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Towards Sustainable Energy Generation: Analyzing Wind Power Potential, Financial Viability, and Environmental Friendliness at Nok Kundi, Balochistan

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Abstract

Pakistan is blessed with versatile renewable energy resources, solar and wind energies. Coastal areas of Sindh and Balochistan are the richest sources of wind energy, where adequate wind speeds are available for electricity generation. The Nok Kundi region of Balochistan has outstanding year-round wind speeds and tremendous potential for wind power generation. This study explores wind power potential, financial viability, and mitigation of carbon footprints. In this regard, simulations on the analysis of wind power potential, and financial viability are conducted in the ETAP and HOMMER software respectively. The data regarding the energy demand of Nok Kundi is obtained from Quetta Electric Supply Company (QESCO) Quetta and the data on wind speeds is obtained from the World Weather Online platform. The ETAP software is used to conduct the load flow analysis of a grid-connected system. The full financial analysis considered the state-of-the-art wind power installation site of 40 megawatts capacity to meet Nok Kundi's energy demand. Furthermore, the simulations are conducted in two scenarios i.e. isolated and grid-connected systems. Financial assessments (including the calculation of required capital and operating expenses) are conducted for both isolated and grid-connected systems by using HOMER software. According to the findings of the research, the grid-connected system provided significant benefits in terms of revenues and seamless grid connections. The proposed wind power plant can potentially help reduce the carbon footprints. The present research concluded that the proposed wind power plant can produce 47,581,913 kWh/year and at the same time can mitigate the generation of 47.20 million Kg of carbon/year and an average of 3.93 million Kg/month. This research contributes to providing a detailed feasibility of wind power plants from financial and environmental perspectives. This study addresses Sustainable Development Goal# 13 (SDG 13: Climate Action).

Keywords: Wind power generation, Feasibility analysis, Load flow analysis, Windmills, Grid-tied system, renewable energy, SDG 13

INTRODUCTION

Most of the electrical energy is produced through the combustion of fossil fuels (oil, coal, gas) and they also cause the emission of greenhouse gases which are dangerous to the environment of the planet (Ghenai et al., 2017). Consuming fossil fuels, which harm the planet and quickly run out of supply, serves as the main source of energy in today's societies. Since climate change is been a concern for the whole world for the past few decades and this is the reason the consumption of fossil fuels in the energy generation sector is being reduced day by day. This is the reason, renewable energy has attracted the attention of the energy sector due to its eco-friendliness (Ahmed & Mahammed, 2012; Hussein, 2016; Messaoud & Abdessamed, 2011). Based on the data presented in the Economic Survey for the year 2020-21, hydropower generation increased its energy contribution to the energy mix by 26% from July to April of the year 2021. The amount of electrical power produced from Re-Gasified Liquefied Natural Gas (RLNG) has increased by 91.66% and has now reached a capacity of 7,325 MW/year (TIN, 2021). These power generation methods are associated with high costs.

Therefore, many countries are moving towards renewable sources of energy because of their positive environmental impacts (Hussein, 2016). Renewable energy sources can play a significant role in the achievement of growing energy needs and they can potentially decrease the consumption of fossil fuels which are being used in energy consumption (Shalby et al., 2022). Among the various kinds of renewable energy sources, wind energy is one of the reasonable sources that require less investment initially (Teshnizi et al., 2021). Renewable energy sources, including wind, hydroelectric, solar, and biomass might be regarded as affordable, dependable, safe, and capable of supplying power to an ever-growing population (Ishfaq et al., 2018). Wind energy can potentially meet the increasing demand for energy (Benatiallah et al., 2010) and wind power generation is observed to be increasing (Kumar et al., 2010).

In an effort to generate electricity, the Pakistani government has teamed up with China as part of the China-Pakistan Economic Corridor (CPEC) initiative. Their joint focus is on implementing wind energy projects to tap into the power of wind (Reve, 2017). Alternative Energy Development Board (AEDB) conducted a project called the Rural Electrification project in southern Baluchistan which consists of 7 wind sites that include Nok Kundi having a wind potential surpassing Gharo, Sindh by 50%. Nok-Kundi is a perfect wind passage for construction projects since it has speeds of wind that are about 12.5% greater than normal (Khan, 2013).

Currently, the government has shown commitment to using renewable energy resources for electricity generation. During July-April FY2022, there was an increase in renewable energy share as compared to the previous years. A share-by-share comparison of various power production sources is provided in Figure 1 (a) and (b) (Ministry of Finance, 2022).

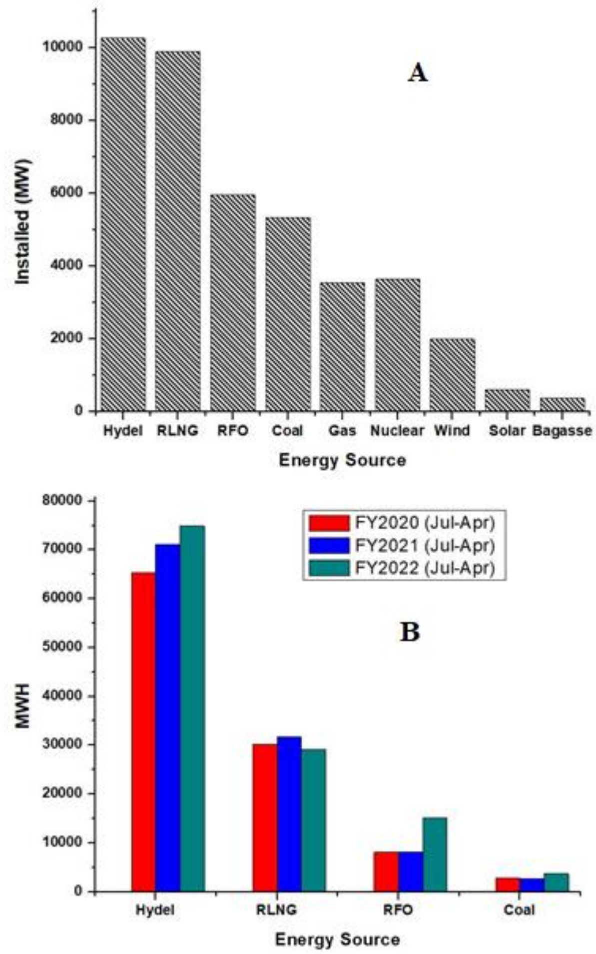

Figure 1. (A) Energy mix of Pakistan in FY 2021-2022 and (B) Combined energy generation sources in FY 2021-2022. (Source: (Ministry of Finance, 2022)

Electricity deficit remained a serious problem in Pakistan but rather than utilizing its renewable resources this country depended upon fossil fuel to meet its electricity demand. National Renewable Energy Laboratory (NREL) analyzed wind power production in many areas of Baluchistan and found that these areas have potential ranging from average, to good. That study suggested that before beginning any massive wind power-generating projects in certain Baluchistan regions, a modest wind farm should be established to evaluate its performance (Reve, 2010).

There are locations in Baluchistan that have potential for wind energy especially along the coastal belt and, in the Nok Kundi region. These areas range from having moderate to wind energy potential. Such places, nonetheless, have yet to be thoroughly examined. In Baluchistan province, there are areas, with wind currents that can be harnessed to generate power. Surprisingly, despite these circumstances, Pakistan continues to acquire power from Tehran at a cost for these specific locations. The investigation of the generation of wind energy in standalone and interconnected systems would not only assist the Nok Kundi area in meeting its needs but will also assist Pakistan's national power grid in lowering its electricity deficiency.

