenario for the systems.This technique was used as a case study to analyze the Wind-Diesel energy systems and Solar PV-Diesel on Bangladesh's Kutubdia Island.

The wind speed of a few significant cities in Iran's central Yazd Province is analyzed in (Mostafaeipour, 2010b). Additionally, the study of installing wind turbines to harness wind energy is evaluated, and after that, the issue of potential and speed of wind for wind energy at various wind stations is taken into consideration. In order to evaluate the potential for wind power at these locations, authors used 13 years wind speed data collected from 11 stations, between 1992-2005. In order to examine the potential for power generationof wind, the hour based observed data of wind speed for Yazd province at ten-, twenty- and forty-meter height have been statistically evaluated.

The study (Siddique et al., 2015) employs two methods to forecast wind speed time series for Gwadar, a coastal city in Baluchistan, Autoregressive Integrated Moving Average models and Neural Networks backpropagation algorithm. Power output for a 50MW wind farm has been determined based on the predicted wind speed, with the right turbine and ideal hub elevation selected for installation. A financial analysis of such a wind farm near Gwadar is also provided. The software was used to survey 317 turbines at elevations of 60, 80, 100, and 120 meters, representing a range of ratings and manufacturers.

The study aims to evaluate Turkmenistan's potential for wind energy by considering hourly wind speed data from 18 distinct places over the course of a normal meteorological year (Bahrami, Teimourian, Okoye, & Khosravi, 2019b). The country's sites' power and energy densities are determined using the commonly used and well-validated two-parameter Weibull distribution function. Additionally, fifteen commercially available wind turbines are used and contrasted with one another for the sites under consideration in terms of capacity factor, energy output, and annual power output. The system's viability is then evaluated using the economic measure indicator known as the LCOE (levelized cost of energy).

The main purpose of the study (Baloch et al., 2016) is to examine and forecast the country's energy condition in relation to the key wind corridor's characteristics in the south of the nation. Moreover, the author picked the most ideal wind corridors in the southern Pakistan, which has a coastline with potential for wind energy of approximately 1100 kilometers (km). Also made an effort to demonstrate conceptually why this wind zone is better for meeting domestic consumer demand. Additionally, in this work the primary difficulties encountered when implementing wind farms in the future.

Weibull, lognormal, and Rayleigh probability distributions are now being applied for wind energy assessment at six locations along Pakistan's coastal strip (Sumair et al., 2021). From 2015 to 2018, the Pakistan Meteorological Department provided data on wind for six places every 60 minutes at a height of 50 m. Based on the coefficient of determination (R2), root mean square error, and mean absolute percentage deviation, these distributions were compared. Comparative analysis revealed that the Weibull distribution, followed by the lognormal and Rayleigh distributions, is the most accurate. When wind speed and power density (PD) were compared, Karachi had the highest wind speed and PD at 5.82 m/s and 162.69 W/m2, while Jiwani had the lowest wind speed and PD at 4.62 m/s and 76.76 W/m2, correspondingly.

In (Rogers et al., 2019) authors use fundamental engineering procedures and a geographic modeling technique to ascertain an island's highest possible installed wind capacity using the Caribbean Island of Barbados as a case study. Publicly accessible historical hourly meteorological data from throughout the world is identified in order to promote further research for other islands, and it is used as part of a technical evaluation to calculate the anticipated yearly energy yield. The study discusses the critical issues that need to be solved if SIDS (small island development states) are to utilize its wind resource and emphasizes the challenges faced by wind energy development on small islands when compared to mainland nations. A levelized cost of energy is predicted by economic analysis of Barbados' anticipated annual energy yield.

The authors in (Baloch et al., 2019) choose six probable wind zones that are located within 1100 kilometers of coastal areas. With the assistance of the Pakistan Metrological Department, only one-year raw data of wind speed is taken into consideration in this study and is collected from suitable wind zones at different heights. Additionally, this project promotes domestic and foreign investment in wind energy projects in windy zones, thereby opening Pakistan's community to commercial opportunities for power generation and resolving the country's energy crisis.

Through the examination and demonstration of a 50 MW wind farm, the study (Ahmad et al., 2022) aims to evaluate the viability and efficacy of wind energy potential along the coastline of Pakistan by selecting four distinct zones (Karachi, Gawadar, Pasni, and Ormara). For the chosen zones, seasonal data from the previous four years are utilized to depict the effectiveness of the wind in terms of wind speed, wind directions, and wind density. Artificial neural networks and computer-based predictive models are also used to estimate wind efficiency, primarily using recorded wind seasonal data. The economic feasibility of the wind farm is suggested by a comparison of several turbine designs taking into account geographical, operational, and financial variables and installation. For a variety of locations and turbine designs, the factors of energy output, economic viability, ecological impact, and fuel-saving are examined.

Figure 5. Map showing the locations of the zones along Pakistan's southern coast (Ahmad et al., 2022)

The author in the study (Himri et al., 2020) takes into account the investigation of wind characteristic atlases. The Office National de la Météorologie (ONM) the Meteorological Office in Algeria collected hourly mean wind data from 2003 to 2008, which is used in the study. Determined and examined are the energy flux, wind speed, frequency distribution, direction of wind, shape and scale variables for the Weibull distribution. The cost of producing electricity (COE), the SPP (Simple Payback Period), the Year to Positive Cash Flow are all factors, the Annual Life Cycle Savings, the Internal Return rate, Positive Cash Flow, and the Net Present Value, and used by RETScreen software to calculate the wind farm's financial feasibility.

The purpose of (*EBSCOhost | 148270275 | The goal of this study (Techno-Economic Analysis and Planning for the Development of Large-Scale Offshore Wind Farm in India., n.d.)* is to build a large offshore wind farm in southern coastline area of India. To find a suitable site for the establishment of an offshore wind farm, seven candidate locations were chosen for the wind resource assessment research. Using the corresponding power curves and wind speed data, the best turbine was also chosen for each location. The WAsP, open wind, LSR (least square regression), MLH (maximum likelihood), and methods were used to determine scale and shape parameters of Weibull. These algorithmic techniques were used to identify the speed of wind carrying highest energy and the most frequently occurring wind speed. All four of these methods accurately captured the wind data at all locations, according to the correlation coefficient (R2). However, open wind performed somewhat better compared to MLH, which was followed by LSR and WAsP methodologies.

The study (Rafique et al., 2018c) examines the viability of building a wind farm of Power 100 MW connected to the grid in five Saudi Arabian cities. The outcomes show that the suggested power plant is technically and financially feasible. All of the locations are determined to be cost-effective, with the most viable location of Dhahran for the integration of the wind farm among the others. An analysis of sensitivity was also carried out to examine the effect of different incentives on the return on investment of the project.

To determine the most appropriate to least suitable location for the wind farm installation regarding various factors/criteria, The authors of (Ali et al., 2017) gathered data for locations with a capacity factor (a crucial predictor of a power plant's value) of twenty-five percent or higher for 600 kW turbines that generate electricity. Based on the wind speed (m/s)parameters, wind power density (W/m2), from grid station distance (km), capacity factor, population density, and transit cost, four possible sites are evaluated using the Analytic Hierarchy Process. The findings indicate that the preferred location is significantly influenced by the average yearly wind power density and wind speed.

The Analytical Hierarch Process (AHP), an MCDM approach, and GIS are combined in (Konstantinos et al., 2019) to propose a methodology for choosing the best locations for the integration of wind farms. The computed locations are then rated according to their suitability for installation using TOPSIS(Technique for Order Preference by Similarity to Ideal Solution) The usage of this methodology can assist decision-makers in quickly resolving competing criteria and presenting the best options that are favored by stakeholders and the general public while still being cost- and environmentally friendly.

