Techno-Economic Feasibility Study to Install 30 MW Grid-connected Wind Farms in Saudi Arabia

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Nomenclature

A	Swept area
BCR	Benefit-cost ratio
C	Scale parameter
CF	Capacity factor
C_n	Cash flow for N years
CO_2	Carbon Dioxide
C_p	Power coefficient
f	Frequency
GHG	Greenhouse Gases
IRR	Internal rate of return
K	Shape parameter
LCOE	Levelized Cost of Energy
N	Years
NPV	Net Present Value
P	Power
$\wp$	Cumulative distribution function
r	Discount rate
SPP	Simple payback period
tCO_2	Tons of CO_2
V_h	Wind velocity at hub height
V_m	Mean wind speed
V_r	Wind velocity at the reference height
Z_h	Hub height
Z_r	Reference height
α	Power law coefficient
p	Probability density function
v	Wind speed
ρ	Density

Abstract:

The Saudi Green Initiative is a key component of Saudi Arabia's 2030 vision to increase reliance on clean energy production, reduce GHG emissions, and protect the environment. Wind energy is a promising source of clean and renewable energy that can contribute significantly to this goal. This study investigates the feasibility of installing 30 MW wind farms at two locations in Saudi Arabia (Yanbu and Neom) using hourly mean speed data obtained from NASA from 2020 to 2022. The study calculates and analyzes the mean wind speed, dominant wind direction, Weibull distribution scale, and shape parameters. RETScreen software is used to estimate the annual energy production, evaluate economic feasibility in terms of various financial metrics, and assess the feasibility of different wind turbines (DeWind, Gamesa, GE,

and Suzlon). The study finds that both sites are technically and economically feasible for wind farm installations, with Neom's Gamesa G114 wind turbine offering the highest capacity factor. The levelized cost of energy ranges from $ 0.039 to $ 0.078 per kWh, which is comparable to the cost of tariff in Saudi Arabia. Overall, the study suggests that wind energy can play a significant role in achieving the Saudi Green Initiative's goals and that further investment and development in this area could yield significant benefits for the country's economy, environment, and energy security.

1. Introduction:

The rapid growth of the world's population is accompanied by a massive increase in energy demand. The global energy system is confronted with two important issues: ensuring a sufficient and secure energy supply and lowering greenhouse gas emissions [1,2]. Currently, the majority of the world's countries rely on fossil fuels, such as oil, natural gas, and coal, as primary energy supplies, which are depleting and are the corresponding source of greenhouse gas emissions. As a result, it is vital to replace fossil fuels with clean, sustainable, and renewable energy resources such as solar, wind, biomass, hydropower, and geothermal [3,4]. Wind energy is predicted to play an important role in meeting load demands in future global energy scenarios [5–7]. Wind energy has shown to be a cost-effective and commercially viable energy source. Wind power generation has an advantage over other renewable energy technologies because of its technological maturity, and low-cost energy generation. Furthermore, the long life of wind turbines, and the short time necessary for installation and operation following site evaluation [8]. Based on the global energy council [9], the cumulative installed capacity of wind power climbed from 23,900 MW in 2001 to 651,000 MW in 2019. China, the United States, the United Kingdom, and Germany account for the vast majority of wind energy output worldwide [10]. Dumat Al-Jandal Project is the first large-scale wind farm in Saudi Arabia and one of the biggest wind farms in the Middle East with a capacity of 400 MW [11]. The Dumat Al-Jandal wind farm is being built in accordance with Saudi Arabia's target of installing 16GW of wind capacity by 2030 and generating 50% of its electricity from renewable sources [12]. Consequently, several research on wind energy and resource assessments for various cities in Saudi Arabia have been studied and published. These Studies involve the assessment of wind energy trends using various methodologies and techniques, different optimization designs, wind power distribution analysis, and region estimation [13,14]. Azorin-Molina et al. [15] investigated the variability and changes in measured wind speed near the surface at several Saudi Arabian sites from 1978 to 2013. On a yearly basis, they discovered a (- 0.058 m/s) decrease in wind speed across the country. Baseer et al. [16] investigated the wind power characteristics of Jubail using hourly mean wind speed measured at various altitudes above ground level using wind data from 2008 to 2012. The study showed that approximately 6825 MWh can be produced annually by using a 3 MW wind turbine and the capacity factor found is equal to 25%. Rehman et al. [17] investigated the cost of wind electricity in 20 Saudi cities. The study analyzed meteorological wind data from 1970 to 1982 and proposed that the maximum generated electricity at the lowest cost was reached in Yanbu.

Additionally, Rafique and Rehman et al. [18] studied the feasibility of installing a 100 MW capacity Wind Farm under different climatic conditions in Saudi Arabia. The results showed that the proposed locations are technically and economically feasible, with Dhahran being the most feasible site among the others for the installation of the wind farm. AlQdah et al. [19]studied the potential of wind energy in Medina by using the Weibull distribution. The study found that the scale and shape factors for Medina were 3.467 and 2.923 m/s with the possibility of producing 8648 kWh/year by using an Aventa AV-7 wind turbine. Additionally, Bassyouni et al. [20] investigated the wind power potential of Jeddah using a Weibull distribution approach. The study determined that, in the current context, wind power potential may be leveraged for off-grid power generation applications.

In this study, the main objective is to analyze the wind data and perform the economic feasibility analysis of the wind farm in two new locations in Saudi Arabia with an installed capacity of 30 MW for each location. Four different wind turbines from different manufacturing companies will be studied and analyzed based on the annual energy production and the levelized cost of energy (LCOE) for these various turbines.