LITERATURE REVIEW

If we take a glance at our neighbouring countries, a lot of research work on wind potential will appear. Wind energy potential needs to be developed at the regional level, as documented by numerous published research papers. Researchers investigated the wind characteristics of Kiribati using the Weibull parameters (Mostafaeipour, 2010) and discovered the moment method (MM) is the most precise. (Hulio et al., 2017) examined the wind parameters and power potential at Nooriabad (Pakistan) using five ways to improve the reliability of the Weibull parameter. The authors examined the wind resource in Chad, a country in north-central Africa, applying the Weibull probabilistic function (Soulouknga et al., 2018). Iranian researchers contributed to the estimation and evaluation of wind potential in various places of Iran at various heights (Mirhosseini et al., 2011; Mohammadi & Mostafaeipour, 2013; Mostafaeipour, 2010; Mostafaeipour et al., 2011, 2013). Furthermore, a researcher examined the wind potential for Tehran city based on eleven years of data on wind speed (Soulouknga et al., 2018).

Numerous researchers from Pakistan have evaluated the wind power potential of different geographical areas of Pakistan. For example, Ullah et al. (2010) carried out a potential assessment of the Kati Bandar area located in the southern coastal areas of Sindh, Pakistan, they concluded that the average wind speed across the year is 7.16m/s at a height of 50m above the ground (Ullah et al., 2010). Baloch et al. (2016) discussed the status and potential of Pakistan to generate electricity by wind resources (Baloch et a., 2016). Hussain et al. (2017) worked on the calculation of the power potential of Nooriabad, Sindh, Pakistan, and carried out an extensive calculation on wind potential and it was found that the area has a sufficient wind potential available and is suitable for the wind power plant installation. The results of the economic assessment showed that electrical energy generated at this location will cost 0.02189 USD/kWh (Hulio et al., 2017b). Asghar et al. (2022) analyzed the wind potential of different four zones of southern Sindh (Asghar et al., 2022). Gul et al. (2019) calculated the wind power potential for Hyderabad, and Sindh, and used the probabilistic approach to analyze the wind potential and financial assessment for the wind power plants. The energy cost in Hyderabad was calculated ranging from 19.27 to 32.80 USD/MWh (Gul et al., 2019). Wadho et al. (2023) modelled a large-scale wind farm by using MATLAB and discussed the simulation-based study of different faults and their effects on the dynamic behavior of Wind turbines (Wadho et al., 2024). Shoaib et al. (2017) performed the calculations of the wind power potential of the Baburband location in Pakistan, the researcher used the Weinbull Distribution method to calculate the wind power potential and important distribution parameters using different statistical methods like Energy Pattern Factor Method (EPFM), Method of Moment (MoM) etc. (Shoaib et al., 2017).

Himri et al. (2008) calculated the wind power potential of three wind sites in Algeria and found that the wind speeds were adequate for energy generation during the daytime (Himri et al., 2008). Using wind power density data, the study analyzed the distribution and intensity of onshore wind resources on a continental, national, and international scale. Five regions were found to have significant hotspots of plentiful wind resources: northern/northwestern Europe, northern Asia, southern South America, central-south-eastern Asia, and central-northern North America. These areas were reported to have excellent, outstanding, and superb wind power density ratings and makeup about 3% of the world's land area. Asia is the continent with the greatest potential for wind energy, followed by North and Central America, South America, Europe, Africa, Australia, and Oceania. Eight countries including China, Canada, the US, Argentina, Russia, Chile, Norway, and Afghanistan are known as wind potential epicentres. These results guide large-scale wind power installations worldwide, facilitating the shift towards a carbon-free economy (Bandoc et al., 2018). Ucar and Balo (2010) analyzed the dominating wind directions, mean wind speeds, wind potential, and frequency distributions, this research investigated the viability and potential of wind energy resources in Turkey's coastal regions. The average mean wind speed is higher in Balıkesir and Çanakkale. The scale parameter (c) fluctuates between 2.52 m/s and 8.34 m/s annually, whereas the Weibull shape parameter (k) ranges from 1.54 to 1.86 annually. Using four wind turbines with capacities of 600 kW, 1500 kW, 2000 kW, and 2500 kW, the study performed a technical evaluation of power generation and determined the annual energy output and capacity factor (average output divided by max. power capacity of the turbine) for each turbine (Ucar & Balo, 2010).

All the above studies have been carried out for the wind potential assessment of the different regions of Iran and Pakistan. On the other hand, only the wind potential of the Sindh province of Pakistan has been analyzed extensively so far, but on the other hand, some potential sites of Balochistan are yet to be analyzed which are equally rich in terms of wind potential. In previous studies as discussed above, the researchers have focused on the wind potential calculations and the feasibility analysis of wind turbines only, and most of the research is focused on the potential of the Sindh wind corridor. This study reveals the wind potential of a new wind corridor present in Balochistan and provides a complete package of wind power generation for that location. This research focuses on the calculation of wind potential, load flow analysis, and financial analysis of wind farms by developing an aggregate wind power plant model for the selected wind site considering its load requirement. Additionally, carbon footprint calculations are a novel approach of this study which completes wind power plants' overall feasibility along with its environmental impact.

MATERIALS AND METHODS

Figure 2 depicts the research methodology. This research activity is carefully divided into various steps as follows:

1. Site Selection: Nok Kundi Area of Balochistan is considered for the Wind Power Plant installation because of its adequate wind power potential.
2. Data Collection: Load and Wind data has been collected from the sources mentioned in the abstract.
3. Load Flow analysis: A load flow study of the proposed system has been carried out using ETAP software.
4. Financial Analysis: Financial analysis has been made on the basis of two system models, grid-connected and isolated models
5. Comparison: A comparison of the system has been done on the basis of per-unit cost.
6. Environmental impact analysis: Carbon footprints have been calculated on the basis of the energy generated by the proposed system.

Data Collection

In the present research paper, two datasets are used: One data set consisted of the electrical load data of Nok Kundi which is obtained from the Quetta Electric Supply Company (QESCO) office in Quetta. By using the electrical load data, an aggregate wind model is developed using ETAP Software for the electrical load flow analysis of the proposed wind farm. The second dataset contains wind speed and it is collected from worldweatheronline.com (WWO, 2024). The discussed variables (electrical load of Nok Kundi and wind speed) of data are collected from the previous three years.

Data of Wind Speed

Wind speed is one of the main factors which is highly considered when a site is selected for the installation of a wind farm. The contribution of wind speed factor while selecting a site is reported to be 90% (Bastidas-Salamanca & Rueda-Bayona, 2021). In this regard, at very first the wind speed of the site is collected and