The study (Raza et al., 2023) presents a thorough framework for site suitability for utility-scale solar PV and wind energy projects, considering criteria essential to each technology and only using criteria that are necessary for a range of scenarios that incorporate Multi-Criteria Decision Analysis (MCDA) and Geographic Information System (GIS). For the construction of small-scale solar PV systems in remote places that can be without access to energy, an innovative technique is also taken into consideration. In order to rank factors according to their significance to the selection process, a total of eight sub-criteria were taken into account in the site selection process for wind and solar energy. The resulting methodology was used in a case study of Pakistan, a developing nation with a continuing electricity crisis and a mounting climate change emergency.

The research (Shah et al., 2023) focuses on potential wind farm deployment sites that would be highly suitable throughout Pakistan. Three to five sites are chosen from each of Pakistan's twenty provinces. For techno-economic and environmental feasibility analyses, respectively, SAM and RETScreen are used. In addition to site interviews and online surveys, the study also includes a social effect assessment component. It was found that Sothgun produced 287,766 MWh of power annually while displaying the highest capacity factor of 65.1%, demonstrating the best-suited techno-economic feasibility. Among the 20 locations chosen, Chakwal had the lowest capacity factor at 42.1% and produced 184,398 MWh of power annually. The LCOE varied from 2.43 to 4.24 /kWh, with Manzoorabad and Chakwal displaying the lowest and highest values respectively.

CHAPTER 3

3. METHODOLOGY

The purpose of this project is to investigate all facets of utilizing agricultural waste as a renewable energy source, from field collection to electricity generation. To determine where and how much agricultural residue exists across Pakistan, first a map is drawn up and an assessment is made. Following the completion of these maps, the best locations for the garbage-fueled power plants could be determined.

3.1 Study Area

According to the United Nations' 2019 World Population Prospects report, Pakistan is expected to have a population of roughly 225.2 million in 2021, making it the world's fifth most populous nation. Because of its position in northwest Asia, Pakistan shares borders with a number of countries. Iran is to the south and west, and India and China are to the east. Afghanistan is located to the west. The Arabian Sea forms the southern boundary of Pakistan, which has a total of 1064 kilometers of shoreline. This includes both the Makran and the Sindh coasts.The first step in improving the wind resource data file is validating the information in it. In this research, we measure wind speed patterns using ERA-5 reanalysis data, which is a combination of historical observations and various climatic models. However, before it is used, it undergoes extensive validation versus terrestrial stations. Wind speed data is notoriously unstable, thus it must undergo extensive preprocessing before it can be used in any further investigations.

3.2 Data Validation

A series of careful procedures are carried out during preprocessing to ensure the accuracy, reliability, and suitability of this data for assessing wind energy potential at the specified location. Data collection from weather stations or wind towers, elimination of outliers, application of rigorous quality control protocols, standardization of data format, translation of data variables for validation, consolidation of data into user-defined temporal intervals, visual elucidation of trends and outliers, and thorough documentation of all preprocessing steps are all part of the preprocessing phase. The initiative aims to provide validated and trustworthy wind resource data by following to these guidelines. This data collection is crucial for evaluating the potential and viability of wind energy harvesting at the chosen site in Pakistan. The next sections provide an in-depth explanation of the wind resource datasets used for testing.

3.3 Ground Data

Beginning in 2016, thanks to AEDB and WB's partnership, data gathering continued throughout the year and resulted in the acquisition of a full dataset by the end of 2018. This dataset was the backbone of the investigation, as it included data from each site for at least two years. A two-year ground-monitored wind dataset provided the basis for preliminary evaluations, drawing on the findings of previous studies. Measurements were taken at four different heights (20 m, 40 m, 60 m, and 80 m) to create a complete vertical profile of the wind. Wind data was collected at 10 m and 50 m, and then extrapolated using the power law (equation 1). Wind speeds at an altitude of 80 appeared as the core for further investigations after the whole set of observations was integrated. The temporal granularity of 10 minutes in the wind data enabled a finer viewpoint and improved the ability to capture subtle fluctuations.

Table 1. Details of Ground data sets used in validation.

Parameters	**Units**
Date and Time	ISO8601
Wind speed Max,Min,Avg	m/s
Relative Humidity	%
Air Pressure	hPa(mean sea level)
Temperature	Celsius

the meticulous validation of wind speed ERA-5 reanalysis data spanned 12 carefully selected locations across Pakistan. This endeavor constitutes a pivotal facet of an enterprise generously backed by the World Bank. For your convenience, the precise coordinates of these investigated locales are enumerated in Table 2.

In the context of Quetta, however, a nuanced approach was undertaken. The calculation of wind speed at an elevation of 80m was executed employing equation 1. This was necessitated by local regulations that limited mast height to a maximum of 67m for the Quetta/S7 mast.

The construction of these masts diligently adhered to the benchmarks articulated in the EIA 222-G/ TIA standards. The installation procedures meticulously followed the directives delineated in the IEC Standard 61400-12-1. Ensuring the robustness of the project's design was validated through independent assessments, while stringent oversight was exercised over the civil engineering and installation processes at every juncture.

Below, you will find succinct but comprehensive insights into the topographical features, geographical attributes, and climate nuances distinctive to each of these sites.

Table 2. Ground Data Sites

Site	Site Annotation	Longitude	Latitude
Bahawalpur	S1	71.81	29.33
Chakri	S2	72.74	33.32
Gwadar	S3	62.35	25.28
Haripur	S4	73.03	33.97
Peshawar	S5	71.79	33.92
Quaidabad	S6	71.89	32.35
Quetta	S7	66.94	30.27
Sadiqabad	S8	70	28.21
Sanghar	S9	69.04	25.82

Sujawal	S10	68.18	24.52
Tando	S11	68.87	25.12
Umerkot	S12	69.57	25.08

3.3.1 Bahawalpur, Punjab

Nestled within the province of Punjab, Pakistan, Bahawalpur emerges as one of the region's most scorching cities. Notably, the zenith of heat unfurls during the month of June, while the nadir of chill settles in during January, exhibiting a temperature spectrum that spans from 7°C to 41°C.

Within this arid expanse, the focal point of our data acquisition rests upon the Quaid-e-Azam solar park. This site is meticulously chosen to be emblematic of our dataset, emblematic for its unique attributes. A desert-like terrain defines the area, characterized by a level expanse unmarred by obstructive features. At an elevation of 123 meters, the site affords a panorama where horizons stretch uninterrupted.

3.3.2 Chakri, Punjab

The next site selected for wind measurement in this study is Chakri, it lies in district Rawalpindi and province Punjab. The site elevation is 360 m and the nearest population is situated 2 km from the study area. The lowest and highest temperature of the selected site is 4° C and 38 °C respectively.

3.3.3 Gwadar, Baluchistan

The city of Gwadar is located in the southwestern part of the Pakistani province of Baluchistan. A hot desert climate surrounds this seaside enclave, which is located on the Arabian Sea. The summers are hot and dry, and the winters are dry and pleasant, but the seasons here are otherwise erratic. A mean average summer temperature of 36 degrees Celsius gives way to the cosy embrace of a mean average winter temperature of 16 degrees Celsius.

The rocky landscapes that characterize the geography of Gwadar add to the city's unique charm. The city's 13-meter elevation gives its residents a close connection to both the land and the sea. The setting up of a mast on the flat grounds of a school serves as a point of reference for our investigation. This spot has very little surrounding roughness, making it ideal for measuring wind speeds and directions.

3.3.4 Haripur, KPK

Haripur is a city in the district Hazara in the KPK province. The area is majorly flat, having 5-7 m fruit trees at distance of 150 m from mast. A storage barn is constructed at a distance of 22-150 m from the mast. Summers are wet and sweltering while winters are partly cloudy and short. The hottest days are observed in June and coldest in January.

