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Evaluation of the technical and environmental feasibility of replacing a steam generation unit with wind turbines at the Zawia refinery, Libya

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تقييم الجدوى الفنية والبيئية لاستبدال وحدة توليد بخارية بتوربينات رياح في مصفاة الزاوية، ليبيا

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Abstract

This study provides a comprehensive technical and environmental assessment of the traditional steam power generation unit (3.5 MW) that operates on heavy fuel oil at the Zawia Refinery, Libya, and examines the replacement of it with a wind farm based on ENERCON E-53 (800KW) wind turbines. Wind speed data from the reference height (50 m) to the height (80 m) were analysed using the power law method, and with the Weibull distribution, the expected power and annual energy production for the Enercon E-53 wind turbine were estimated using the turbine's power curve, in order to determine the number of wind turbines required as an alternative to the steam turbine. The environmental impact of the annual CO2 emissions from the steam turbine and wind turbines was also calculated. Based on the results obtained, it was found that energy production increases with the height of the turbine axis. A wind farm consisting of 12 turbines was proposed, producing approximately 26 GWh/year, which is equivalent to the annual production of the steam power generation unit. Environmental assessments based on life cycle emission factors indicated that replacing the steam unit with the proposed wind farm could reduce carbon dioxide emissions from approximately 20,848 tonnes of CO2 annually to nearly 391 tonnes of CO2 annually, equivalent to a reduction of over 98%. Based on the results, it has been shown that integrating wind energy into industrial facilities is a technically feasible and environmentally sustainable

solution to reduce reliance on fossil fuels and support the transition to clean energy systems in Libya.

Keywords: wind energy, Weibull distribution, wind turbine (Enercon E-53), Zawiya refinery, carbon emissions.

الملخص

تقدم هذه الدراسة تقييمًا تقنيًا وبيئيًا شاملاً لوحدة توليد الطاقة البخارية التقليدية (3.5 MW) التي تعمل بزيت الوقود الثقيل في مصفاة الزاوية، ليبيا، والتحقق في استبدالها بمزرعة رياح تعتمد على توربينات الرياح ذات الصنف ENERCON E-53 (800KW). تم تحليل بيانات سرعة الرياح من الارتفاع المرجعي (50 m) الى الارتفاع (80 m) باستخدام طريقة قانون القوة، وبتوزيع ويبل (Weibull) تم تقدير القدرة المتوقعة وإنتاج الطاقة السنوي لتوربين الرياح Enercon E-53باستخدام منحنى القدرة للتوربين، لغرض تحديد عدد توربينات الرياح المطلوبة كبديل للتوربين البخاري. كما تم حساب الأثر البيئي للانبعاث السنوي لغاز (CO_2) للتورين البخاري وتوربينات الرياح. استنادًا إلى النتائج التي تم الحصول عليها تبين ان إنتاج الطاقة يزداد مع ارتفاع محور التوربين، وتم اقتراح مزرعة رياح تتكون من 12 توربين تنتج حوالي (26 GWh/year)، وهو ما يعادل الإنتاج السنوي لوحدة توليد الطاقة البخارية. أشارت التقييمات البيئية التي تعتمد على عوامل انبعاث دورة الحياة إلى أن استبدال الوحدة البخارية بمزرعة الرياح المقترحة يمكن أن يقلل انبعاثات ثاني أكسيد الكربون من حوالي 20,848 طنًا من ثاني أكسيد الكربون سنويًا إلى ما يقرب من 391 طنًا من ثاني أكسيد الكربون سنويًا، مما يعادل تقليلاً يتجاوز98%. بناءً عن النتائج تبين أن دمج طاقة الرياح في المنشآت الصناعية هو حل تقني قابل للتطبيق ومستدام بيئيًا لتقليل الاعتماد على الوقود الأحفوري ودعم الانتقال الى أنظمة الطاقة النظيفة في ليبيا.

الكلمات المفتاحية: طاقة الرياح، توزيع ويبل، توربين الرياح (Enercon E-53)، مصفاة الزاوية، الانبعاثات الكربونية.