2. Materials and Methods:

2.1. Selected locations and project description:

According to the Renewable Energy Atlas, Saudi Arabia is ranked 13th in the world, with one of the highest onshore wind output capacities, and is naturally endowed with renewable energy sources. Higher wind speeds exist in Saudi Arabia in the northeast, central, and near the western mountainous regions [21]. In this context, this feasibility study aims to investigate the wind energy potential in Yanbu [24.2047° N, 37.817° E] and Tabuk near Neom [28.167° N, 34.638° E]. The first location is on the eastern coast of Madinah province and the second is in the northeast of Tabuk province. Figure 1 shows the selected locations and the wind speed contours for Saudi Arabia at a 10 m height from the ground [22].

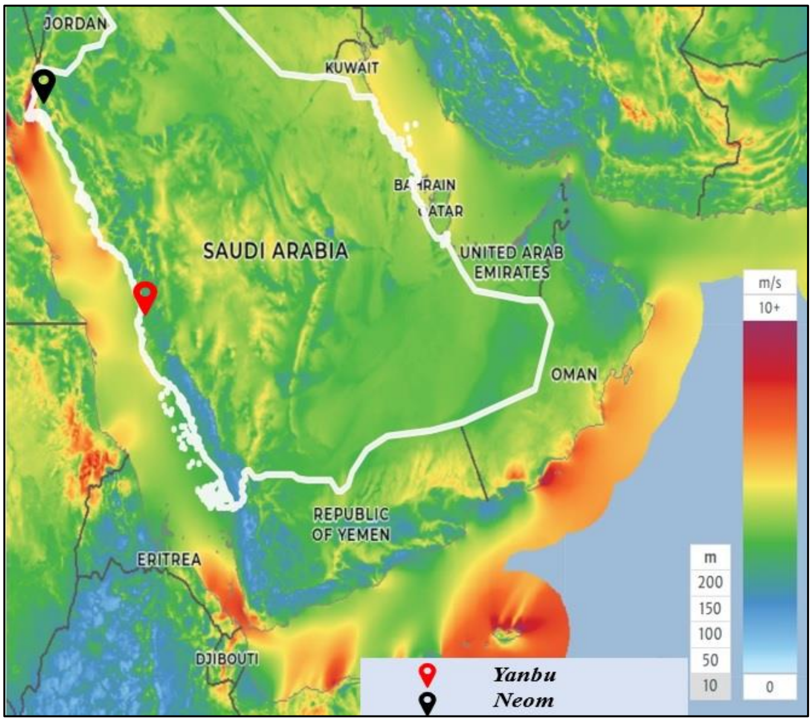

Figure 1: Wind velocity contours for Saudi Arabia and selected locations in Yanbu and Tabuk.

Researchers and engineers have used various technologies and analyses to develop various wind turbine configurations by determining the optimum working conditions. In this study, two methods for estimating wind energy potentials in the proposed sites are RETScreen software and the Bins method. The wind data records were obtained from the NASA power website from 2020 to 2022 [23]. However, in RETScreen software, the wind records are not taken from the same location. Thus, to do so, the shape factor is obtained for this location by using the Weibull distribution and then updating it in the software. Each wind farm in the proposed location has a capacity of 30 MW, and different wind turbines will be assessed to achieve the best performance based on energy production and economic parameters such as LOCE.

2.2. Wind power and energy output by Weibull distribution and Bins method:

Wind speed variations affect wind turbine power generation. As a result, it is critical to quantify the variation in windspeed over time. Weibull distribution is one of the common methods used to estimate the wind speed for a particular location. The Weibull probability density function (PDF) can represent various wind regimes and can be calculated by [24,25]:

$$p(V) = \frac{K}{C}\left(\frac{v}{C}\right)^{K-1} Exp\left(-\left(\frac{v}{C}\right)^{K}\right) \qquad (1)$$

where v is the wind speed, K is the shape parameter, and C is the scale parameter. The two parameters can be calculated graphically by knowing the cumulative distribution function (CDF) which is equal to the integral of the probability density function.

$$\wp(V) = 1 - Exp\left(-\left(\frac{v}{C}\right)^{K}\right) \qquad (2)$$

By taking the natural logarithm to Equation (2) on both sides, then:

$$\ln(-\ln(1 - \wp(V)) = K\ln(v) - K\ln(C) \qquad (3)$$

If Equation (3) is taken to be equal to the linear function $y = aX + b$, then the shape parameter is equal to the slope of the function (a) and the scale parameter is equal to $Exp\left(\frac{b}{K}\right)$ where (b) is the interception of the linear equation.

Additionally, the Wind data can be grouped as well in the form of a frequency distribution known as the bins. Therefore, the average wind velocity can be calculated:

$$V_m = \frac{\Sigma f_i V_i}{\Sigma f} \quad (4)$$

In which, V_i is the wind speed, f_i is the frequency of the wind speed, and f is the number of hours in a year (8760 hours). Furthermore, the wind speed must be converted from data recorded height to the hub height using power law:

$$\frac{V_h}{V_r} = (\frac{Z_h}{Z_r})^\alpha \quad (5)$$

where V_h is the wind velocity at the hub height, V_r is the wind velocity at the reference height (10 m), Z is the height, and α is the power law coefficient. For smooth terrain such as sand, the power law coefficient ranges from 0.10 to 0.14. Hence, for this study, a value of 0.14 is an excellent approximation value when the site characteristics are yet to be determined [26]. The wind power then can be calculated by:

$$P = \frac{1}{2}\, \rho\, C_p A\, V_m^3 \quad (6)$$

where ρ is the density of air, A is the swept area of the wind turbine, and C_p is the power coefficient which depends on the type of the wind turbine. Lastly, the capacity factor (CF) is calculated by:

$$CF = \frac{P}{Rated\ Power \times no.of\ hours} \quad (7)$$

Tables 1 and 2 show the wind turbines' specifications and the loss coefficient in energy production calculation that were used in this study [18,25,27–29].