3.3.5 Peshawar, KPK

Peshawar is KPK's capital and largest city. The chosen location is 387 meters above sea level, and the nearest building is 400 meters away, inside the grounds of a school. It is situated 15 kilometers south of the Cherat hills. The chosen location features a flat, muddy landscape. Summers are around 40 degrees Celsius, while winters are a cool 4 degrees Celsius.

3.3.6 Quaidabad, Punjab

Quaidabad is situated in the northwestern region of Punjab. The elevation of the area is 192 m and the terrain is flat. The temperature conditions are quite severe, it goes on extreme of 50° C in summers and lower as 0° C in winters.

3.3.7 Quetta, Balochistan

Quetta is the largest city in Baluchistan and its capital. The climate veers toward the dry side. The typical temperature ranges from -2 degrees Celsius to 35 degrees Celsius. Days are at their warmest in July and their coldest in January. The school's wind tower is located at an elevation of 1582 meters, while the closest building is located 250 meters away. The area is mostly flat, with a few ridges more than 5 kilometers away.

3.3.8 Sadiqabad, Punjab

Sadiqabad can be found in the Punjabi city of Rahim Yar Khan. Cholestane desert is the location of the wind mast. The location chosen features a few sand dunes but mostly is flat. The 76 m elevation used for this study. Climate is mild, with highs of 43 degrees Celsius in June and lows of 9 degrees Celsius in January.

3.3.9 Sanghar, Sindh

District Singharis located in the middle of Sindh province, which is known for its dry climate. The average annual temperature ranges from 9 to 44 degrees Celsius in this region, with May being the warmest month and January the coldest.

Our attention is drawn to a wind mast in the area for this reason. Its 20-meter height makes it a sentinel amid an otherwise flat and featureless area. The mast is set apart from the surrounding landscape by its location at least a kilometer from any human population.

3.3.10 Sujawal, Sindh

The settlement of Sujawal is a noticeable geographic outcropping in the middle of Sindh Province. Located at an elevation of 17 meters, the area features the typical dry environment of its surroundings. The climate is shaped by a dynamic interplay of factors, with average temperatures ranging from 32.4 degrees Celsius to 18.2 degrees Celsius.

There is a clear line of sight from the surrounding landscape to the installation site for the wind mast. The nearest human settlement is located two kilometers away, making the area calm and ideal for precise measurements. In addition, the nearest farm house is located 250 meters away, thus reducing the likelihood of interference from that location.

3.3.11 Tando Ghulam Ali, Sindh

Tando, Sindh Province, Pakistan, is located at an elevation of 25 meters within the Badin district. The aridity of the soil here provides an interesting backdrop for agricultural endeavours. The temperature is mild and pleasant, with a pleasant sea breeze caressing the area for around eight months out of the year.

May is the hottest month of the year, with average high temperatures of 41 degrees Celsius. Tando's coldest days, in a symphony of opposites, are in January, when the thermometer settles at a composed 12°C..

The site designated for our wind mast beckons with an expanse that is as flat as it is unhindered by obstructions, allowing the wind to traverse freely, contributing to the veracity of our data collection efforts.

3.3.12 Umerkot, Sindh

Umerkot is situated in Sindh. It has an elevation of 17 m and the wind mast is located at flat terrain with no nearby obstructions. The temperature range of the area is 12° C to 41°C.

3.4 ERA-5 Reanalysis

The European Centre for Medium-Range Weather Forecasts (ECMWF) presents ERA5, the gold standard of modern climate reanalysis. ERA5 is like opening a chest of knowledge since it reveals a history of the atmosphere, land, and sea on an hourly basis. Estimates of inherent uncertainties provide depth to this compendium and herald in a new era of all-encompassing knowledge.

The Climate Data Store, which provides access to ERA5's well-organized data, is important to this achievement. This information is presented in a very neat grid format, with a typical resolution of 0.25 degrees latitude and longitude. These grids provide an abundance of atmospheric data, covering an amazing 37 different pressure levels.

ERA5's immediate benefits are one of its most notable features. A significant achievement in the field of real-time meteorological observation, it provides daily updates, offering a snapshot that is only five days removed from the present. The historical depth of this dynamic accessibility goes all the way back to 1940, when data archives were first discovered.

3.5 Geospatial data

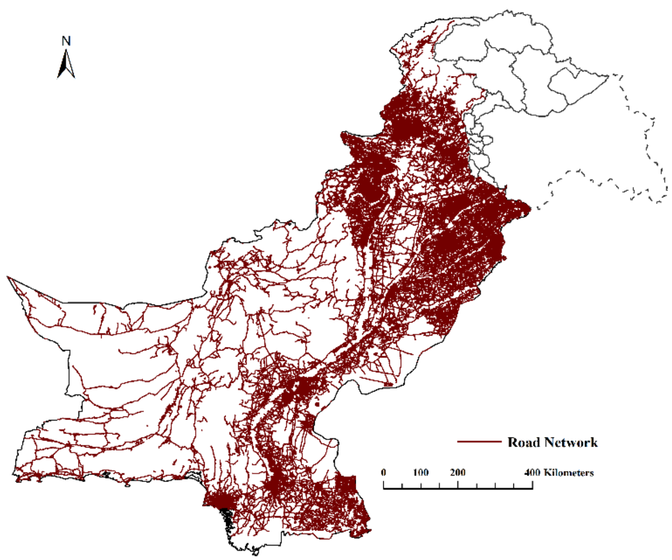
The maps of the geospatial data sets used in this study are presented in Figure 7 and their details with their respective sources are given in Table 3.

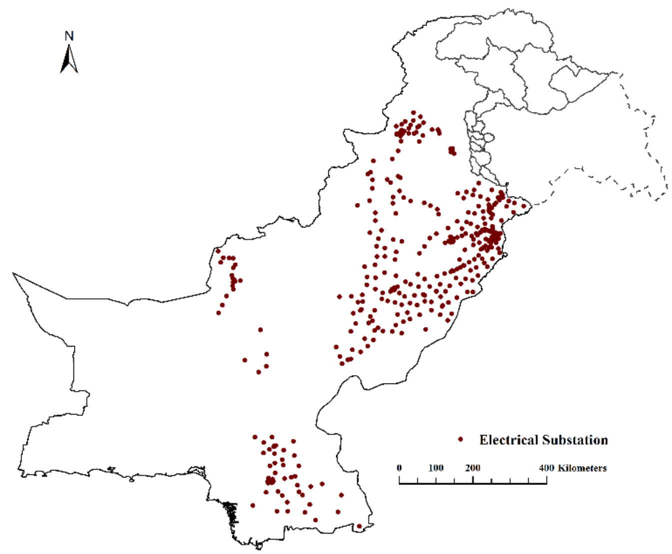
Table 3. Geospatial datasets used in the study