1.Introduction

The increasing global demand for energy, along with growing environmental concerns related to greenhouse gas emissions, has accelerated the transition towards renewable energy systems. In Libya, the energy sector still heavily relies on fossil fuels, particularly in industrial facilities such as oil refineries, where steam-based power generation units are widely used [3, 4].

These systems are associated with high fuel consumption and significant carbon dioxide (CO2) emissions [13, 14]. Wind energy has emerged as one of the most promising renewable energy technologies due to its environmental sustainability and technological maturity [7, 9].

The coastal areas of Libya, especially the northwestern regions such as Zawia, exhibit wind characteristics that make them suitable for wind energy deployment [1, 5].

This study aims to evaluate the feasibility of replacing the traditional steam-based power generation unit (3.5 MW) at the Zawia refinery with a wind power system, focusing on energy production and environmental impact. This study contributes to bridging the gap between renewable energy potential and industrial energy demand in Libya.

2. Literature Review

Several research studies have investigated the application of wind energy systems in coastal and industrial regions.

Hassan et al. [1] conducted a wind energy assessment for the Zawiya region in northwest Libya using statistical wind analysis methods. Their findings confirmed that the region has suitable wind characteristics for large-scale electricity generation.

Elfituri [5] performed wind resource modeling and mapping for the northwestern coast of Libya. The study demonstrated that coastal regions possess stable wind speeds and significant renewable energy potential.

Khan and Iqbal [10] developed a Weibull-based model for estimating wind turbine power curves and annual energy production. Their study concluded that Weibull statistics provide accurate predictions for wind energy performance.

Abdullah [8] investigated the reduction of CO_2 emissions through renewable energy integration in oil refinery operations. The results showed that replacing conventional fossil fuel systems with renewable energy technologies can significantly reduce greenhouse gas emissions.

Al-Mashat and Khatib [3] studied renewable energy development opportunities in Libya and highlighted the importance of wind energy systems in supporting sustainable industrial development.

Fadai [6] analyzed wind power potential in Mediterranean regions and reported that moderate wind speed areas can achieve efficient wind turbine performance and acceptable capacity factors.

These studies demonstrate that wind energy systems are technically feasible and environmentally beneficial for industrial applications. However, limited studies have specifically addressed replacing steam-based generation units in Libyan oil refineries using wind turbines, which represents the focus of the present study

3. Methodology

The wind speed data used in this study were obtained from research [1], which represents the Zawiya area located on the northwestern coast of Libya.

The calculations were performed using the monthly average of the wind speed data referenced in study [1]. Excel was used to analyse the data at the reference height (50 m) and the turbine hub height (80 m) according to the following equations [16]:

3.1 Application of the power law to convert wind speed from the reference height (50 m) to the turbine hub height (80 m) using the shear coefficient {α = 0.14}. This value is consistent with coastal terrain conditions, as is commonly practiced in wind energy studies [7].

$$V_2 = V_1 (h_2/h_1)^{\alpha} \quad (1)$$

Where V_2 is the wind speed at the turbine hub height h_2, and V_1 is the wind speed at the reference height h_1.

3.2 Calculating the average wind speed from the equation:

$$\overline{V} = \frac{1}{n}\left[\sum_{i=1}^{n} \overline{V}i\right] \quad (2)$$

Where n is the number of wind speed data points, V1 is the wind speed for (i) reading.

3.3 Calculating the standard deviation of wind speed from the equation:

$$\sigma = \sqrt{\frac{1}{n}\sum (Vi - \overline{V})^2} \quad (3)$$

3.4 Calculation of the Weibull variable for the dimensionless shape factor (K) for the average wind speed from the equation:

$$K = \left[\frac{\sigma}{\overline{\overline{V}}_i}\right]^{-1.086} \quad (4)$$

3.5 Calculation of the Weibull variable for the scale parameter (C):

The measurement coefficient or the characteristic property of wind speed is a variable speed that depends on the average wind speed at the study site. It can be calculated from the equation:

$$C = \left[\frac{1}{n}\sum_{i=1}^{n} Vi^{k}\right]^{\frac{1}{K}} \quad \ldots (5)$$

3.6 Calculation of the Weibull probability function for wind speeds from the equation:

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad \ldots (6)$$

3.7 The annual energy produced by the turbine was calculated using the following equation:

$$Energy = T\sum_{v=0}^{v=25} f(v)P(V) \quad \ldots (7)$$

Where T is the number of hours in a year (8760 hr.), $f(v)$ is from equation (6), and P(V) is the output power from the wind turbine taken from the power curve [2] for the Enercon E-53 (800 KW) turbine from figure (1).