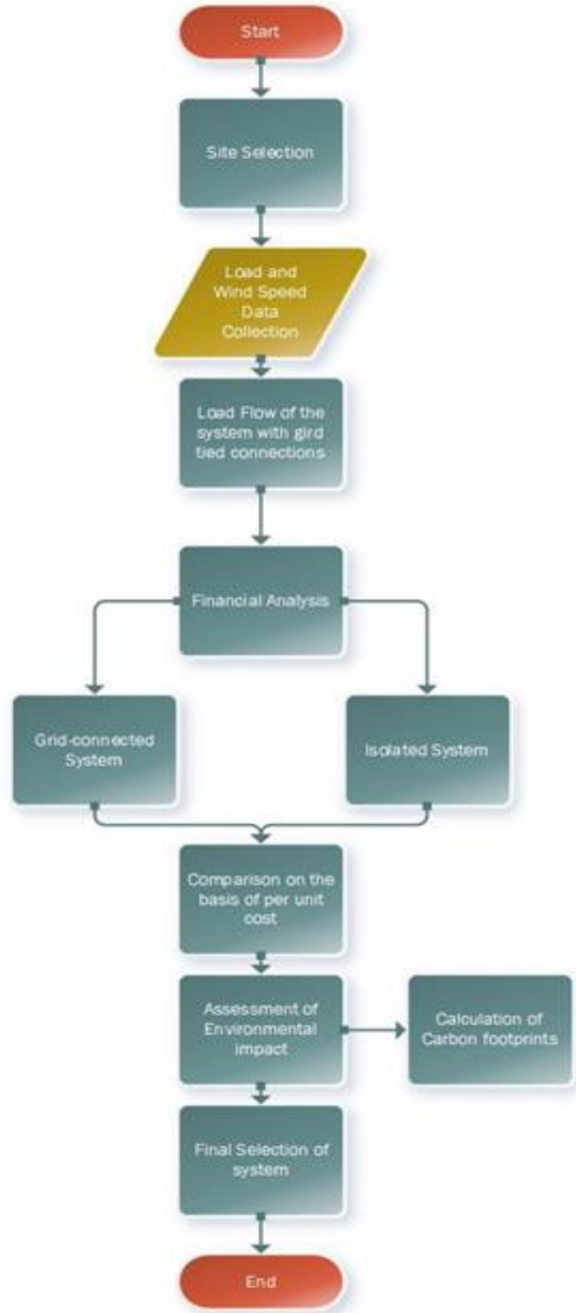

Figure 2. Flowchart of Methodology

the authors came to know that the wind potential of Nok Kundi is suitable for wind electricity generation because the typical wind speed is about 16.5 Km/h. The capacity factor of 51.2% is considered for power generation by wind turbines. The mean wind velocity in Nok Kundi is recorded as 16.5 Km/h at an altitude of around fifty meters during the year. The analysis also shows the fastest winds throughout the summer season as given in Figure 3.

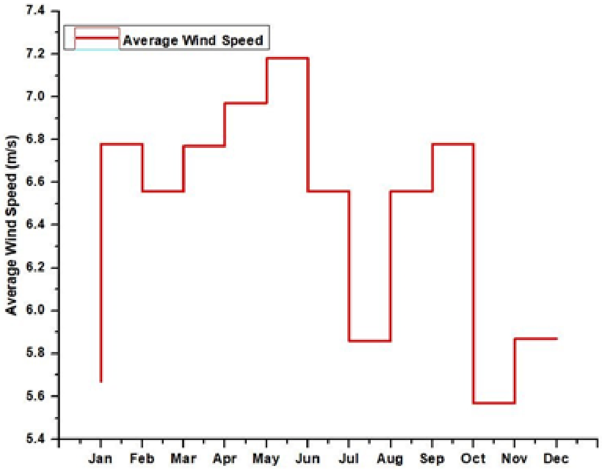

Figure 3. Annual average wind speed at Nok Kundi (Source: (Ministry of Finance, 2023)).

The wind speed data for the past three years shows that the average wind speed is more than sufficient to generate a handsome amount of electricity throughout the year (see Figure 4 A). It has been calculated that average wind speeds of 16.05 Km/h, 14.9 Km/h and 15.125 Km/h are available throughout the years 2021, 2022 and 2023 respectively. The summer months are found to be windy every year as compared to the winter as depicted in Figure 4 A and B.

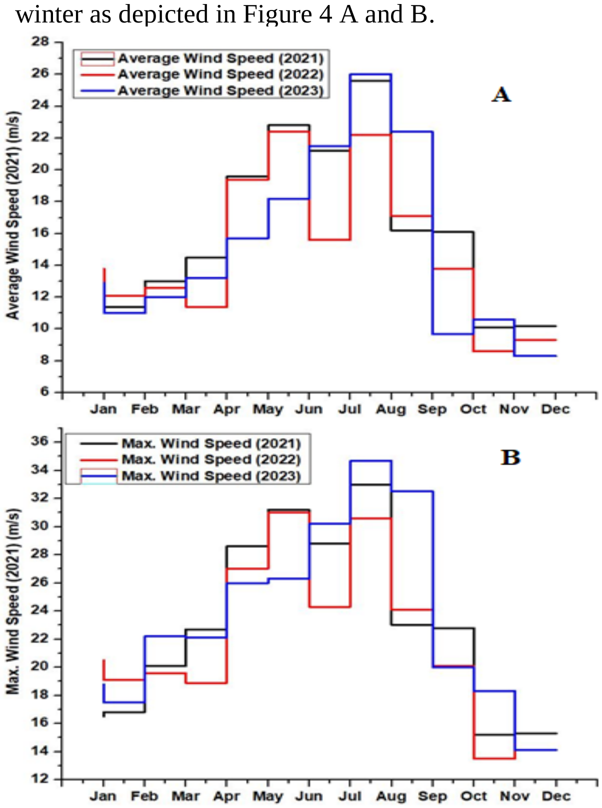

Figure 4. Average wind speed (A) & Maximum wind speed (B) from 2021 to 2023 at Nok Kundi area Baluchistan (Source: (WWO, 2024)).

Nok Kundi Estimated Load

Nok Kundi is situated in the district Chaghi of Baluchistan near Dalbandin as shown in Figure 6 with coordinates 28° 049.6N, 62° 045.0E. The wind potential of Nok Kundi is suitable for wind electricity generation because the typical wind speed is over 6.4 m/s (WWO, 2024). The average and maximum wind speed at the Nok Kundi area of Baluchistan is collected from 2021 to 2023 as given in line charts (see Figure 3 to Figure 4) plotted from Origin software which is used to visualize the collected data.

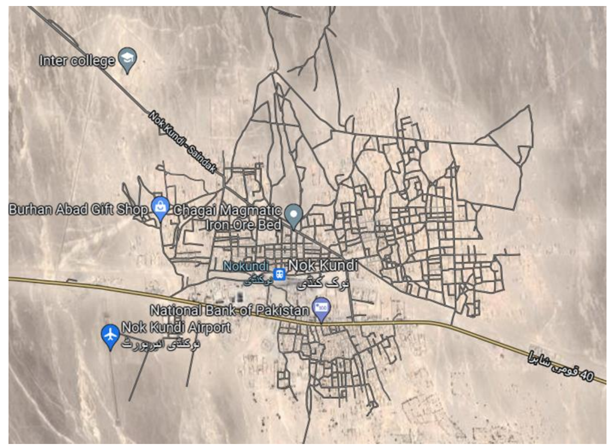

Figure 5. Nok Kundi City Balochistan (Courtesy Google map) (Captured on: 12-20-2022).

According to the Population Census Report 2017, the population of Nok Kundi is about twenty-three thousand with almost ten thousand homes (Pakistan Census 2017 report) (PBS, 2017). According to QESCO report the average load of the Nok Kundi region is about 11MW with the peak load in the summer being about 18MW.

Calculations and Cost Assessment

The following equations are used for the calculation of the costs of wind turbines since it is important to analyze the cost factor in order to prepare the feasibility (Fazelpour et al., 2017; Khahro et al., 2014). Suppose that s is the life span of the wind turbine, C_{om} is the operation and maintenance cost (1.5–2% of wind turbine cost (Fazelpour et al., 2017; Mathew, 2006)) and I_c is an initial investment, then the discount operation cost is equal to the present cost and can be calculated as follows.

$$PC(C_{om})_{(1-s)} = nI_c \frac{(1+r_i)^s - 1}{r_i(1+r_i)^s} \qquad \text{Eq. 1}$$

In the above expression, PC is the Percent Cost and Com (indicates the insurance, taxes, salaries and rent) can be evaluated as a percentage (%) of Ic and ri represents the Real Interest Rate then accumulated Net Present Cost (NPC) can be calculated as follows.

$$NPC_{(1-s)} = I_c\left[1 + n\left[\frac{(1+r_i)^s - 1}{r_i(1+r_i)^s}\right]\right] \quad \text{Eq. 2}$$

The turbine's annual operation cost can be obtained as:

$$NPC = \frac{NPC_{(1-s)}}{s} = \frac{I_c}{s}\left[1 + n\left[\frac{(1+r_i)^s - 1}{r_i(1+r_i)^s}\right]\right] \quad \text{Eq. 3}$$