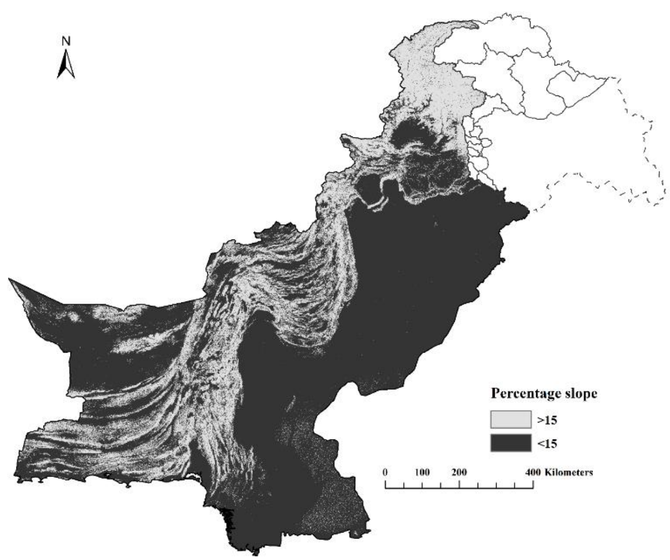
Data type	Data format	Spatial resolution	Source
Slope (Digital surface model) and elevation	GeoTIFF	30m × 30m	https://www.diva-gis.org/datadown
Land cover	NetCDF	300m × 300m	(C3S-LC, 2021)
Population density	Raster	1km × 1km	(WorldPop and CIESIN,

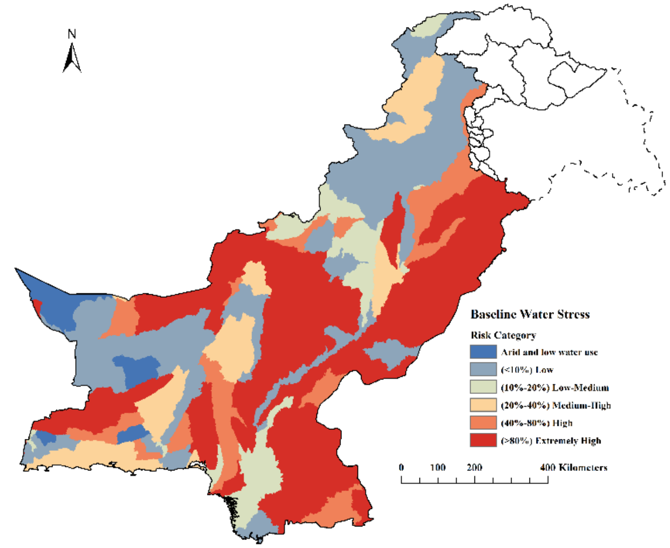
	2020)

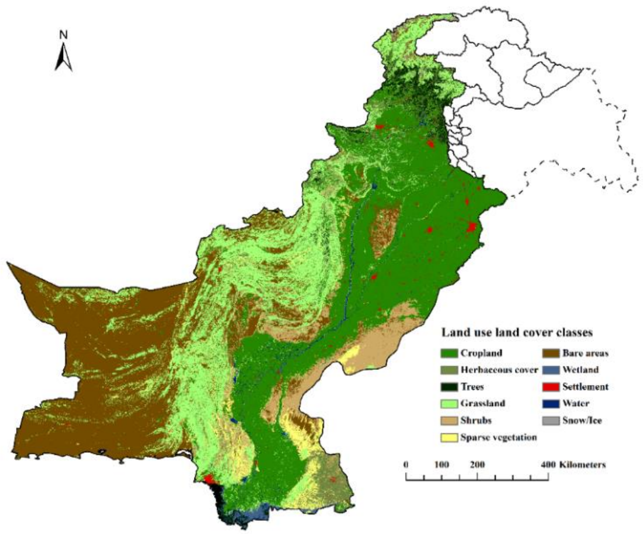
[a]The vector layers (points, polylines and polygon features) were later converted to raster on the same resolution of LULC i.e. 300m x 300m


N
Road Network
0 100 200 400 Kilometers


N
Electrical Substation
0 100 200 400 Kilometers


N
Percentage slope
>15
<15
0 100 200 400 Kilometers


N
Baseline Water Stress
Risk Category
Arid and low water use
(<10%) Low
(10%-20%) Low-Medium
(20%-40%) Medium-High
(40%-80%) High
(>80%) Extremely High
0 100 200 400 Kilometers



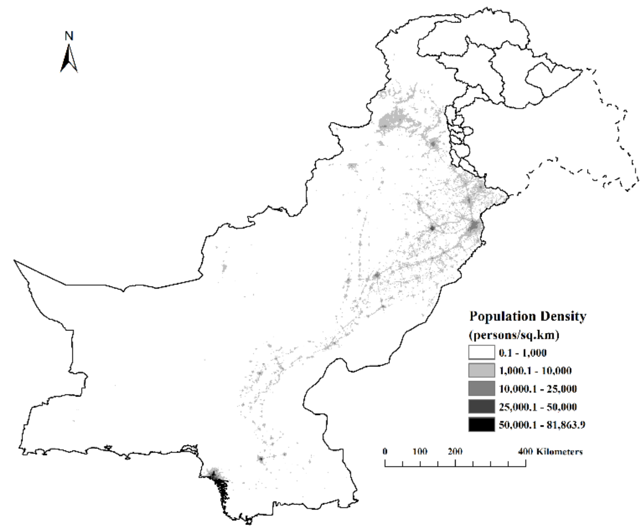


Figure 6. Geospatial Datasets Used in Studies

LULC Land use data is provided by European Space Agency-Climate Change Initiative (ESA-CCI) for the year 2020, was taken which is having resolution of 300m*300m and contained 22 classes. Reclassification of this data was done (C3S, 2021) to group various classes as given Table 4.

Table 4. Reclassification of LULC for land suitability

	Class Name	Class Description
1	Cropland	Rainfed cropland, Irrigated cropland Mosaic cropland (>50%) natural vegetation (tree, shrub, herbaceous cover) (<50%)
2	Shrub/Grass/Herbaceous	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (< 50%), Mosaic tree and shrub (>50%) / herbaceous cover (< 50%), Mosaic herbaceous cover (>50%) / tree and shrub (<50%), Shrubland, Grassland
3	Trees	Tree cover, broadleaved, evergreen, closed to open (>15%), Tree cover, broadleaved, deciduous, closed to open (> 15%), Tree cover, needle-leaved, evergreen, closed to open (>15%), Tree cover, needle-leaved, deciduous, closed to open (>15%), Tree cover, mixed leaf type (broad leaved and needle leaved), Tree cover, flooded, fresh or brackish water, Tree cover, flooded, saline water
4	Sparse vegetation	Sparse vegetation
5	Bare Areas	Bare areas
6	Settlement/Urban	Urban
7	Water	Water
8	Snow/ice	Permanent snow or ice

3.6 Resource mapping

All the calculations were conducted using Microsoft excel (2021) along with ArcGIS 10.8 (ESRI, 2020) software to develop the desire shape file for data set.

3.6.1 Site suitability

The geospatial site suitability analysis of wind depends upon the following steps:

i. Selection of factors to be incorporated in the analysis,

a. Development of land suitability maps such as slope, elevation
b. Development of wind speed profile map from data set of 20 years

b. other factors e.g., road and Transmission Network Map etc.

ii. Processing data for site suitability by AHP

a.Giving the chosen parameters a priority and relative class weights, and

b. ArcGIS (weighted overlay) is used to create maps of suitability.

These steps are discussed in detail in the following sub-sections.

3.6.1.1 Preparation of thematic maps for site suitability

Distance from transmission lines becomes a critical factor after wind speed mapping is completed. After collecting information on transmission lines, we use that information to establish a series of buffer zones at distances of 0.5 km, 1 km, 3 km, 6 km, and 12 km. In parallel, Pakistan's road system (here depicted as a series of complex polylines) is acquired. The same buffer strategy is used, this time with distances of 1, 2, 3, and 5 kilometers. Weighted overlay analysis, as described by Waewsak et al., is made easier by these buffers (2020).

Land use classification is also very important to our site selection process. Wetlands, metropolitan areas, bodies of water, and areas with prolonged snow or ice cover are not considered feasible possibilities because of their incompatibility with human activities. Barren places, agricultural lands, shrub/grassland/herbaceous territories, arboreal domains, and sparsely vegetated areas are the five additional types of land use.