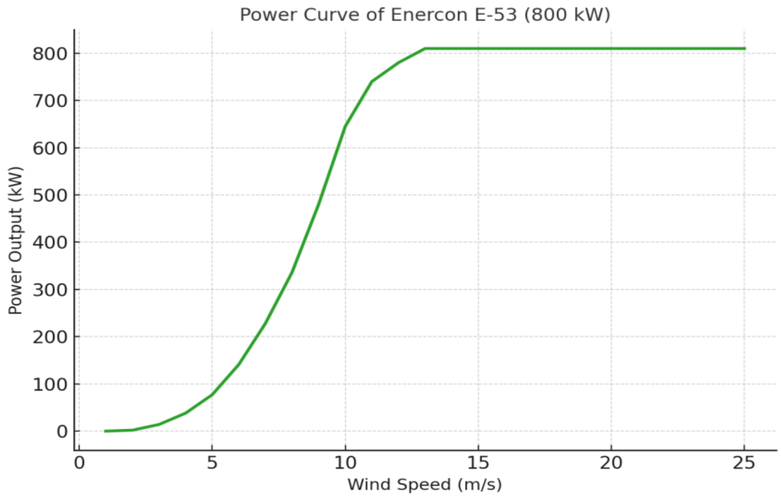

Figure (1): Power curve for the Enercon E-53 turbine with a capacity of (800kw)

The technical specifications of the (ENERCON E-53) turbine from the manufacturer's data [2] are detailed in Table (1).

Table (1): Technical specifications of the Enercon E-53 turbine

Turbine model	Enercon E-53
Rated power (kw)	800 kW
Rotor diameter (m)	52.9 m
Swept Area	2,200 m²
Cut-in wind speed (m/s)	3 m/s
Rated wind speed (m/s)	12 m/s
Cut-out wind speed (m/s)	25 m/s

3.8 Calculation of the annual capacity factor:

$$C_f(\%) = \frac{\text{wind energy produced (Wh/year)}}{\text{rated wind energy produced (wh/year)}} \times 100 \quad \ldots\ldots\ldots (8)$$

3.9 Calculating the environmental impact of the annual CO_2 emissions for steam turbines and wind turbines:

The existing steam generation system produces high emissions of carbon dioxide (CO_2). Where the emission factor for using heavy fuel oil is approximately ($0.8\ Kg\ co_2/KWh$) [13] [14].

Accordingly, the annual emissions of the steam unit are calculated from equation (9):

$$E_{CO_2(steam)} = AEP_{\{steam\}} * 0.8 \ldots\ldots\ldots (9)$$

The annual emissions for wind energy systems are calculated from equation (10), where the emission factor for the turbine's life cycle is (0.015 (Kg CO_2)/KWh) [15].

$$E_{CO_2(wind)} = AEP_{\{wind\}} * 0.015 \ldots\ldots\ldots (10)$$

4. Results

Figure (2) shows the monthly average wind speed for the year in which the reference height (50 m) [1] and the axis height (80 m) were calculated, where it is evident that as the height increases, the wind speed also increases.