Eo (annual energy output of the turbine) can be obtained by the following expression:

$$E_o = 8760 \text{ x } C_f \text{x } P_{ra} \quad \text{Eq. 4}$$

Here P_{ra} is a rated power of Turbine and C_f is a capacity factor. Now per Unit (kWh) cost of the electricity generated can be calculated as follows:

$$\text{Cost of Energy (COE)} = \frac{NPC}{E_o} = \frac{I_c}{8760s}\left[\frac{1}{C_f \cdot P_{ra}}\right]\left[1 + n\left[\frac{(1+r_i)^s - 1}{r_i(1+r_i)^s}\right]\right] \quad \text{Eq 05}$$

Choice of Wind Turbine Type

Doubly-fed induction generator (DFIG) or Wound Rotor Induction Generator (WRIG) variable-speed Wind Turbines are used while modelling power plants in the present research. As seen in **Error! Reference source not found.**, the use of variable-speed wind turbines with doubly-fed induction generators is made possible by a power electronic converter. This arrangement connects the stator directly to the grid and connects the generator's rotor via a back-to-back (AC-DC-AC) converter. Because the power electronic converter only uses 20–30% of the total power, this kind of WT is highly useful for large power wind turbine systems. It makes it easier to develop small-size converters, which leads to minimal power losses and cost-effectiveness (Wadho et al., 2024).

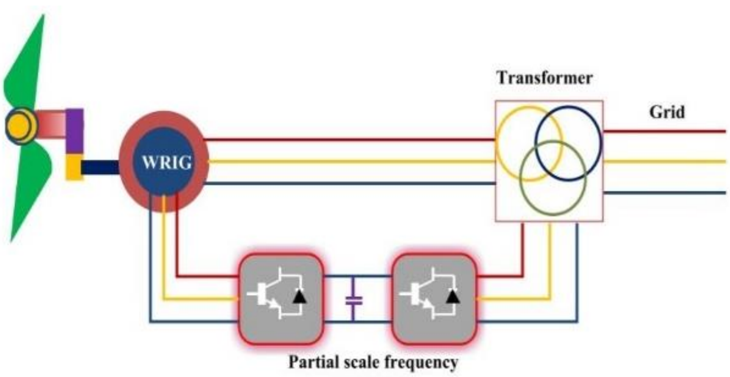

Figure 6. Variable Speed with DFIG (Type-C) (Source: (Wadho et al., 2024)).

Table 1. Wind turbine specifications.

Wind Turbine	Specifications
Rated power (MW)	2
Minimum speed (m/s)	3
Maximum speed (m/s)	25
Clearance from the ground (m)	50-80
Ratio of gearbox	1:106 for (50 Hz)
Alternator	DFIG
Frequency (Hz)	50

Wind speed is the most important factor to be considered when selecting windmills for power generation. According to the average wind speed of Nok Kundi 16.4 Km/h (Wadho et al., 2024), the ENERCON E82 E2, 2 MW windmill is an appropriate option. Windmill hub altitudes range from 50-80 meters. Table 1 contains the Wind Turbine specifications which are selected during the modeling and simulation of the power plant.

DATA ANALYSIS

At the very first, the load flow analysis of the modelled wind farm is conducted by using ETAP software. The analysis indicated the magnitude of the required electric load and on the basis of those results, the second step of analysis is conducted. The second step is the financial analysis of the wind power plant. The financial analysis is carried out under two different scenarios, 1) the proposed wind power plant is connected to the grid and 2) the proposed wind power plant was used as a stand-alone system. The analysis associated with the mentioned scenarios is conducted by using HOMER software. The obtained results are put in the data analysis software (Origin Lab) to visualize the data. At last, the mitigation of carbon footprints by the proposed wind power plant is estimated and the associated graphs are plotted and presented in this piece of research.

Software used

Three software were used in the present research. At the very first, the collected data is put into origin software for plotting graphs of average wind speed and maximum wind speed. Secondly, the wind power plant model is developed in ETAP software and it is simulated; furthermore, it is used to conduct the load flow analysis of the wind power plant model; thirdly, HOMER software is used to conduct the financial analysis of the developed wind power plant model. At last, the data generated from HOMER is transferred to Origin software for plotting graphs.

RESULTS

Load flow analysis in ETAP

The load of Nok Kundi varies from winter to summer and it varies from 5MW to 18MW in peak demand. The power rating of each wind turbine is 2MW and -1.239 MVAr with the voltage of each wind turbine being 0.62KV, 2599 amperes, and a power factor of 85%. After that, a 50 MVA transformer T1 is connected which steps up this voltage to 33 KV at bus 2. Transformer T3 with a rating of 50 MVA is connected which further steps up this voltage to 132 KV at bus 5. Then, across buses 5 and 6, a line of transmission is built to link this network and integrate this system into the national grid. Voltage is stepped up to 132 KV and is synchronized with the grid of QESCO which is available in Nok Kundi. After connecting with the grid with a load of 10 MVA, it can be seen that the megawatts received are calculated to be 37.78 MW; which showed a loss of about 2.22 MW with -27.786 MVAr. Load flow analysis of a proposed wind power plant for the Nok Kundi area of Baluchistan using the ETAP platform is shown in Figure 7.