A final land use and land cover (LULC) map is produced by applying further exclusions; this map is a crucial input for the Analytic Hierarchy Process (AHP). The refinement procedure that results in the final LULC map is directed by the exclusions described in Section 2.3.2. Figure 4 provides a visual illustration of this complex procedure.

3.6.1.2 Exclusion Criteria Applied on Different Maps

Various factors were incorporated for the exclusion in wind speed and LULC map. This included future expansion of urban areas, slope, surface water bodies. Future urban area growth, slopes, and surface water bodies were all incorporated. Using the (Urban areas) Settlement class from ESA-CCI Land cover, future urban area expansions were removed from the LULC map. The underlying population in these urban communities was identified using population density (WorldPop and CIESIN, 2020) to predict their growth to accommodate the future population. Considering 25 years' service life of the wind power plant, percentage increase in population was calculated using Eq. (2).

$$Percentage\ population\ increase = \frac{P_{2045} - P_{2020}}{P_{2020}} \qquad (2)$$

The entire estimated population of Pakistan for the years 2020 and 2045, respectively, is taken as P2020 and P2045 (UN, DESA, 2019). The extension of the corresponding urban settlements was then shown using the QGIS plugin utilizing the population of the key urban regions that had been retrieved.

Mountain peaks, plateaus, and alluvial plains constitute all part of Pakistan's due to its diversified topography. According to Chukwuma et al. (2021), sites with slopes more than 30% were omitted since building there is difficult and expensive. Pakistan's terrain's slope was calculated using data from the ALOS world 3D - 30m digital surface model.

Wind Map is generated from the ERA-5 Copernicus data set and 20 year average map is generated and the areas having wind speed less than 4m/s were excluded from the wind map. As energy generated from these areas is very low.

3.6.1.3 AHP for site suitability

The Analytic Hierarchy Process (AHP) stands as a robust decision-making methodology, orchestrating the identification of essential criteria and quantifying their relative significance. Delving into the intricacies of employing AHP, a comprehensive framework emerges as outlined in literature (Saaty, 2008).

The inception of this process within our study revolved around the objective of gauging site suitability for residue-based power plants. This pivotal aim fueled the initiation of the AHP procedure. Subsequently, a systematic hierarchy was meticulously constructed, sculpting the framework for the development of distinct criterion factors, as elaborated upon in section 2.3.1.

Central to this process was the creation of a pair-wise comparison matrix. This matrix served as the fulcrum upon which the chosen criteria were balanced and assessed. This foundational step galvanized the subsequent stages of the AHP methodology.

and is shown in Table 5.

Table 5. Pair-wise comparison matrix of main criteria factors

	Elevation	**Slope**	**Distance from road**	**Land use**	**Distance from Grid station**	**Elevation**
Elevation	1	0.33	0.33	0.33	0.2	0.11
Slope	3	1	1	1	0.3	0.14
Distance from road	3	1	1	1	0.3	0.14
land use	3	1	1	1	0.3	0.14
Distance from Transmission line	5	3	3	3	1	0.2
Wind speed	9	7	7	7	3	1

Relative weights were assigned to each criterion using a 1-to-9 scale, 1 being the least and 9 being the most important, in the above table.
As shown in Figure8 AHP scale for criteria weighting, relative weights were assigned to each criterion using a 1-to-9 scale, with 1 being the least important and 9 denoting the most significant.

Intensity of weight	Definition
1	Equal importance
3	Weak/moderate importance
5	Essential or strong importance
7	Very strong or demonstrated importance
9	Absolute importance
2, 4, 6, 8	Intermediate values between two adjacent values

Figure 7. AHP Scale

Table 6. Input Sub criteria for Geospatial Suitability Analysis

Criteria	Unit	Sub-Criteria	Score
Wind Speed	m/s	4.0-5.1	1
		5.1-5.6	3
		5.6-6.0	5
		6.0-6.4	7
		>6.4	9
Distance from Road	km	0.1 to 1	9
		1 to 3	7
		3 to 5	5
		5 to 10	3
		>10	1
Land Use		Bare Land	9
		Sparse Vegetation	7
		Shrub/Grass/Herbaceous	5
		Cropland	3
		Treecover	1
Distance from Transmission lines	km	0.5 to 1	9
		1 to 4	7
		4 to 6	5
		6 to 12	3
		>12	1
Slope	%	0-6	9
		6 to 12	7
		12 to 18	5
		18 to 20	3
		Extremely High (>20%)	1
Elevation	m	150-281	1
		281.1-462	3
		482.1-649	5

	649.1-835	7
	835.1-1050	9

The pair-wise comparison matrix's eigenvector was then used to generate the criterion weights. The following equations were used in consistency checks to evaluate the accuracy of assigned and computed weights (Aly et al., 2017). Eq. (3) is used to obtain the consistency index (CI).

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad (3)$$

Where n is the size of the matrix or the number of components, and _max denotes the highest eigenvalue. The Consistency Ratio (CR) was then determined using Eq. (4) utilizing this CI

$$CR = \frac{CI}{RI}$$

Where RI is the random index, Saaty (2008) estimated and provided the average of the CI values for random matrices of the same size.

3.6.1.4 Weightage Overlay

ESRI's ArcGIS Desktop 10.8's weighted overlay tool was used to perform AHP after the relevant data had been downloaded, maps had been created, and the selection criteria had been specified. For vector feature data, like where substations and roads are located, buffers were created for various distance ranges. Afterward, these thematic layers were converted into raster layers so that they would all have the same data format and coordinate system for use in a GIS implementation that allows for the overlay of thematic layers. The raster layers developed for AHP are processed using ArcMap's weighted overlay feature.

A scale value was applied to the input weightings of the sub-criteria, and a percent weighting scheme was applied to the final weightings in the pair-wise comparison matrix. Values in the resulting raster range from zero to nine, with zero indicating the least acceptable and nine indicating the most appropriate, and the sum of all effects should be one hundred. Sites with pixel values between 0 and 1 were considered the least suitable, those with values between 2 and 3 were considered somewhat suitable, those with values between 4 and 5 were considered fairly suitable, and those with values between 8 and 9 were considered highly suitable.

Table 7. Input weights assigned to sub-criteria factors

Intensity of weight	**Definition**
1	Equal importance
3	Weak/moderate importance
5	Essential or strong importance
7	Very strong or demonstrated importance
9	Absolute importance
2, 4, 6, 8	Intermediate values between two adjacent values

The weights of criteria were then calculated as the eigenvector of pair-wise comparison matrix. To check the reliability of assigned and calculated weights, consistency checks were performed using the following equations (Aly et al., 2017). Consistency Index (CI) is calculated using Eq. (11)

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (11)$$

Where n is the number of factors or size of matrix and λ_{max} is the maximum eigen value. This CI was then used to calculate the Consistency Ratio (CR) using Eq. (12).

$$CR = \frac{CI}{RI} \quad (12)$$

Where RI is random index, an average of CI values calculated for random matrices of same size, calculated, and given by (Saaty, 2008)

3.6.1.5 Weighted overlay

Following the formulation of selection criteria, relevant data was obtained to generate maps, which were then altered, processed, and overlaid in ESRI's ArcGIS Desktop 10.8 using the weighted overlay tool to carry out AHP. Buffers were set up for certain distances in the vector feature data that includes the road network and the placement of substations. Since using a GIS for overlapping thematic layers necessitates that all levels utilise the same data format and coordinate system, these were transformed into raster layers. ArcMap's weighted overlay tool is used to process the raster layers that have been prepared for AHP.