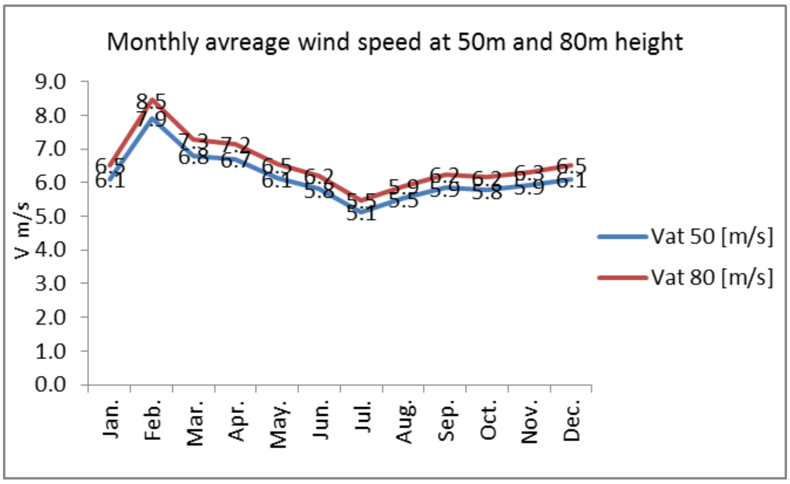

Figure (2): Monthly average wind speed at heights of 50 m and 80 m

When the turbine shaft height is (50 m), the annual energy production ($\sum_{v=0}^{v=25} f(v)P(V)$ reached approximately (205.66 KW) per turbine, resulting in an annual energy production value from equation (7):

$$AEP\{50\} = 1{,}801{,}581\ KWh/year = 1.80\ GWh/year$$

From equation (8), the capacity factor at this height reached (25.7%), which aligns with the performance of coastal wind sites in North Africa [5].

And at a turbine hub height of 80 m, it resulted in a significant increase in annual energy production by 20.5% $\sum_{v=0}^{v=25} f(v)P(V)$) approximately (247.57 KW) per turbine as shown in Figure (3).

The energy produced at this height reached:

$$AEP\{80\} = 247.57 * 8760 = 2{,}168{,}713\ KWh/year = 2.17\ GWh/year$$

The capacity factor also increased to 30.9%, confirming the feasibility of adopting high-axis turbines to achieve greater efficiency.

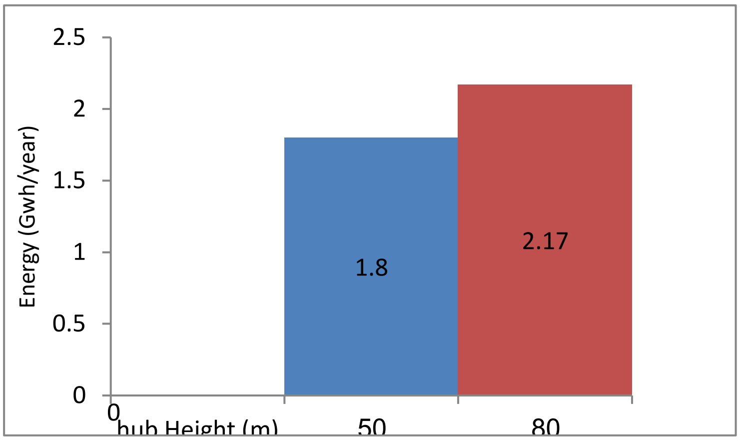

Figure (3): The effect of turbine hub height on annual energy production

The number of wind turbines required as an alternative to the steam turbine:

The nominal capacity of the steam unit is (3.5 MW), and it operates year-round (8760 hours), with a capacity factor of (0.85) which represents the optimal operating conditions for power plants [17] [18]. Thus, its approximate annual production is:

$$AEP_{\{steam\}} = 3.500 * 8760 * 0.85 = 26060\, MWh/Year$$
$$= 26.06\, GWh/Year$$

A total of 12 turbines of the Enercon E-53 model at a height of 80 m have been proposed as an alternative to the energy produced by the steam turbine.

$$AEP_{\{wind\}} = 2.17 * 12 = 26.04 \text{ GWh/year}$$

Table (2) shows a comparison of wind turbine performance at two different heights, where the results are better at a height of (80 m).