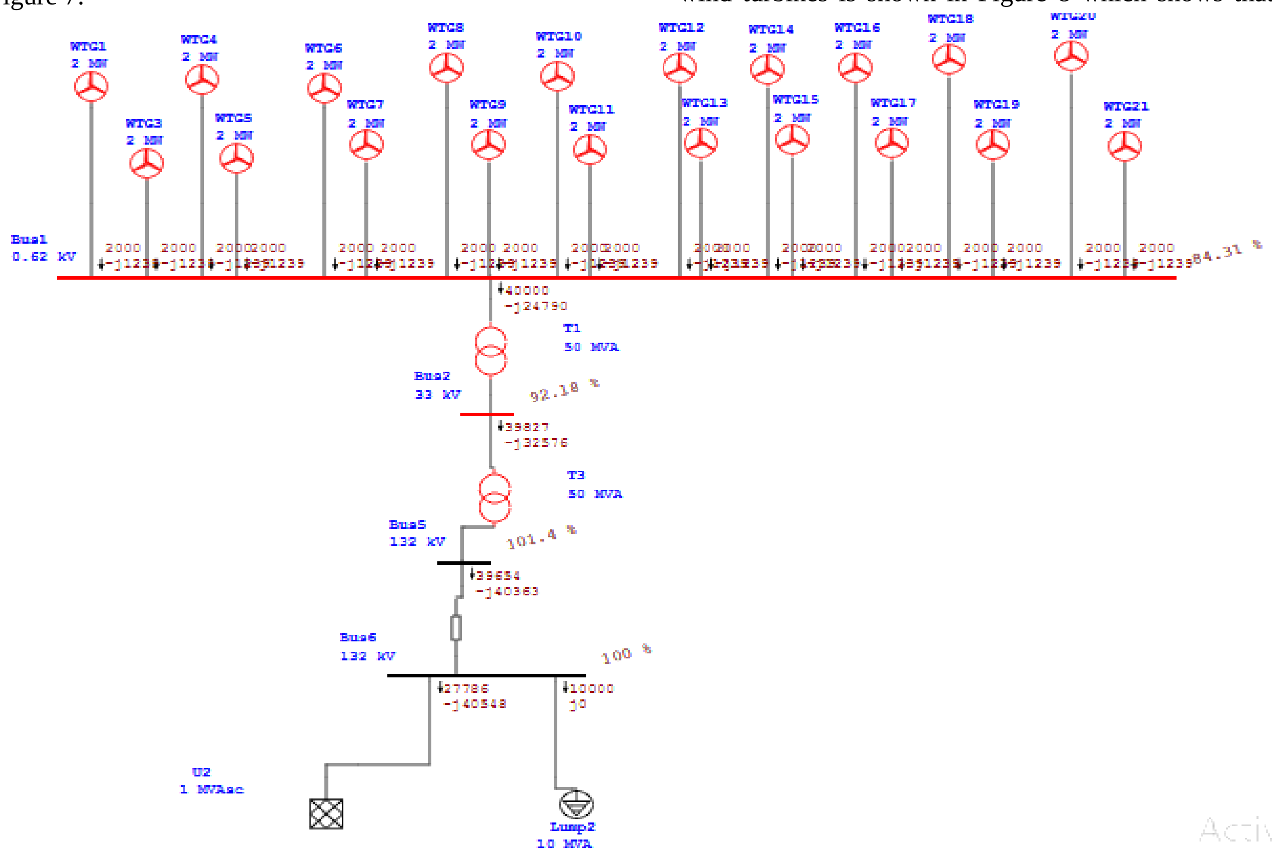

Figure 7. Proposed wind power plant and its load flow diagram

With the use of ETAP software, load flow analysis for Nok Kundi is conducted. This model has 20 wind turbines, 2 MW and 0.624kV each. At a point of common collection, 33 KV/132 KV is synchronized with the regional grid.

Nok Kundi's power consumption varies between 5 and 18 MW. Each turbine produces 2 MW of electricity. It operates at an output voltage of 0.62 KV with a power factor of 85%. At bus 5, a 50 MVA transformer is attached to raise the voltage to 132 KV. To keep synchronized with this network with the nearby grid, a transmission connection is linked between buses 5 and 6. The chosen turbine, with a doubly fed induction generator, exchanges reactive power based on voltage profiles. DFIGs and line inductance cause a drop in power factor. At the collection grid, it uses capacitor banks to make up for the pre-synchronization.

Power Generation Scenarios

Scenario 1: Isolated Wind Power Generation

Nok Kundi has a wind speed of more than the required average wind speed for electricity generation. A standalone system is not grid-tied but it delivers power directly to the load instead. This piece of research presents a feasibility analysis of electricity generation from wind turbines. Monthly power generation from wind turbines is shown in Figure 8 which shows that power output from wind turbines depends upon the wind speed. The figure also indicates the variations in the wind speed throughout the year, wind speed of the

Table 2. Load flow analysis								
Bus	**Voltage**			**Load flow**				
ID	**KV**	**% Mag**	**Ang.**	**ID**	**MW**	**MVAr**	**Amps**	**%PF**
Bus 1	0.62	84.30	15.6	Bus 2	40.0	-24.79	51982.0	85.0
Bus 2	33.0	92.17	8.1	Bus 1	-39.91	32.45	976.6	77.4
				Bus 5	39.94	-32.45	976.6	77.4
Bus 5	132.0	101.36	1.9	Bus 6	39.82	-40.32	244.2	70.1
				Bus 2	-39.82	40.32	244.2	70.1
Bus 6	132.0	100	0.0	Bus 5	-37.77	40.14	244.2	67.7

selected area was found to be greater in the summer season; this is the reason, the generation of electricity density is greater in the summer season than the rest of the year as shown in Figure 8.
Furthermore, the results of the simulation are given in Table 3.

Table 3. Power output results of a standalone system	
Specification	**Rated value**
Overall capacity (kW)	40,000
Output (kW)	20,500
Factor of capacity (%)	51.2
Overall production (kWh/year)	179,580,100

Scenario 2: Grid-Tied Wind Power Generation

The simulation results of a grid-tied wind power system were analyzed and discussed under this

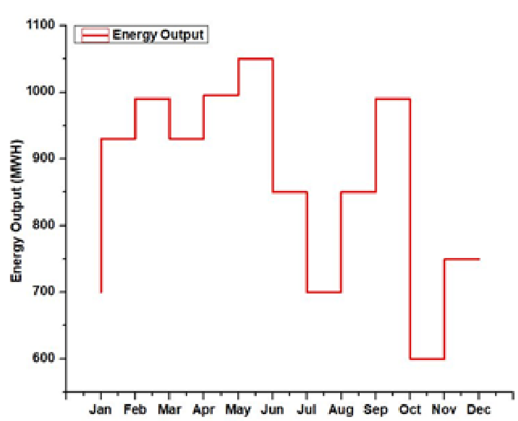

Figure 8. Monthly wind turbine output in MWh

Table 4. Energy purchase from the local grid	
System	**Output (kWh/year)**
Wind turbines output	179,580,100
Electricity purchased from the grid	289,364
Overall output	179,869,464

heading. Megawatt output from wind turbine E-82 E2 with respect to the months of the year in a grid-tied system. The megawatt output varies with the wind speed which varies throughout the year. Months having more average wind speed have more power output. After meeting the load requirement, the excessive electricity is sold to the national grid and in case of low output from wind turbines, the energy is purchased from the national grid in months like June, October and December as can be seen in Figure 9.
The energy sold to the grid will give a good profit which will make the wind power plant

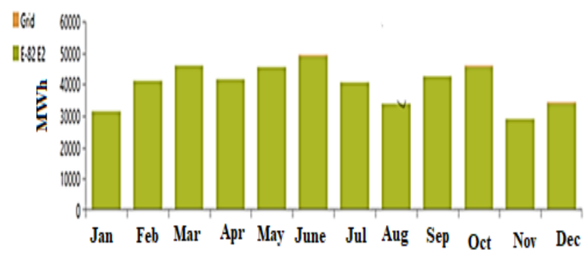

Figure 9. Monthly output of wind farm and energy needed from the grid

more economical. Grid-tied systems are more practical than stand-alone systems due to the interchange of electricity to the national grid and the ability to make a reasonable profit. Energy output from wind turbines and the energy purchased from the national grid can be facilitated through a grid-tied system. The overall energy purchase from the local grid for the low wind speed months is given in Table 4.

Hourly Power Output of Grid-Tied Wind Turbine System

Figure 10 depicts the hourly production of wind turbines. It can be seen that during the windy days of the year, the power generation output was found to be greater than the less windy days of the year. The power output was found to be greater from 12:00 to 20:00 hours of the day because the wind speed was found to be greater in the mentioned hours.
The total operational hours of the wind turbines can be seen in Table 5, which were 8593 hours/year; it can also be seen as all the loads have been met and therefore, unmeet load in the grid-tied system was found to be negligible: hence, the energy purchased in the grid-tied system can be saved largely.

COST ANALYSIS

The cost analysis was conducted in three steps, firstly, the cost of the standalone system was discussed, and then the energy mix and costs were discussed along

Table 5. Power Output and complete datasheet of wind turbine	
System Specification	**Value**
Overall capacity (kW)	40,000
Average output (kW)	20,500
CP (%)	51.2
Overall generation (kWh/year)	179,580,100
Total duration of operation (Hours/year)	8593
Wind infiltration (%)	87.85
Unmeet load (kWh/year)	0

with the simulated results. Lastly, the economic comparison of both systems was conducted.

A. Cost Summary of Stand-alone System

The calculation of total capital cost and operating expenses is important for the estimation of overall cost. The results given in Table 6 were obtained from HOMER software. In a standalone wind system, the additional generated energy cannot be sold to the national grid and all the generated power is used to meet the required load; which is why there is no possibility of generation profit. The cost of fuel is zero in wind power generation because wind is a renewable source of energy and it is used to generate electricity by using wind turbines. Table 6 shows the summary of the cost of the standalone system.