The input weights of sub-criteria were assigned under scale value, and the final weightages in the pair-wise comparison matrix were assigned as the percentage of influence. The sum of all of the factors having an effect should equal 100, and the resulting raster values will be in the range from 0 (the least appropriate) to 9 (the most appropriate). Pixels with values of 0 and 1 were classed as the least suitable, pixels with values of 2 and 3 as slightly suitable, pixels with values of 4 and 5 as moderately acceptable, and pixels with values of 6 and 7 as highly suitable. Information from the most promising potential sites was extracted and put to use in techno-economic analyses.

3.6.2 Techno- economic analysis

Coordinates (25.43955°, 62.54791) have been proposed for the wind farm site, and these points are equidistant from both the city's core and the new industrial zone. The local population is spread out in a fairly even fashion, while the area's main winds blow inland from the ocean over a very small mountain pass. The onshore wind flow from the ocean is amplified and accentuated by the geography of this area, making it ideal for the construction of wind farms. The World Bank's Energy Sector Management Assistance Programme (ESMAP) has collated regional wind energy statistics and made them available online for free use. The yearly minimum and maximum wind speed variability indexes of 0.77 and 1.2 in Figure S1 demonstrate that Gwadar has a large and consistent wind energy potential. The index's low variability over long time periods is indicative of the wind speed's consistency. With an RMSE of less than 0.1 on average, the long-term wind regime of the region is depicted in Figure 2. This research hints at wind patterns that are stable and low-volatile over a long period of time. Wind power is extremely location-dependent. Having strong wind speeds throughout the year makes a location economically viable for the building of wind turbines, as stated by Baloch et al. (2016). The data on wind speeds bolsters the feasibility of using wind turbines to generate electricity. The data set for Gwadar estimates the yearly average wind speed to be 4.65 m/s at a height of 80 m. This value has a standard deviation of 6.31 m/s. When wind speeds rise above 6 metres per second, the incidence rate rises dramatically. The site location is relatively smooth because there are few or no barriers present that could cause frictional resistance.

The economic evaluation and implementation of projects at a given area depend critically on the determination of wind availability and variability. Wind data at the regional level is gathered using towers of varying heights (20 m, 40 m, 60 m, 80 m, etc.). The 2018 information is collected every 10 minutes. This information is collected and used by the World Bank in their yearly report and worldwide wind maps (Anon., 2021e). Due to its location on undeveloped rural property, the suggested site location is financially viable. This has resulted in reduced expenditures for things like land acquisition and monetary compensation. As a result, the overall system expenditure decreases, and the levelized cost of power falls (LCOE). Costs for ancillary services like transmission and distribution are expected to be cheaper ifthe suggested site compared to a centralized generating system situated elsewhere.

3.6.3 Methodological Approach

Wind farm technical feasibility studies often center on pinpointing the sweet spot between wind turbine selection and wind farm layout. In this analysis, we look at the four most common kinds of wind turbines in the area. If you have to choose between several turbines, go with the one that has the highest capacity factor, lowest LCOE, and shortest payback period. There are two potential wind farm layouts being researched at the moment. It is crucial for the Jamshoro region to apply the best design plan in order to maximize capacity utilization while minimizing land use. An appropriate spacing decision that maximizes capacity factor while limiting land consumption can be determined by analyzing technical design parameters including row offset, turbine spacing, and row spacing. To determine if it is financially viable to build a wind farm, it is necessary to analyze the economies of Pakistan, India, and Iran, all of which share a similar coastal climate. It is crucial to evaluate the impact of numerous financial elements, such as inflation and debt ratio, to maintain long-term economic viability. The impact of inflation and debt percentage on the levelized cost of electricity (LCOE) and net present value is investigated through the development of an empirical model (NPV). The connection between these factors is then represented mathematically by a single equation.

The System Advisory Model (SAM), developed by the National Renewable Energy Laboratory, is used to perform the technical evaluation of a 50 MW wind farm from a performance and economical perspective (NREL). The use of wind energy (De Araujo, 2019) is a prime example of a renewable energy source that has shown positive results after being incorporated in techno-economic feasibility analyses. The wake effect and the impact of various technical parameters on the capacity factor of wind farms are just two examples of the technical variables accounted for by SAM's comprehensive models for wind farm design. Wind energy, for example, is one renewable energy source that has benefited from the use of RET Screen, another energy modelling application (Riaz and Khan, 2021). (Salehin et al., 2016). The software can verify the yearly energy output, determine economic indicators like payback period, and assess the possibility for reduced emissions of greenhouse gases.

3.6.4 Wind Resource analysis

The first step in establishing the viability of wind energy locations is the examination of wind resources in various parts of Pakistan. This requires archival data collection from weather stations or wind towers on wind direction and speed. Several factors, including wind speed, turbulence, and the distribution of wind directions, are evaluated to determine a location's potential for harnessing wind energy.

In SAM, the wind resource analysis is used to choose the turbine. Wind resource analysis is used to ascertain the true state of wind velocity at a given location. The turbine is chosen based on the data's frequency distribution.

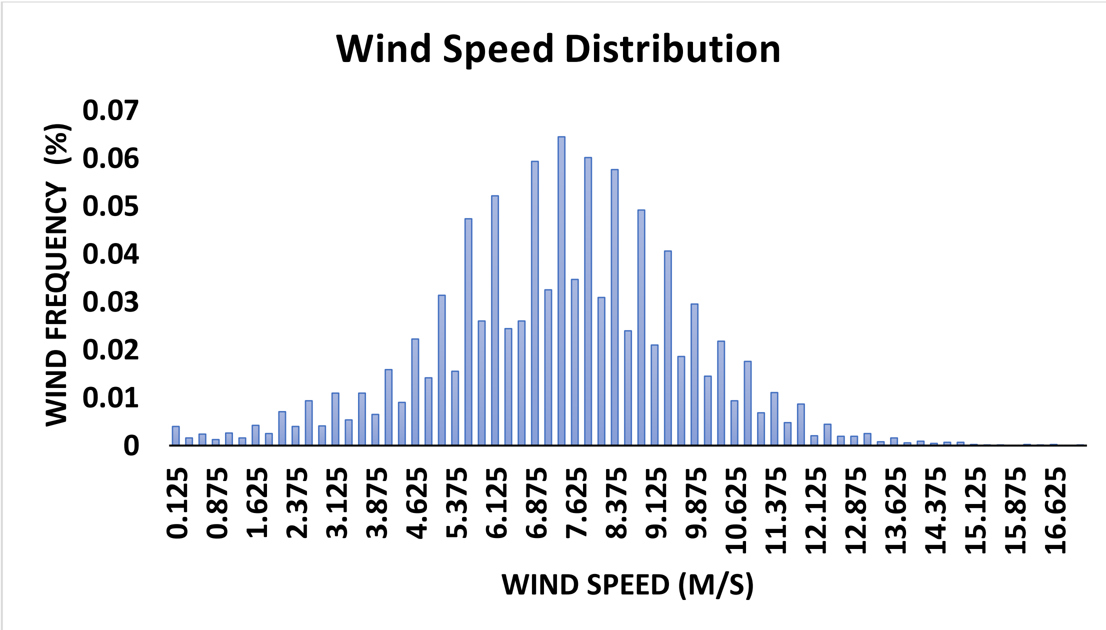


Figure 8. Wind Speed Data Distribution

3.6.5 Wind Turbine Selection and Optimization

The availability of a resource file is crucial when choosing wind turbines. Both the capacity factor and the availability of wind turbines in the area are taken into account during the selection process. The Gamesa 114-2 MW, Siemens, and Vestas turbines are widely employed in Pakistan. Table 8 and figure 10 below illustrate the maximum capacity factor and optimal turbine curve that Gamesa provided based on the data resource file.