Table 1: Wind turbines' main specifications.

Model	DeWind	Gamesa G114	GE Wind 1.85	Suzlon S95
No. of Turbines	30	15	16	14
Rated power per Turbine, MW	1	2	1.85	2.1
Rotor Diameter, m	62	114	82.5	95
Hub Height, m	68.5	106	100	100
Cut_in Speed, m/s	2.5	2.5	3	3.5
Rated Speed, m/s	11.5	10	13	11
Cut_off Speed, m/s	23	25	25	25

Table 2: Losses coefficients in the wind Turbine.

Losses	Selected Value
Array losses	3%
Airfoil losses	2%
Miscellaneous losses	2%
Availability	98%

2.3. Economic analysis of wind energy:

The economic analysis of wind energy production is carried out by considering the following financial parameters:

2.3.1. Internal rate of return (IRR):

The IRR is the discount rate at which the net present value (NPV) of the project is equal to zero. It can be determined by using the following equation [30]:

$$\sum_{n=0}^{N} \frac{C_n}{(1+IRR)^n} \quad (8)$$

where N is the life of the project in years and C_n is the cash flow for N years. If the IRR is greater than the value of the discount rate, then the project will be financially viable

2.3.2. Net present value (NPV):

The NPV of a project is the difference between the sum of inflow cash and outflow cash [31].

$$NPV = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n} \quad (9)$$

Where r is the discount rate for the project. The positive value of NPV shows that the project is feasible.

2.3.3. Simple payback period (SPP):

The SPP is defined as the number of years required to recover the original capital cost of investment of the project [31].

$$SPP = \frac{C_i - C_s}{C_a} \quad (10)$$

The subscripts C_i, C_s, and $C_a$are stand for the initial cost, scrap cost at the end of the project, and the average annual cash flow respectively.

2.3.4. Equity payback:

Equity payback represents the length of time that it takes for the owner of the project to recoup its initial investment out of the project cash flow generated [31].

2.3.5. Benefit-cost ratio (BCR):

The BCR is an economical measure of the desirability of the project. It refers to the ratio of the net benefits to the cost of the project [31].

2.3.6. Levelized cost of energy (LCOE):

LCOE is an economic measure used to compare the lifetime costs of the generated electricity across various technologies available. It involves the initial cost, discount rate, fuel cost, operation, and maintenance cost [32]. The LCOE is often given in $/kWh. Table 3 shows the financial parameters used in the calculation [33–35]

Table 3: Financial parameters.

Factor	Value	Unit
Inflation rate	3	%
Discount rate	0	%
Project life	25	Year
Debt ratio	25	%
Debt interest rate	0	%
Debt term escalation	20	Year
Electricity export escalating rate	3	%

Since there is only one wind farm in Saudi Arabia at the existing time. Therefore, in this study, the capital cost of the wind farm was estimated to be 1400 $/kW based on the average global wind farms and Dumat Al-Jandal Project prices for constructing wind farms [36–38], and the annual operation and maintenance cost was estimated to be 45 $/kW of the wind farm capacity [39]. Additionally, the discount rate for feasibility of renewable power technologies in Saudi Arabia is typically taken as 0% [40]. Hence, in this study, the same discount rate will be used as well.

2.4. Estimation of energy and economics with RETScreen:

RETScreen is a clean energy simulation tool that can be used to evaluate energy production, costs, GHG emissions reduction, financial viability, and risk for various types of energy production technologies. Based on the input data to the software, RETScreen can estimate the annual energy production and the capacity factor of the installed wind turbine. Moreover, the economic parameters described in the above section can be evaluated via the built-in mathematical expressions in the software. Figure 2 shows the flow chart procedures for the optimization analysis used in RETScreen.

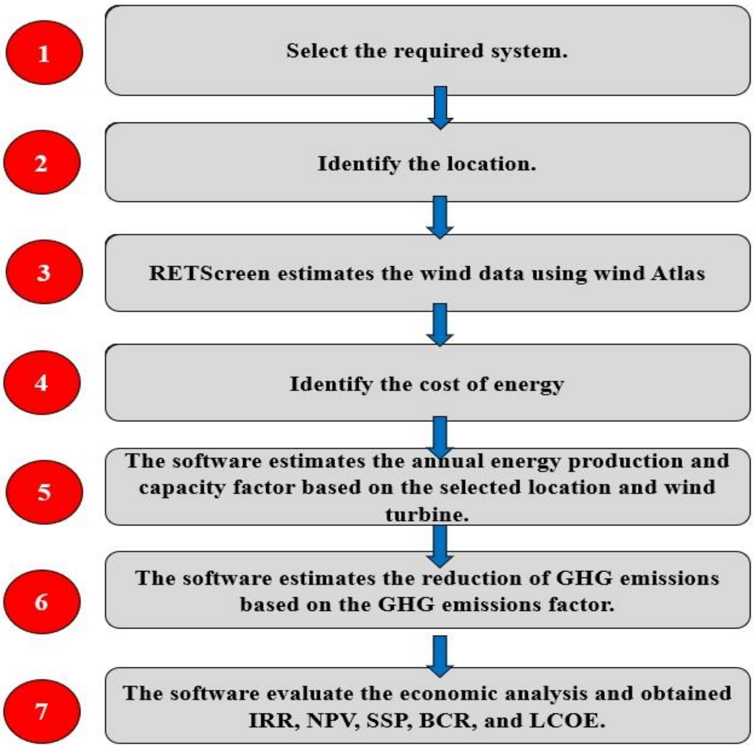

Figure 2: Flow chart Procedures used in RETScreen Software.