Table 6. Cost summary of the isolated system	
Parameters	**Cost**
Overall capital (million USD)	32.95
Electricity cost per kWh (USD)	0.641
Cost of operating energy (USD/year)	32,950,000
Cost of fuel (USD)	0

B. Energy Mix with Grid

A grid-tied network is a technology which allows generating revenues by selling extra power to the grid. It can also take electricity from the electrical grid in times of excessive demands or insufficient wind. The quantity of electricity sold and obtained from the power grid is represented in Table 7.

According to the data (Table 7), the total quantity of energy bought from the electrical grid is 2,89,364 kWh/year, whereas, surplus generated power that can be sold to the grid is 47,581,913 kWh/year.

C. Economic Comparison of Both Systems

A detailed cost analysis of grid-connected and stand-alone systems is provided in Table 8. Grid-connected systems are more practical and adaptable over stand-alone wind energy generation since they interchange electricity with the national grid while maintaining fair profitability.

ESTIMATION OF CARBON FOOTPRINT

The power sector contributes a maximum percentage of CO2 emissions (Pradhan et al., 2022). Therefore, due to environmental concerns, the use of renewable energy has been supremely used at global and regional levels (Yuni et al., 2023). In this regard, the wind farm at Nok Kundi was proposed in the present research and its financial analysis is discussed in detail. This heading is associated with the estimation of reduced carbon footprint, mitigated carbon footprints and mitigated surplus carbon footprints as a result of the proposed model wind power plant.

In the present research paper, it was assumed that the power plants that supply electricity in the Nok Kundi area produce electricity from coal; therefore, the carbon prints caused by the combustion of coal were estimated considering the power consumption capacity of the Nok Kundi area. Furthermore, carbon footprints considering the power generation capacity of the proposed wind power plant were also estimated to project overall mitigation of the carbon footprints by the proposed model.

The index m refers to a month of a year, EDCp refers to the carbon footprints (in Kg) that are generated to meet the energy demand in the Nok Kundi area, ED is the energy demand in kWh, and Ei is the CO_2 emission index i.e. 992g/kWh (Butt et al., 2021) as calculated for coal. MCp is a total mitigated carbon footprint, E refers to the energy produced by the power plant, and MSCp is the mitigated surplus carbon footprint. The values of carbon footprints were calculated by using the equations from 6 to 8.

The annual energy demand of Nok Kundi was calculated to be 2, 89,364 kWh as given in Table 7 and

$$EDC_p = \sum_{m=1}^{12} ED_m \; E_i \qquad \text{Eq. 06}$$

$$MC_p = \sum_{m=1}^{12} E_m \; E_i \qquad \text{Eq. 07}$$

$$MSC_p = \sum_{m=1}^{12} E_i \left(E_m - ED_m\right) \qquad \text{Eq. 08}$$

as discussed earlier the power plants which are supplying electricity in Nok Kundi generate electricity from coal; therefore, if Nok Kundi purchases electricity from the grid then the magnitude of generated carbon

Table 7. Energy mix with grid

Months	Electricity Demand (kWh)	Electricity Generated from the Proposed Model (kWh)	Surplus Generated Electricity After Fulfilment (kWh)	Generated Revenues (USD)
Jan	25,860	30,953,57	3,069,497	1,14432
Feb	15,678	41,014,09	4,085,731	1,516,94
Mar	16,664	45,345,29	4,517,865	1,677,15
Apr	24,360	41,1630,5	4,091,945	1,522,13
May	25,159	45,177,45	4,492,597	1,670,63
Jun	25,148	48,589,73	4,833,825	1,796,88
Jul	29,349	40,157,58	3,986,409	1,484,74
Aug	34,833	33,331,59	3,298,326	1,231,98
Sep	28,772	42,24769	4,195,997	1,562,10
Oct	21,408	45,289,64	4,507,556	1,674,92
Nov	45,022	28,818,36	2,836,814	1,065,57
Dec	23,051	33,731,02	3,350,051	1,247,19
Annual	**2,89,364**	**47,581,913**	**47,552,98**	**17,594,60**

footprints to meet the energy demand of Nok Kundi throughout the year is given in Figure 11.

Table 8. A comprehensive review of both models

Cost	Stand-alone System	Grid-tied System
Overall principal cost (million USD)	32.950	32.950
The total net present cost (million USD)	32.950	25.350
Electricity Cost per kWh (USD)	0.641	0.037
Running cost per year (USD)	49,410	-2,704,305

A look at the figure indicates a maximum of carbon footprints in the month of November; it is because of greater energy demand in the mentioned month (see Table 7). It was estimated in the present research, that Nok Kundi produces 0.31 million Kgs of carbon footprint per year and as per the proposed model wind power plant, the Nok Kundi area can save itself from producing an average of 0.03 million Kgs of carbon footprint per month as given in Figure 11.

The data given in Figure2 is calculated by using Eq. 7. The proposed wind power plant has the capacity to generate 47, 581, 913 kWh/year (see Table 7). If the same amount of energy is produced by the combustion of coal, it will result in the generation of 47.20 million Kg of carbon in the environment per year and an average of 3.93 million Kg per month. Considering the proposed wind power plant model, it can potentially help in reducing the carbon footprints of the area. Additionally, the estimation of overall mitigated carbon footprints by producing green energy through the proposed wind power plant is visualized in Figure2.

Surplus carbon footprint is the value obtained after the subtraction of the carbon footprint generated to produce the energy equivalent to the capacity proposed wind power plant from the carbon footprint generated to meet the energy demand of Nok Kundi and it is visualized in Figure . The authors estimated that the mitigated surplus carbon footprint by the proposed wind power plant will be 46.89 million kg, and 3.91 kg per year and per month respectively.

DISCUSSION

In light of the potential evaluation and financial analysis of the wind power generation of Pakistan, Sindh Province produces a significant amount of wind power. On the other hand, Balochistan is also considerably rich in this context. As compared to these results, the average wind speed obtained at the Nok Kundi area was found to be 16.4km/h. The cost per unit is 0.037 USD/kWh, which indicates that the selected site is suitable for wind power generation to produce electricity for a far-located rural area and surplus energy during windy months can also be supplied to the grid.

Different economic and potential assessment studies have been considered in the literature for different wind corridors in Pakistan. Most of the effective wind corridors are southern coastal areas of Sindh and some areas of Balochistan. Like, Ullah et al. (2010) worked on the wind power potential assessment of the Kati Bandar area located in the southern coastal areas of Sindh, Pakistan, they concluded average wind speed around the year was 7.16m/s at a height of 50m above the ground (Ullah et al., 2010). Hulio et, al. (2017a) found wind speed of 5.233 m/s to 6.55m/s at the height of 50m at the same location and the unit cost was calculated to be 0.02189 USD/kWh (Hulio et al., 2017b). Gul et al. (2019) calculated the cost/kWh and is in a range from 0.01927 USD to 0.032 USD (Gul et al., 2019). The unit cost of electricity generation in this study is calculated to be 0.037 USD/kWh with a grid-tied system and 0.641 USD/kWh with a stand-alone system. During the financial analysis, it was found that 25.35 million USD could be saved by selling the surplus energy to the grid. Being a small city, having a load of approximately 18MW, Nok Kundi can be a

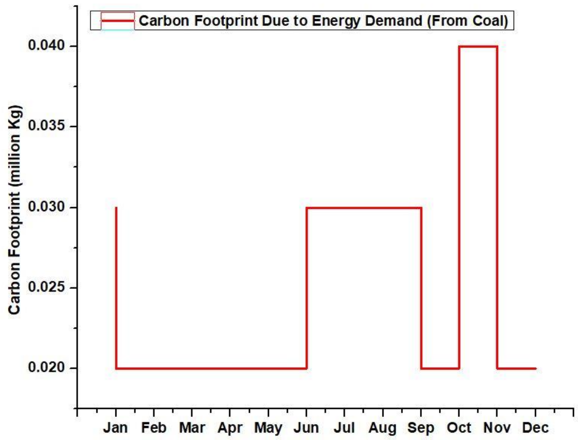

Figure 10. Estimated carbon footprint generated as a result of energy demand if coal is used by the power plants to generate electricity

