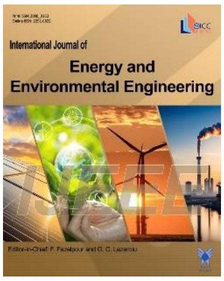

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Financial Modeling of Social and Environmental Impacts of Wind Farm in Urban Zones: A Case Study of Zawia-Libya

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Original Research

Abstract

This study presents both a physical and monetary evaluation of the key social and environmental impacts linked to the development of a 20 MW wind farm in Zawia, Libya. The analysis considers a range of externalities, including carbon footprint, water use, noise emissions, visual impacts, shadow and shadow flicker, land occupation, and potential electromagnetic interference. The project is planned on a 2 km² site and will incorporate 10 Gamesa G-114 wind turbines. Using the System Advisor Model (SAM) for energy yield estimation, the annual electricity generation reaches approximately 104,240.6 MWh. The project's initial capital cost is estimated at $39.36 million. The conventional levelized cost of energy (LCoE), calculated without factoring in social or environmental externalities, stands at $86.84/MWh. When externalities are monetized, they contribute an additional $7.92/MWh, representing nearly one-third of the operation and maintenance expenses ($25/MWh). If the evaluation internalizes only the carbon footprint, the LCoE decreases to $49.43/MWh. Conversely, when all social and environmental impacts are fully incorporated, the adjusted LCoE rises to $57.35/MWh. These findings highlight the critical importance of integrating external costs into wind energy assessments, providing a fairer comparison with conventional energy sources and strengthening the case for renewables in competitive energy markets.

Keywords: Wind energy, Levelized cost of energy (LCoE), Social and environmental impacts, Shadow flicker, Carbon footprint, Monetary value of environmental impacts

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1. Introduction

Global communities are increasingly seeking strategies to mitigate the environmental pollution associated with conventional energy sources, while simultaneously adopting energy-saving measures and promoting alternative energy options. Renewable energy (RE) and energy efficiency have emerged as critical solutions to global energy challenges, offering pathways to address both environmental and social concerns. RE contributes to the diversification of energy supply systems and provides opportunities for socio-economic development, including job creation and improved energy access for communities [1].

Driven by growing concerns regarding climate change and global warming, the global installed capacity of RE experienced a 50% increase in 2024. The total installed capacity of renewables—including solar, wind, hydropower, geothermal, marine, and biogas—reached approximately 4,448.1GW, with wind energy accounting for 1,021GW. This rapid expansion highlights a worldwide transition toward renewable and sustainable energy technologies [2].

Although renewable energy technologies such as solar, wind, marine, geothermal, hydropower, and biomass are often considered environmentally friendly, they are not entirely free from negative impacts. Reported challenges include biodiversity loss, land use changes, habitat disturbance, water consumption, air emissions linked to manufacturing and operation, disposal-related pollution, and noise generation [3–12]. Dai et al. [13] examined potential environmental challenges associated with wind farm development, consolidating evidence from prior case studies and recommending strategies to mitigate adverse effects. They emphasized the importance of implementing mitigation measures across the design, construction, and operational phases of wind projects. Despite these drawbacks, the overall benefits of wind energy are often found to outweigh the associated limitations.

To better understand urban wind energy deployment, a hybrid Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis was conducted [14]. The results indicated that strengths and opportunities accounted for 0.693, compared to only 0.307 for weaknesses and threats, underscoring the relative advantages of wind energy development.

Nevertheless, environmental concerns associated with wind turbines remain significant. These include impacts on wildlife safety, ecosystem disruption, noise, visual intrusion, electromagnetic interference, and potential effects on local climate [15–17]. Beyond environmental considerations, social acceptance represents another critical dimension [18,19]. The literature on social acceptance often focuses on local resistance and opposition, with much of the work seeking to provide descriptive accounts of community attitudes and the factors that drive opposition [15,20].

Wind energy stands out among renewable energy sources for its capacity to reduce the adverse social and environmental consequences of conventional energy [21,22]. Its deployment offers several socio-economic advantages, including job creation, poverty reduction, climate change mitigation, and pollution reduction, which collectively enhance public health and human well-being. Furthermore, wind energy projects can stimulate rural economic diversification by generating tax revenues, land lease payments, lower electricity costs, and additional financial incentives.

However, wind energy development also raises concerns related to land use change, which can strongly influence biodiversity and local vegetation by altering habitat quantity, quality, and availability [23,24]. Long-term studies are therefore essential to assess bird and bat fatalities, wildlife disturbance, and potential habitat loss [25]. Incorporating strategies to avoid, minimize, and mitigate negative impacts on biodiversity remains a key component of responsible wind energy development.

Despite the rapid global expansion of renewable energy technologies, limited research has quantitatively incorporated the monetary valuation of social and environmental externalities into the economic assessment of wind energy projects, particularly in developing countries such as Libya. Previous studies have largely emphasized environmental assessments or technical performance, with insufficient attention given to integrating these impacts into cost analyses that directly influence energy market competitiveness.