3. Result and discussion:

3.1. Wind speed analysis:

The wind data used in this study was obtained by NASA from 2020 to 2022 at an altitude of 10 m. In this study, MS EXCEL is used to analyze and calculate the wind records to obtain the average wind speed, wind directions, and Weibull distribution parameters.

Figure 3 shows the diurnal variations of wind speed for 3 years for Yanbu and Neom. For both selected sites, the hourly wind speed is not below 3 m/s but it does not exceed 7 m/s. In Neom, the highest wind speeds are after midnight between 1 AM and 6 AM. The wind speed then starts to decrease but not less than 3 m/s, and then the mean wind speed begins to increase during the evening period up to midnight. On the other hand, Yanbu has a consistent average diurnal wind speed at the beginning of the day from 1 AM to 10 AM. The wind speed then starts to increase to the peak at 6 PM. This shows that the systems at the two locations can operate consistently during the day and night time. Moreover, hybrid systems of wind turbines and PV modules can maintain the permanency of power production since Saudi Arabia is considered one of the top ranked countries with high solar radiation. Thus, no storage system will be required for such project.

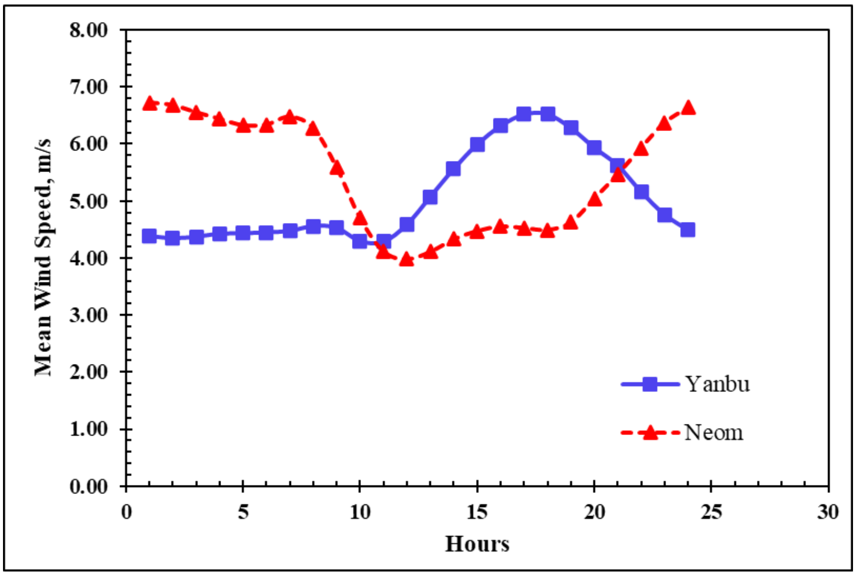

Figure 3: the diurnal variations of average wind speed in Yanbu and Neom.

Figure 4 shows the seasonal average wind speed during the data taken period. The monthly average wind speed in the two proposed locations is not below 4 m/s. In Neom, the seasonal wind speed fluctuates between 5 m/s and 6 m/s. Yanbu has a high average wind speed drop from April to June. Despite these variations, the seasonal wind speed shows the system can operate comparatively at consistent wind speed and power production rates.

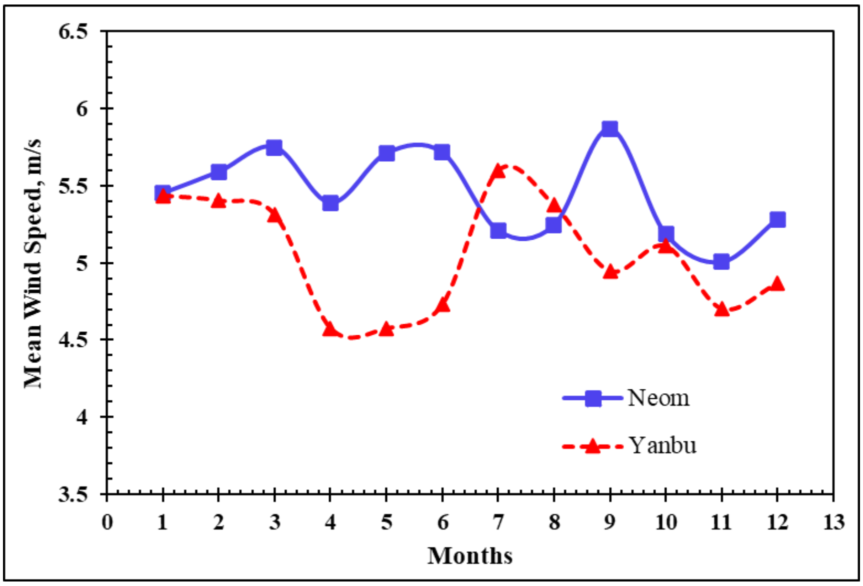

Figure 4: the seasonal variations of average wind speed in Yanbu and Neom.

Figure 5 illustrates the yearly variations in the average long-term wind speed. It can be seen that the yearly mean wind speed has the same pattern throughout the data taken period. Hence, it gives an indicator to investors of the availability of wind energy production in the coming years.