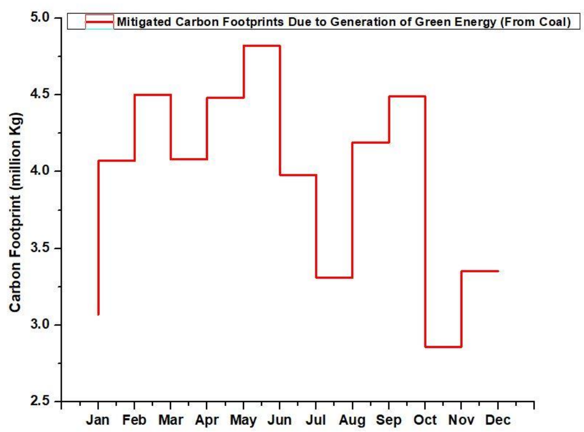

Figure 11. Estimated mitigation of carbon footprint if coal is used by the power plants to generate electricity

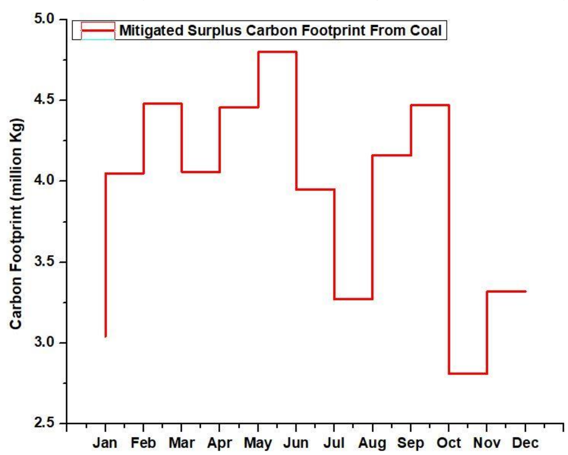

Figure 12. Estimated mitigation of surplus carbon footprint generated if coal is used by the power plants to generate electricity

green city by employing the 40MW wind farm at the selected location. This can potentially be beneficial from a financial perspective and it will also help in reducing the carbon footprints caused by the generation of electricity from fossil fuels.

This research also estimates the minimization and mitigation of carbon footprints by proposing a wind power plant. It is indicated by the analysis that the average energy demand of Nok Kundi is 26,275 kWh per month and the total energy demand can be calculated as 2,89,364 kWh/year. Since the power production capacity of the proposed wind power plant was calculated to be 47,581,913 kWh/year which is far greater than the present energy requirement (2.89,364 kWh/year) of Nok Kundi Moreover, a handsome amount of revenue has been earned while selling the surplus energy. Nok Kundi utilizes fossil fuel power with an average of 0.03 and 0.31 million kgs of carbon footprint generated per month and year respectively to meet the energy demand. Therefore, the proposed wind power plant can eradicate the carbon footprint which can be produced as a result to meet the energy demand of the area.

CONCLUSION

The modelling results for both grid-connected and standalone wind farm systems suggested that the initial cost of each system is 32,950,000 USD. The typical price of power from an individual windmill is around 0.641 USD/kWh, whereas the price for electrical power from a grid-tied wind turbine energy system is approximately 0.037 USD/kWh. When surplus electricity is sold back, to the power grid the revenue generated helps lower the cost of this system to 25.350 million USD. Due to the interchange of power to the national grid and the potential to make a reasonable profit, grid-tied systems are more viable than stand-alone wind generation systems. Additionally, the proposed power plant can result in the mitigation of the carbon footprints that are produced while the generation of electricity from the combustion of fossil fuels. Since the proposed wind power plant is a potential source of producing green energy, therefore, it is quite useful for the society and environment. The present research concluded that the proposed wind power plant can produce 47,581,913 kWh/year and at the same time can mitigate the generation of 47.20 million Kg of carbon per year and an average of 3.93 million Kg per month.

AKNOLOWDGEMENT

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REFERENCES

Ahmed, S. A., & Mahammed, H. O. (2012). A Statistical analysis of wind power density based on the weibull and ralyeigh models of “Penjwen region” Sulaimani/Iraq. Jordan Journal of Mechanical and Industrial Engineering, 6(2), 135–140.

Asghar, R., Ullah, Z., Azeem, B., Aslam, S., Hashmi, M. H., Rasool, E., Shaker, B., Anwar, M. J., & Mustafa, K. (2022). Wind Energy Potential in Pakistan: A Feasibility Study in Sindh Province. Energies 2022, Vol. 15, Page 8333, 15(8333). https://doi.org/10.3390/EN15228333

Baloch, M. H., Kaloi, G. S., & Memon, Z. A. (2016). Current scenario of the wind energy in Pakistan challenges and future perspectives: A case study. Energy Reports, 2, 201–210. https://doi.org/10.1016/J.EGYR.2016.08.002

Bandoc, G., Prăvălie, R., Patriche, C., & Degeratu, M. (2018). Spatial assessment of wind power potential at global scale. A geographical approach. Journal of Cleaner Production, 200, 1065–1086. https://doi.org/10.1016/J.JCLEPRO.2018.07.288

Bastidas-Salamanca, M., & Rueda-Bayona, J. G. (2021). Pre-feasibility assessment for identifying locations of new offshore wind projects in the Colombian Caribbean. International Journal of Sustainable Energy Planning and Management, 32, 139–154. https://doi.org/10.5278/ijsepm.6710

Benatiallah, A., Kadia, L., & Dakyob, B. (2010). Modelling and Optimisation of Wind Energy Systems. Jordan Journal of Mechanical and Industrial Engineering, 4(1), 143–150.

Butt, D., Myllyvirta, L., & Dahiya, S. (2021). CO2 Emissions from Pakistan’s Energy sector. In Center of Research on Energy and Clean Air. https://energyandcleanair.org/wp/wp-content/uploads/2021/07/CO2-Emissions-from-Pakistans-Energy-sector_30_07_2021.pdf

Fazelpour, F., Markarian, E., & Soltani, N. (2017). Wind energy potential and economic assessment of four locations in Sistan and Balouchestan province in Iran. Renewable Energy, 109, 646–667. https://doi.org/10.1016/J.RENENE.2017.03.072

Ghenai, C., Salameh, T., & Janajreh, I. (2017). Modeling and simulation of shrouded Horizontal Axis Wind Turbine using RANS method. Jordan Journal of Mechanical and Industrial Engineering, 11(4), 235–243.

Gul, M., Tai, N., Huang, W., Nadeem, M. H., & Yu, M. (2019). Assessment of Wind Power Potential and Economic Analysis at Hyderabad in Pakistan: Powering to Local Communities Using Wind Power. Sustainability, 11(5), 1391. https://doi.org/10.3390/SU11051391

Halasa, G. (2010). Wind-Solar Hybrid Electrical Power Generation in Jordan. Jordan Journal of Mechanical and Industrial Engineering, 4(1), 205–209.

Himri, Y., Rehman, S., Draoui, B., & Himri, S. (2008). Wind power potential assessment for three locations in Algeria. Renewable and Sustainable Energy Reviews, 12(9), 2495–2504. https://doi.org/10.1016/J.RSER.2007.06.007

Hulio, Z. H., Jiang, W., & Rehman, S. (2017a). Technical and economic assessment of wind power potential of Nooriabad, Pakistan. Energy, Sustainability and Society, 7, 1–14. https://doi.org/10.1186/S13705-017-0137-9/TABLES/7.