Table (2): Comparison of Wind Turbine Performance at Two Different Heights

Parameter	50m Height	80m Height
Average Power (kW)	205.66	247.57
Annual Energy (GWh)	1.80	2.17
Capacity Factor (%)	25.7	30.9
Turbines Required	12	

The results show that increasing the height of the wind turbine hub from (50 m) to (80 m) leads to an improvement in annual energy by a percentage of:

$$\frac{2.17 - 1.80}{1.80}(100) = 20.5\%$$

Environmental Impact:

From an environmental perspective, the traditional steam-based system produces significant carbon dioxide emissions due to the combustion of fossil fuels, which can be calculated from equation (9):

$$E_{CO_2\{steam\}} = 26.06 * 10^6 * 0.8 = 20848000\ kg$$
$$= 20848\ ton\ CO_2/year$$

While wind energy systems produce minimal emissions calculated from equation (10):

$$\mathrm{E}_{\mathrm{CO_2\{wind\}}} = 26.04 * 10^6 * 0.015 = 390600\ \mathrm{kg}$$
$$= 390.6\ \mathrm{ton\ CO_2/year}$$

Therefore, the net decrease is:

Reduction_CO_2 $= 20848 - 390.6 = 20457.4\ ton/year$

And the percentage reduction in carbon dioxide emissions equals:

$$\frac{20848 - 390.6}{20848} \times 100 = 98.1\%$$

The above results are illustrated in Figure (4), and Table (3) shows the results of carbon dioxide emissions between the two systems.

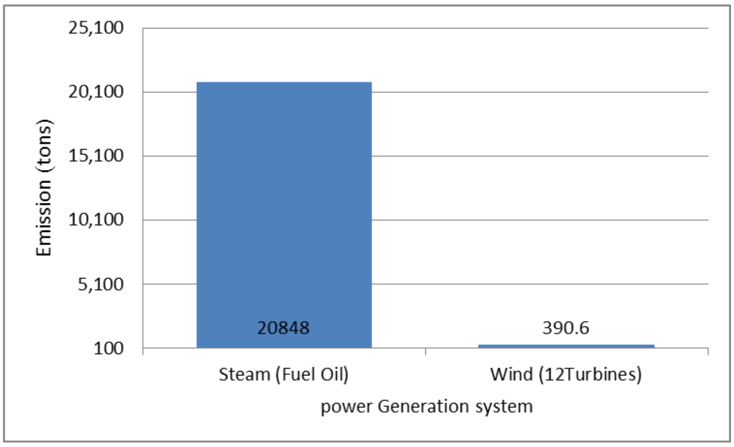

Figure (4): Comparison of carbon dioxide emissions

Table (3) shows the results of carbon dioxide emissions between the two systems.

System	Annual Energy (GWh)	Annual emission (tons)	Emission reduction rate
Steam (Fuel Oil)	26.06	20,848 ton	98.1%
Wind (12 Turbines)	26.04	390.6 ton	

5. Discussion

The important results of this study can be summarized as follows:

1- The results show that wind energy can effectively replace steam-based power generation in industrial applications.

2- The results indicate that increasing the hub height from (50 m) to (80 m) leads to an approximate 20% increase in annual energy production due to the increase in wind speed, as well

The capacity increases from 25.7% to 30.9%, highlighting the significant impact of improving hub height on wind energy efficiency.

3- The environmental analysis shows a significant reduction in carbon dioxide emissions, highlighting the clear advantage of wind energy over fossil fuel systems.

6. Conclusions

Based on the results, the following can be concluded:

1- Wind energy can effectively replace the traditional steam power unit at the Zawiya refinery.

2- The proposed system (wind farm) achieves an annual energy output equivalent to that of the current steam plant and reduces carbon dioxide emissions by more than 98%.

3- The results confirm that wind energy is a technically feasible and environmentally sustainable solution for industrial applications.

Recommendations:

1- Due to the inability to obtain wind speed data for more recent years, we recommend verifying the results using wind speed data from 2016 or later.

2- Despite the environmental and energy advantages, wind fluctuations remain a barrier, necessitating integration with storage systems or hybrid systems to ensure reliable operation. Therefore, it is strongly recommended to integrate an energy storage system to ensure the reliability and continuity of power supply.

3- Economic analysis and optimization of hybrid systems that integrate wind energy with storage technologies.

4- State support to encourage investment in industrial renewable energy.

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