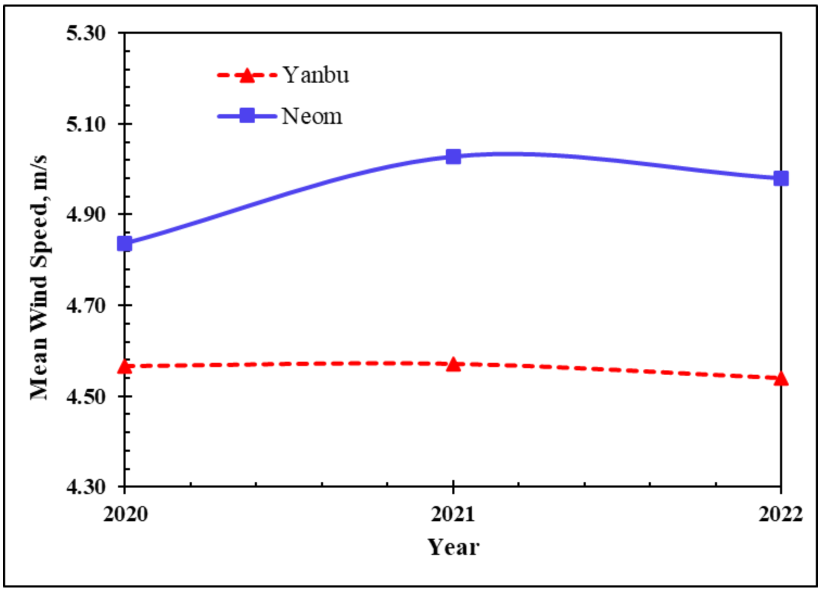

Figure 5: The annual variations of average wind speed in Yanbu and Neom between 2020 -2022.

Figure 6 shows the probability density function for both Yanbu and Neom. The scale and shape parameters obtained are 2.05 and 6 m/s for Yanbu and 2.54 and 6.5 m/s for Neom. Figure 7(a, b) shows the wind rose for Yanbu and Neom respectively. It is shown from the Figures that the most prominent wind direction in Yanbu is from the north direction which is about 39.62% of all the time, whereas in Neom, the most prominent wind direction is the north-west direction and it is about 40.45% of all the time. Finally, at 10 m above the ground, the frequencies of wind speed above 3 m/s in Yanbu and Neom are 77% and 78% respectively, which means that the wind power generation is available with these percentages in the two proposed sites.

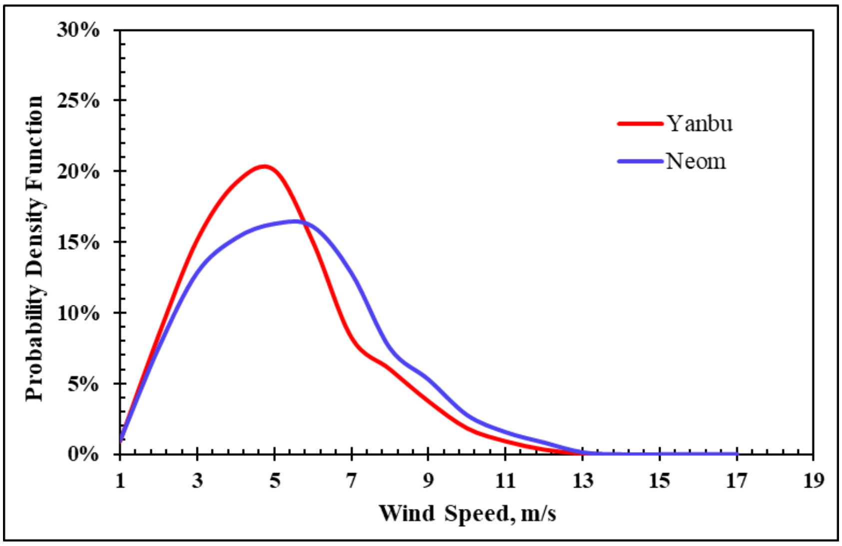

Figure 6: the probability density function for both Yanbu and Neom.

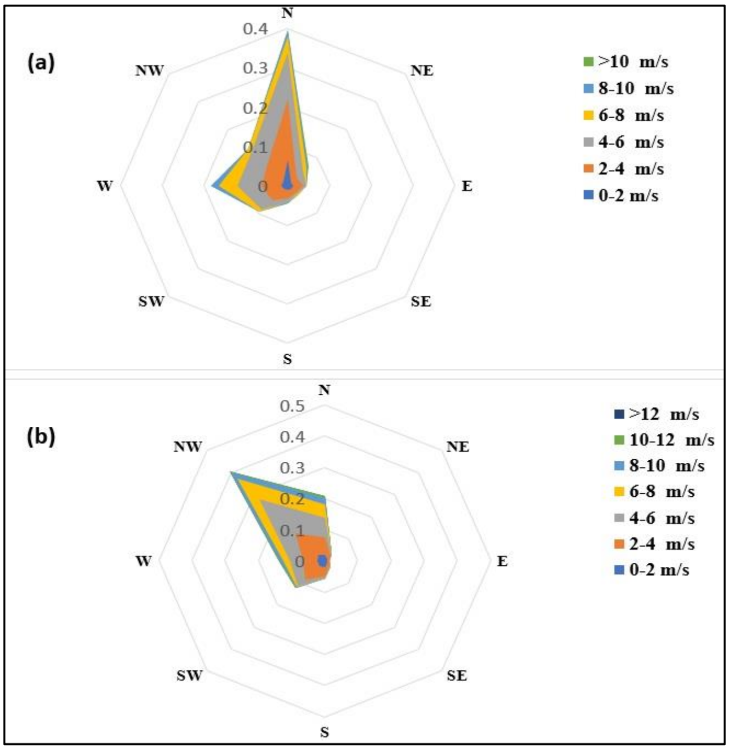

Figure 7: wind rose direction for (a) Yanbu (b) Neom.

3.2. Energy production calculations:

The annual energy production in the two proposed locations was estimated by using two different approaches, namely the Bins method for frequency distribution, and the RETScreen model, as already mentioned in the above section. Table 4 shows the annual energy production in MWh and the capacity factor (CF) via the four wind turbines assessed in this study.