Hulio, Z. H., Jiang, W., & Rehman, S. (2017b). Technical and economic assessment of wind power potential of Nooriabad, Pakistan. Energy, Sustainability and Society, 7(35), 1–14. https://doi.org/10.1186/S13705-017-0137-9/TABLES/7

Hulio, Z. H., Jiang, W., & Rehman, S. (2017c). Technical and economic assessment of wind power potential of Nooriabad, Pakistan. Energy, Sustainability and Society, 7(1), 1–14. https://doi.org/10.1186/S13705-017-0137-9/TABLES/7

Hussein, N. (2016). Greenhouse gas emissions reduction potential of Jordan’s utility scale wind and solar projects. Jordan Journal of Mechanical and Industrial Engineering, 10(3), 199–203.

Ishfaq, S., Ali, S., & Ali, Y. (2018). Selection of Optimum Renewable Energy Source for Energy Sector in Pakistan by Using MCDM Approach. Process Integration and Optimization for Sustainability, 2, 61–1. https://doi.org/10.1007/S41660-017-0032-Z/TABLES/20

Khahro, S. F., Tabbassum, K., Mohammad Soomro, A., Liao, X., Alvi, M. B., Dong, L., & Manzoor, M. F. (2014). Techno-economical evaluation of wind energy potential and analysis of power generation from wind at Gharo, Sindh Pakistan. Renewable and Sustainable Energy Reviews, 35, 460–474. https://doi.org/10.1016/J.RSER.2014.04.027

Khan, T. (2013). High potential: Balochistan energy resources waiting to be exploited. The Express Tribune. https://tribune.com.pk/story/649120/high-potential-balochistan-energy-resources-waiting-to-be-exploited

Kumar, V. S., Zobaa, A. F., & Kannan, R. D. (2010). Power quality and stability improvement in wind park system using STATCOM. Jordan Journal of Mechanical and Industrial Engineering, 4(1), 169–176. http://jjmie.hu.edu.jo/

Mathew, S. (2006). Wind energy: Fundamentals, resource analysis and economics. In Wind Energy: Fundamentals, Resource Analysis and Economics (Vol. 1). Springer Berlin Heidelberg. https://doi.org/10.1007/3-540-30906-3/COVER

Messaoud, M., & Abdessamed, R. (2011). Modeling and optimization of wind turbine driving permanent magnet synchronous generator. Jordan Journal of Mechanical and Industrial Engineering, 5(6), 489–494.

Ministry of Finance. (2022). Energy. In Hart Crane. https://doi.org/10.12987/9780300236262-015

Ministry of Finance. (2023). Energy. In Pakistan Economic Survey 2018-19. https://www.finance.gov.pk/survey/chapters_19/14-Energy.pdf

Mirhosseini, M., Sharifi, F., & Sedaghat, A. (2011). Assessing the wind energy potential locations in province of Semnan in Iran. Renewable and Sustainable Energy Reviews, 15(1), 449–459. https://doi.org/10.1016/J.RSER.2010.09.029

Mohammadi, K., & Mostafaeipour, A. (2013). Using different methods for comprehensive study of wind turbine utilization in Zarrineh, Iran. Energy Conversion and Management, 65, 463–470. https://doi.org/10.1016/J.ENCONMAN.2012.09.004

Mostafaeipour, A. (2010). Feasibility study of harnessing wind energy for turbine installation in province of Yazd in Iran. Renewable and Sustainable Energy Reviews, 14(1), 93–111. https://doi.org/10.1016/J.RSER.2009.05.009

Mostafaeipour, A., Sedaghat, A., Dehghan-Niri, A. A., & Kalantar, V. (2011). Wind energy feasibility study for city of Shahrbabak in Iran. Renewable and Sustainable Energy Reviews, 15(6), 2545–2556. https://doi.org/10.1016/J.RSER.2011.02.030

Mostafaeipour, A., Sedaghat, A., Ghalishooyan, M., Dinpashoh, Y., Mirhosseini, M., Sefid, M., & Pour-Rezaei, M. (2013). Evaluation of wind energy potential as a power generation source for electricity production in Binalood, Iran. Renewable Energy, 52, 222–229. https://doi.org/10.1016/J.RENENE.2012.10.030

PBS. (2017). Final Census Results. Pakistan Bureau of Statistics. https://www.pbs.gov.pk/content/final-results-census-2017

Pradhan, B. B., Chaichaloempreecha, A., Chunark, P., Rajbhandari, S., Pita, P., & Limmeechokchai, B. (2022). Energy system transformation for attainability of net zero emissions in Thailand. International Journal of Sustainable Energy Planning and Management, 35, 27–44. https://doi.org/10.54337/ijsepm.7116

Reve. (2010). Balochistan (Pakistan) can generate at least 5,000 MW of wind power. Reve. https://www.evwind.es/2010/05/17/balochistan-pakistan-can-generate-at-least-5000-mw-of-wind-power/5623

Reve. (2017). Pakistan to produce 2,050 MW wind energy. Reve.

https://www.evwind.es/2017/07/05/pakistan-to-produce-2050-mw-wind-energy/60363

Shalby, M., Abuseif, A., Gomaa, M. R., AhmadSalah, Marashli, A., & Al-Rawashdeh, H. (2022). Assessment of Dust Properties in Ma'an Wind Farms in Southern Jordan. Jordan Journal of Mechanical and Industrial Engineering, 16(4), 645–652.

Shoaib, M., Siddiqui, I., Amir, Y. M., & Rehman, S. U. (2017). Evaluation of wind power potential in Baburband (Pakistan) using Weibull distribution function. Renewable and Sustainable Energy Reviews, 70, 1343–1351. https://doi.org/10.1016/J.RSER.2016.12.037

Soulouknga, M. H., Doka, S. Y., N.Revanna, N.Djongyang, & T.C.Kofane. (2018). Analysis of wind speed data and wind energy potential in Faya-Largeau, Chad, using Weibull distribution. Renewable Energy, 121, 1–8. https://doi.org/10.1016/J.RENENE.2018.01.002

Teshnizi, E. A., Jahangiri, M., Shamsabadi, A. A., Pomares, L. M., Mostafaeipour, A., & El Haj Assad, M. (2021). Comprehensive Energy-Econo-Enviro (3E) Analysis of Grid-Connected Household Scale Wind Turbines in Qatar. Jordan Journal of Mechanical and Industrial Engineering, 15(2), 215–231.

TIN. (2021). Installed capacity to generate 37,261 MW power. The International News. https://www.thenews.com.pk/print/847878-installed-capacity-to-generate-37-261-mw-power

Ucar, A., & Balo, F. (2010). Assessment of wind power potential for turbine installation in coastal areas of Turkey. Renewable and Sustainable Energy Reviews, 14(7), 1901–1912. https://doi.org/10.1016/J.RSER.2010.03.021

Ullah, I., Chaudhry, Q. uz Z., & Chipperfield, A. J. (2010). An evaluation of wind energy potential at Kati Bandar, Pakistan. Renewable and Sustainable Energy Reviews, 14(2), 856–861. https://doi.org/10.1016/J.RSER.2009.10.014

Wadho, M. H., Khan, S., Hassan, S., & Kalwar, M. A. (2024). Simulation-Based Post-Fault Analysis In WECS Using DFIG Systems Under An Unbalanced Fault Scenario. Journal of Applied Research in Technology & Engineering, 5(1), 33–44. https://doi.org/10.4995/jarte.2024.20096

WWO. (2024). Nok Kundi Annual Weather Averages. World Weather Online. https://www.worldweatheronline.com/nok-kundi-weather-averages/balochistan/pk.aspx

Yuni, D. N., Ezenwa, N. J., Urama, N. E., Tingum, E. N., & Mohlori-Sepamo, K. (2023). Renewable Energy and Inclusive Economic Development: An African Case Study. International Journal of Sustainable Energy Planning and Management, 39, 23–35. https://doi.org/10.54337/ijsepm.7413