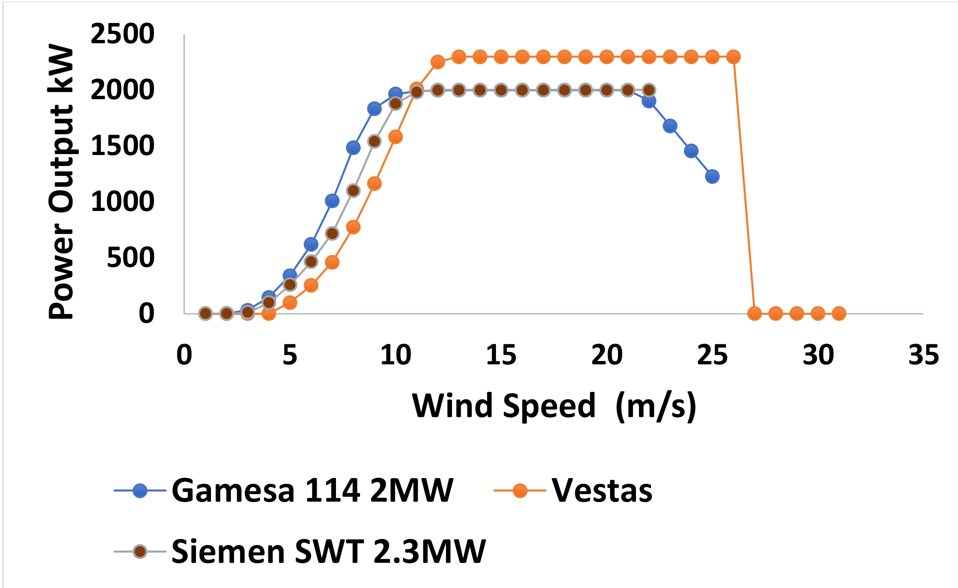


Figure 9. Wind Speed for Turbine Selection

Table 8. Capacity Factor for Wind Turbine Selection

Wind Turbine	Capacity Factor
Gamesa 114 2MW	44.2
Vestas	30.9
Siemen SWT 2.3 MW	38.1

Given the limited impact that wind farms can have, selecting the right wind turbines and then optimising them is essential. Wind turbines not only harvest the wind's kinetic energy, but their wake also reduces the velocity of the wind in the downstream direction. Downstream, the wake dissipates and normal flow conditions are restored. The wake effect describes the cumulative impact of wind speed changes caused by turbine collisions on the energy production of the wind farm. Both the anticipated impact of future wind farms and the wake effects of existing wind farms in the area must be taken into account. The wake impact can be reduced by adjusting the offset of the rows and the turbine/row separation.

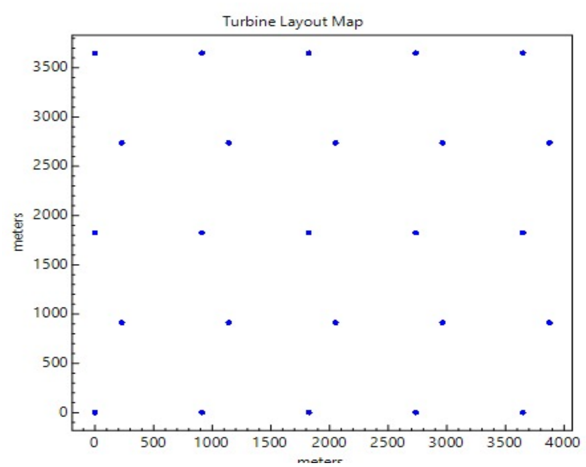


Figure 10. Optimization of Offset of Wind Farm

3.6.6 Techno-economic Analysis Model Application

After a wind farm has been optimized for various losses, economic inputs are modified based on historical case studies, and a feasibility report is generated. The process of identifying and optimizing sites for wind energy generation prompts a techno-economic analysis. Costs associated with purchasing turbines, installing them, and connecting them to the grid must be estimated. Expenses such as maintenance, supervision, and land lease agreements are considered part of the overall cost of operation. Financial models are also developed that factor in electricity rates, capacity factors, and payback dates in order to assess the project's return on investment.

The legal framework and government regulations on renewable energy, especially wind power, are critical for the viability of wind energy projects. Regulations like as net metering, feed-in tariffs, tax benefits, and renewable energy objectives all affect the financial viability of wind producing installations in Pakistan. It is important to understand the legal and regulatory environment in which wind projects are being considered.

It's worth noting that Sindh and Baluchistan, two provinces in Pakistan, are particularly well-suited to harnessing wind power. However, more accurate and site-specific information on potential wind energy locations across the country might be obtained through a comprehensive feasibility assessment conducted by professionals.

CHAPTER 4

4. RESULTS AND DISCUSSION

4.1 Wind Speed Data Validation

Data on the linear regression and correlation between hourly wind speeds are provided in the table below. In this scenario, the NRMSE values are large, from 0.11 to 0.21. This indicates that the discrepancy between forecasted (satellite) and observed (ground) wind speeds is larger in these cities. The percent nRMSE values range from 11 percent to 21 percent, representing the average deviation or error relative to the range of the ground wind speed observations. For each city, the correlation column displays the coefficient between ground wind speed data and satellite wind speed readings. This table displays a positive linear relationship between ground-based and satellite-based data of wind speed, with correlation coefficients ranging from 0.71 to 0.93. According to the table's correlation coefficients, there is some positive linear relationship between the ground-based and satellite-based data of wind speed for the cities shown. However, there are large discrepancies between the predicted satellite wind speeds and the actual ground wind speeds for these cities, as indicated by the large NRMSE and percent nRMSE values. This indicates that the satellite data likely did not faithfully capture the true wind speeds at ground level.

4.2 Identification of suitable locations

4.2.1 AHP ranked criteria

The final weights of criteria and sub-criteria factors obtained after performing AHP are presented in Table 9.

Table 9. Final weights of criteria and sub-criteria factors

City	Correlation	NRMSE	%nRMSE
Bahawalpur	0.82	0.12	12%
Islamabad	0.89	0.18	18%
Haripur	0.71	0.16	16%
Hyderabad	0.92	0.20	20%
Khuzdar	0.85	0.15	15%

Quetta	0.88	0.16	16%
Quidabad	0.84	0.14	14%
Sadiqabad	0.77	0.18	18%
Sanghar	0.91	0.15	15%
Sujawal	0.83	0.21	21%
TendoGhulam Ali	0.81	0.17	17%
Umerkot	0.87	0.16	16%

Table 10. Consistency Ratio Matrix

Criteria	Weightage Criteria
Elevation	3.65%
Slope	8.27%
Distance from road	8.27%
land use	8.27%
Distance from Transmission Line	19.84%
Wind speed	51.70%

Previous research (S. Ahmad & Tahar, 2014) suggests that the highest-weighted criterion (wind speed, at 51 percent) is the most important when it comes to the AHP's ultimate goal. Assigned that proximity to existing roads negates or reduces the need to invest in enhancing the road network for transporting residue from the field to the plant site, distance from the gearbox was given the second-highest weight (19 percent). Given that the placement of the power plant will have far-reaching environmental consequences on the area, (M. Ahmad & Zeeshan, 2022) discovered that LULC availability for site selection had a weight of 8 percent, the same as the distance from the road.