	Yanbu				Neom			
	DeWind	Gamesa G114	GE Wind 1.85	Suzlon S95	DeWind	Gamesa G114	GE Wind 1.85	Suzlon S95
Annual Energy Production (RETScreen), MWh	58,476	85,768	46,952	68,384	76,878	95,610	61,474	81,749
Annual Energy Production (Bins Method), MWh	59,476	86,611	47,808	69,790	78,461	94,496	60,273	82,749
Capacity Factor (RETScreen), %	22.4	33.1	18.1	26.6	29.3	36.4	23.7	31.7
Capacity Factor (Bins Method), %	22.6	33.3	18.5	27.1	30	36.2	23.1	32.2

Table 4: The annual energy production and capacity factors of wind turbines.

In Yanbu, the annual energy production and capacity factor are approximately the same by using the two methods. The variation between the two methods is about 1%. On the other hand, in Neom, a small difference between the two methods nearly 2%. This variation is due to the long distance between the selected location and the wind station throughout RETScreen. Overall, this difference is considered negligible. However, the annual energy production and the capacity factor in Neom are higher than in Yanbu. The best performance among the wind turbines assessed is Gamesa G114 with a capacity of 2 MW. The variations among these turbines are due to the differences in hub height, swept area, and the efficiency of each turbine. Therefore, for these two locations, class IV wind turbines are recommended to be used for low annual wind speed.

3.3. Economic analysis:

The economic analysis in this study is based on several parameters including IRR, SPP, NPV, BCR, equity payback, and LCOE. The total cost of the wind farm including various expenditures is $42,000,000 by using DeWind and Gamesa (G114) wind turbines, while it costs $41,440,000 for GE wind (1.85), and $41,160,000 for Suzlon (S95) wind turbines since these two designs are approximately have less capacity than 30 MW. Table 5 shows the main economic parameters for each wind turbine used in this study in the two proposed locations.

Table 5: The economic parameters of wind turbines.

	Yanbu				Neom			
	DeWind	Gamesa G114	GE Wind 1.85	Suzlon S95	DeWind	Gamesa G114	GE Wind 1.85	Suzlon S95
Internal rate of return (IRR), %	11.3	19.5	7.5	14.7	16.7	21.9	12.4	18.5
Simple payback period (SPP), Year	12.5	7.6	17.1	9.9	8.7	6.7	11.6	7.9
Net present value (NPV), $	83,879,922	164,661,138	49,594,623	114,599,054	138,263,050	194,540,081	93,220,872	154,752,642
Benefit-cost ratio (BCR)	3.7	6.2	2.6	4.7	5.4	7.2	4	6
Equity payback, Year	9.3	5.7	12.6	7.4	6.5	5	8.6	5.9
Levelized cost of energy (LCOE), $/kWh	0.063	0.043	0.078	0.053	0.048	0.039	0.06	0.044

In Yanbu, the best economic performance was achieved by Gamesa (G114) wind turbines. The energy cost from this type is equal to 0.043 $/kWh, almost less than the current cost of electricity (Tariff), which is equal to 0.048 $/kWh for residential use and 0.08 $/kWh for industrial purposes. Furthermore, the time required to recover the initial investment of the project is 7.6 years after starting the operation of the wind farm.

In Neom, DeWind, Gamesa (G114), and Suzlon (S95) have comparatively excellent economic results. The cost of energy is less or equal to the cost of electricity in Saudi Arabia. Moreover, the time required to recover the initial investment cost is less than the situation in Yanbu.

Overall, based on the above financial analysis results, it is shown that the 30 MW capacity wind power plants in Yanbu and Neom are considered economically feasible.

3.4. GHG emissions reduction:

The utilization of this kind of clean energy for power generation results in the reduction of greenhouse gas emissions to the environment. Based on the GHG emission factor of 0.517 tCO_2/MWh and T&D losses of 7%, the proposed wind farms in the two sites have different GHG reduction capacities. Figure 8 shows the amount of GHG emissions saved for different wind turbines.

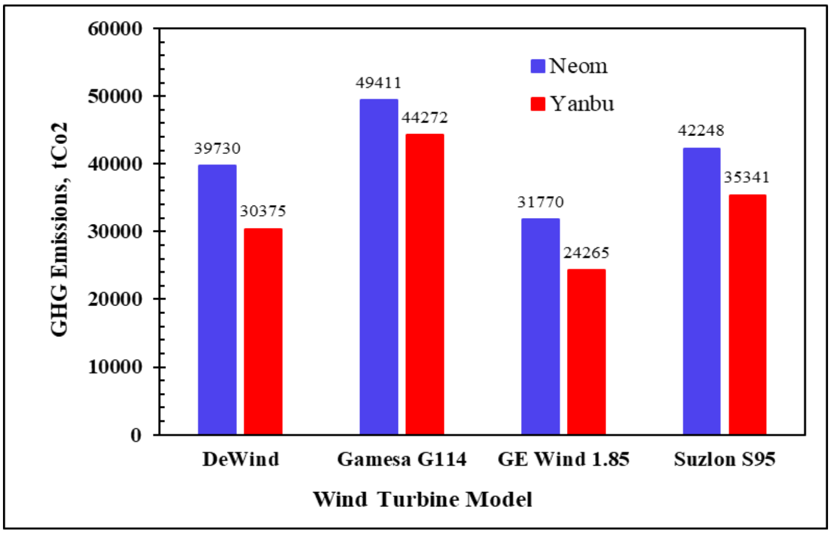

Figure 8: GHG emissions reduction of wind turbines.

The highest rate of GHG emissions reduction is via Gamesa (G114) in Neom with almost 50,000 tCO_2 displaced from entering the local atmosphere during the lifetime of the power plant. Therefore, installing such systems at the suggested sites will save the environment from huge amounts of GHG that may be emitted by using other conventional power plants.

4. Conclusion:

The present study conducted a techno-economic feasibility of constructing 30 MW capacity grid-connected wind power plants in two proposed locations in Saudi Arabia. Various wind turbines were assessed to investigate the potentials of these turbines in Yanbu and Neom, and which of them has the best performance on the level of energy production and economics parameters. The wind speed and directions records were obtained by the NASA Power website for the two locations. Two methods were used to estimate and analyze the annual energy production via Bins methos and RETScreen software. Furthermore, RETScreen software was used to estimate the main economic parameters and GHG emissions reduction. According to the present results, the two suggested locations are shown viable for installing wind power plants. The technical and economic analysis show that Gamesa (G114) has the best performance in which the capacity factor is the highest and the LCOE and SPP are the lowest among the other assessed wind turbines. The proposed wind farms show good environmental impact by offsetting huge amounts of GHG emissions from entering the local atmosphere. Consequently, it is highly recommended to experimentally investigate the potential of these two locations and evaluate the technical and economic challenges that could be encountered during equipment selections, procurement, contracting, government approvals, and so on. Therefore, it is a good opportunity for a learning curve for engineers, utilities, academicians, researchers, and contracting firms for the future deployment of such plants in Saudi Arabia and nearby regions.

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References:

[1] U. Zafar, T. Ur Rashid, A.A. Khosa, M.S. Khalil, M. Rahid, An overview of implemented renewable energy policy of Pakistan, Renewable and Sustainable Energy Reviews. 82 (2018) 654–665. https://doi.org/10.1016/J.RSER.2017.09.034.

[2] M.I. Aydin, I. Dincer, A life cycle impact analysis of various hydrogen production methods for public transportation sector, Int J Hydrogen Energy. 47 (2022) 39666–39677. https://doi.org/10.1016/J.IJHYDENE.2022.09.125.

[3] Statistical Review of World Energy | Energy economics | Home, (n.d.). https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html (accessed April 13, 2023).

[4] S. Jamshidi, K. Pourhossein, M. Asadi, Size estimation of wind/solar hybrid renewable energy systems without detailed wind and irradiation data: A feasibility study, Energy Convers Manag. 234 (2021). https://doi.org/10.1016/J.ENCONMAN.2021.113905.

[5] E. Holt, J. Wang, Trends in wind speed at wind turbine height of 80 m over the contiguous United States using the north American Regional Reanalysis (NARR), J Appl Meteorol Climatol. 51 (2012) 2188–2202. https://doi.org/10.1175/JAMC-D-11-0205.1.

[6] D. Carvalho, A. Rocha, M. Gómez-Gesteira, C. Silva Santos, WRF wind simulation and wind energy production estimates forced by different reanalyses: Comparison with observed data for Portugal, Appl Energy. 117 (2014) 116–126. https://doi.org/10.1016/J.APENERGY.2013.12.001.

[7] M. Sant'Anna de Sousa Gomes, J.M. Faulstich de Paiva, V. Aparecida da Silva Moris, A.O. Nunes, Proposal of a methodology to use offshore wind energy on the southeast coast of Brazil, Energy. 185 (2019) 327–336. https://doi.org/10.1016/j.energy.2019.07.057.

[8] Y.L. Abdel-Magid, Z.M. Al-Hamouz, J.M. Bakhashwain, A variable-structure stabilizer for wind turbine generators, Electric Power Systems Research. 33 (1995) 41–48. https://doi.org/10.1016/0378-7796(95)00925-8.

[9] Global Wind Report 2022 - Global Wind Energy Council, (n.d.). https://gwec.net/global-wind-report-2022/ (accessed March 27, 2023).

[10] IEA (2022), Renewable Energy Market Update - May 2022, IEA, Paris https://www.iea.org/reports/renewable-energy-market-update-may-2022, License: CC BY 4.0, (n.d.).

[11] K. Almutairi, R. Alahmadi, The Feasibility of the First Utility-Scale Wind Farm in Saudi Arabia (The 400 MW Dumat Al-Jandal Project), Journal of Clean Energy Technologies. 10 (2022) 1–10. https://doi.org/10.18178/JOCET.2022.10.1.531.

[12] Dumat Al Jandal Wind Farm, Al Jouf, Saudi Arabia, (n.d.). https://www.nsenergybusiness.com/projects/dumat-al-jandal-wind-farm/ (accessed April 13, 2023).

[13] M. Shoaib, I. Siddiqui, S. Rehman, S.U. Rehman, S. Khan, A. Lashin, Comparison of wind energy generation using the Maximum Entropy Principle and the Weibull distribution function, Energies (Basel). 9 (2016). https://doi.org/10.3390/en9100842.

[14] S. Rehman, M. Mahbub Alam, L.M. Alhems, M. Mujahid Rafique, Horizontal AxisWind Turbine Blade Design Methodologies for Efficiency Enhancement A Review, Energies (Basel). 11 (2018). https://doi.org/10.3390/en11030506.

[15] C. Azorin-Molina, S. Rehman, J.A. Guijarro, T.R. McVicar, L. Minola, D. Chen, S.M. Vicente-Serrano, Recent trends in wind speed across Saudi Arabia, 1978–2013: a break in the stilling, International Journal of Climatology. 38 (2018) e966–e984. https://doi.org/10.1002/JOC.5423.

[16] M.A. Baseer, J.P. Meyer, M.M. Alam, S. Rehman, Wind speed and power characteristics for Jubail industrial city, Saudi Arabia, Renewable and Sustainable Energy Reviews. 52 (2015) 1193–1204. https://doi.org/10.1016/j.rser.2015.07.109.

[17] S. Rehman, T.O. Halawani, M. Mohandes, Wind power cost assessment at twenty locations in the Kingdom of Saudi Arabia, Renew Energy. 28 (2003) 573–583. https://doi.org/10.1016/S0960-1481(02)00063-0.