Table 11. Site Suitability Percentage Area

Site Suitability	Area km^2	% Area of Pakistan
Least Suitable	7.78	0.001
Slightly Suitable	347	0.043
Moderate Suitable	655	0.082
Highly Suitable	491	0.062
Extremely Suitable	329	0.041

4.2.2 Geo-spatial Suitability map

Together with maps depicting other criteria for site appropriateness assessments, these weights were fed into a weighted overlay technique. Figure 12 shows the reclassification of the appropriateness classes from 0 to 9 into 5 classes that resulted from the weighted overlay (Chukwuma et al., 2021). The lack of residue was the primary environmental and economic factor preventing over 98% of the land area from being used, followed by places with steeper slopes and the presence of surface water. About 0.05 percent of the country is comprised of the least and somewhat suitable places. In addition to the lack of or low energy intensity, a significant factor separating these groups is a lack of convenient access to roads and grid stations. Only about 1.05 percent of the potentially useful land is classified as "moderately" or "very" appropriate. The availability of residue was the primary barrier, despite the fact that infrastructure was not difficult to get.

Approximately 360 km2, or less than 0.04 percent of Pakistan's total geographical area, was home to the majority of the "very" and "extremely suitable" places.

4.2.3 Power plant Locations

It is to be noted in Figure 10 that wind resource always flow in the form of corridor. As one can see its making loop like pattern and clustered in few specific areas.

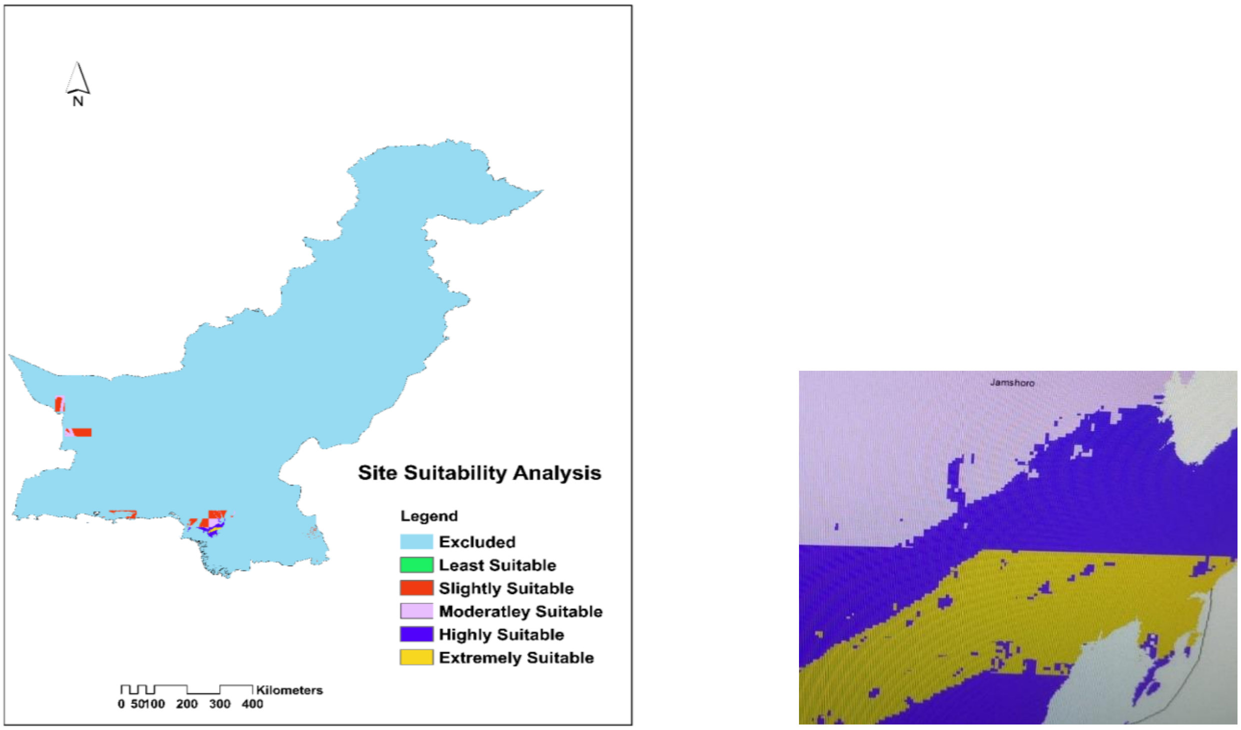


Figure 11. Site Suitability Map

4.2.4 Techno-economic assessment

In this section, we give the outcomes of the techno-economic analysis carried out on the chosen site. Table 12 displays the most important findings from the power plant's technical and financial evaluation. Up to 621 GWh of power can be produced annually if an input of 80 MT/h of straw into the boiler is combined with surplus supplied air. About 70 MW of power can be generated from the plant's steam.

Table 12. Technical and Financial parameters

Technical parameter	Value	Unit
Annual electricity generation		
Plant capacity		
Boiler feedwater usage		
Capital cost	78 million	US$

PDC	3.515 million	US$
NPV	21,195,536 $	$
Gross margin	15.56	%
Return on Investment	15.99	%
Payback Time	7.9	Years
IRR (after tax)	15	%

The net present value (NPV) is a metric used to assess the profitability of investment projects by adding up all cash inflows and outflows over the life of the project. If the net present value (NPV) of the project is more than zero, then the project is profitable. The economic analysis shows that the project's NPV is quite promising. Using a balanced debt-equity structure, the equity-based model depicts the expected return on capital.

rate of return (IRR) over the project's lifetime. In financial analysis, the discount rate used to determine whether or not a project is viable is the internal rate of return (IRR). Since a higher IRR is indicative of greater profitability, it can be used as a metric to rank potential investments. This research yielded a greater internal rate of return (IRR) than the minimal IRR recommended by (NEPRA, 2021). In general, a project is considered feasible if its internal rate of return (IRR) is greater than the discount rate employed in financial analysis (usually the expected rate of return). Since a higher IRR indicates greater profitability, it can be used as a comparative tool when weighing various investment options. This study's IRR is higher than the minimal IRR suggested by (NEPRA, 2021) for biomass-based power projects in Pakistan (which is 15%).

The project's budget and funding resources may play a role in determining whether techno-economic aspects will be implemented. It is recommended that when presenting a financial analysis to others, both a short payback period and a high internal rate of return (IRR) be taken into account. The project's budget and available funds may have an impact on which technological and economic factors are implemented. The payoff is guaranteed to be smaller if the payback period is shorter, and the ROI will be larger if the internal rate of return is higher. Therefore, comparing these two aspects with others is recommended for a complete financial analysis.

CHAPTER 5

5. CONCLUSION AND RECOMMANDATION

5.1 Conclusion

In this study, a methodology was developed to identify suitable locations for wind power plants in Pakistan, by utilization of ERA-5 Reanalysis data along with other geospatial datasets and integration of Analytical Hierarchy Process (AHP) and Geographical Information System (GIS) techniques. The study concludes that the most appropriate site for wind farm development is in the province districts. Moreover, the electricity generation potential of selected site at Jamshoro, estimated to be approximately 193GWh is enough to reduce the electricity shortfall in the country by 10.

The electricity generation potential is the most important factor in site suitability, followed by road accessibility and Land Use Land Cover (LULC) type available. About 90% of the total landscape of a country is excluded from analysis due to environmental and economic constraints. Only 150 km2 (<1%) falls under extremely suitable areas, located in district of Sindh.

Besides optimally siting the power plant, the economic evaluation indicates that other parameters are quite significant as well. There has been much talk around the issue of operational and technical staff unavailability when it comes to operate the wind farms but as seen from the results, they don’t have more influence on the performance.

5.2 Recommendations

Based on the analysis carried out in this study, following recommendations are formed:

- The wind speed availability is of vital importance in assessing the potential, detailed localized survey must be done for more accurate valorization for power generation.
- More factors relating to social and economic prospects should be considered for power plant site suitability.
- Techno-economic analysis under varying financing schemes should be carried out.

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