[18] M.M. Rafique, S. Rehman, M.M. Alam, L.M. Alhems, Feasibility of a 100 MW installed capacity wind farm for different climatic conditions, Energies (Basel). 11 (2018). https://doi.org/10.3390/en11082147.

[19] K.S. AlQdah, R. Alahmdi, A. Alansari, A. Almoghamisi, M. Abualkhair, M. Awais, Potential of wind energy in Medina, Saudi Arabia based on Weibull distribution parameters, Wind Engineering. 45 (2021) 1652–1661. https://doi.org/10.1177/0309524X211027356.

[20] M. Bassyouni, S. Gutub, U. Javaid, M. Awais, S. Rehman, S. Abdel-Hamid, M. Abdel-Aziz, A. Abouel-Kasem, H. Shafeek, Assessment and analysis of wind power resource using weibull parameters, Energy Exploration and Exploitation. 33 (2015) 105–122. https://doi.org/10.1260/0144-5987.33.1.105.

[21] M.T. Naqash, M.H. Aburamadan, O. Harireche, A. Alkassem, Q.U. Farooq, The Potential of Wind Energy and Design Implications on Wind Farms in Saudi Arabia, International Journal of Renewable Energy Development. 10 (2021) 839–856. https://doi.org/10.14710/ijred.2021.38238.

[22] Global Wind Atlas, (n.d.). https://globalwindatlas.info/en/area/Saudi%20Arabia (accessed April 8, 2023).

[23] NASA POWER | Prediction Of Worldwide Energy Resources, (n.d.). https://power.larc.nasa.gov/ (accessed April 8, 2023).

[24] J.F. Manwell, J.G. McGowan, A.L. Rogers, Wind energy explained : theory, design and application, (2009) 689. https://books.google.com/books/about/Wind_Energy_Explained.html?id=roaTx_Of0vAC (accessed April 15, 2023).

[25] F. Alfawzan, J.E. Alleman, C.R. Rehmann, Wind energy assessment for NEOM city, Saudi Arabia, Energy Sci Eng. 8 (2020) 755–767. https://doi.org/10.1002/ESE3.548.

[26] T. Jackson, M. Oliver, Wind energy comes of age: Paul Gipe John Wiley, New York, 1995, Energy Policy. 24 (1996) 491–492. https://doi.org/10.1016/S0301-4215(96)90007-5.

[27] Suzlon S.95-2100 - 2,10 MW - Wind turbine, (n.d.). https://en.wind-turbine-models.com/turbines/474-suzlon-s.95-2100 (accessed April 15, 2023).

[28] DeWind D6 62/1000 - 1,00 MW - Wind turbine, (n.d.). https://en.wind-turbine-models.com/turbines/252-dewind-d6-62-1000 (accessed April 15, 2023).

[29] Gamesa G114-2.0MW - 2,00 MW - Wind turbine, (n.d.). https://en.wind-turbine-models.com/turbines/428-gamesa-g114-2.0mw (accessed April 15, 2023).

[30] S.S. Ahmad, A. Al Rashid, S.A. Raza, A.A. Zaidi, S.Z. Khan, M. Koç, Feasibility analysis of wind energy potential along the coastline of Pakistan, Ain Shams Engineering Journal. 13 (2022) 101542. https://doi.org/10.1016/J.ASEJ.2021.07.001.

[31] Natural resources Canada (NRCan). Clean energy project analysis. , n.d. https://publications.gc.ca/collections/collection_2007/nrcan-rncan/M154-13-2005E.pdf (accessed April 8, 2023).

[32] M. Kamran, Microgrid and hybrid energy systems, Fundamentals of Smart Grid Systems. (2023) 299–363. https://doi.org/10.1016/B978-0-323-99560-3.00006-5.

[33] F. Alfawzan, J.E. Alleman, C.R. Rehmann, Wind energy assessment for NEOM city, Saudi Arabia, Energy Sci Eng. 8 (2020) 755–767. https://doi.org/10.1002/ese3.548.

[34] K. Almutairi, R. Alahmadi, The Feasibility of the First Utility-Scale Wind Farm in Saudi Arabia (The 400 MW Dumat Al-Jandal Project), Journal of Clean Energy Technologies. 10 (2022) 1–10. https://doi.org/10.18178/JOCET.2022.10.1.531.

[35] M.M. Rafique, S. Rehman, M.M. Alam, L.M. Alhems, Feasibility of a 100 MW installed capacity wind farm for different climatic conditions, Energies (Basel). 11 (2018). https://doi.org/10.3390/en11082147.

[36] T. Stehly, P. Duffy, 2021 Cost of Wind Energy Review, (2021) 627281636.

[37] Dumat Al Jandal Wind Farm, Al Jouf, Saudi Arabia, (n.d.). https://www.nsenergybusiness.com/projects/dumat-al-jandal-wind-farm/ (accessed April 15, 2023).

[38] I. Renewable Energy Agency, RENEWABLE ENERGY TECHNOLOGIES: COST ANALYSIS SERIES Volume 1: Power Sector Acknowledgement, (2012). www.irena.org/Publications (accessed April 15, 2023).

[39] Wind Turbine Cost: Worth The Million-Dollar Price In 2022?, (n.d.). https://weatherguardwind.com/how-much-does-wind-turbine-cost-worth-it/ (accessed April 15, 2023).

[40] S. Rehman, M.A. Ahmed, M.H. Mohamed, F.A. Al-Sulaiman, Feasibility study of the grid connected 10 MW installed capacity PV power plants in Saudi Arabia, Renewable and Sustainable Energy Reviews. 80 (2017) 319–329. https://doi.org/10.1016/J.RSER.2017.05.218.