To address this gap, the present study evaluates a proposed 20 MW wind farm near Zawia, Libya, using a combination of field data and computational modeling (SHADOWS PRO 3.5 and MATLAB). The specific objectives are to:

- Quantify noise propagation and shadow flicker durations, benchmarking against WHO and IEA thresholds;
- Estimate shadow and visual impacts;
- Evaluate bird mortality risk;
- Map electromagnetic interference radii for aviation safety, representing a first for Libyan wind energy studies;
- Determine the carbon footprint across the life cycle of the wind turbines.

By integrating these analyses, the study not only provides a comprehensive assessment of environmental and social impacts but also evaluates their financial consequences, enabling a more realistic calculation of the LCoE. This dual approach represents the scientific contribution and novelty of the work, offering a template for sustainable wind farm siting in arid regions that balances energy output with ecological and community safeguards.

2. Description of the wind farm site

The proposed wind farm site is situated approximately 6 kilometers east of Zawia city, within the Guddaim region, at a longitude of 12.47°E and latitude of 32.47°N (Figure 1). The area exhibits favorable wind conditions and several additional characteristics that support the development of the project:

- Adequate wind resources suitable for energy generation.
- Availability of existing power lines and substations to facilitate integration of generated electricity into the grid.
- Sufficient land area, allowing flexibility in selecting
- ptimal locations for turbine installation.
- Relative isolation from densely populated areas, minimizing potential social impacts.
- Opportunities for future expansion with additional installed capacity.
- Accessible transport and communication infrastructure, while remaining suitably distant from the main district roadway.
- Proximity to end-users, reducing electricity transmission losses.

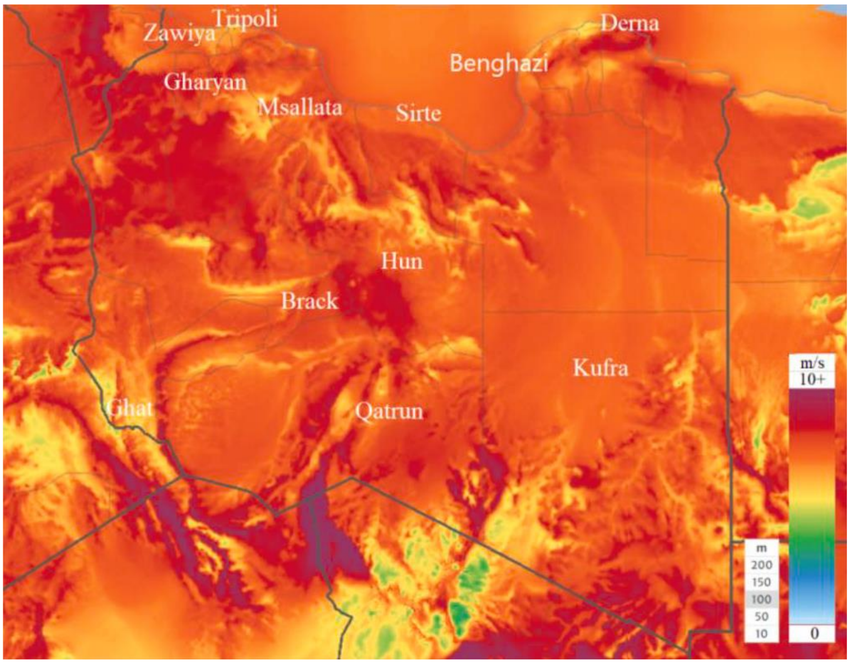

Figure 1. Zawia Location and wind speed at 100 m[Source: https://globalwindatlas.info/area/Libya/]

3. Methodology

Figure 2 presents the methodology overview for environmental and economic assessment of the proposed wind farm. The details of the methodology are as follows:

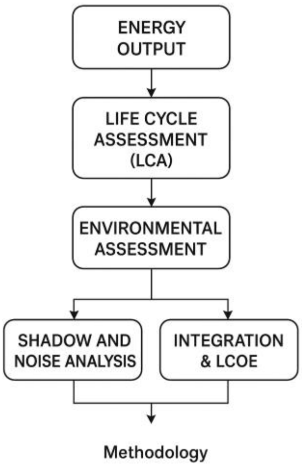

Figure 2. Methodology Overview for Environmental and Economic Assessment of the Proposed Wind Farm

- Energy Output Assessment

The proposed 20 MW wind farm was designed, and its expected energy production was calculated under optimal conditions based on a previous study [26]. The assessment considered turbine specifications, site wind resources, and layout optimization to estimate annual energy yield.

-Life Cycle Assessment (LCA)

A complementary Life Cycle Assessment (LCA) was conducted to evaluate the environmental performance of the proposed wind farm [27]. LCA is a systematic methodology that quantifies environmental impacts throughout the entire life cycle of a system—from raw material extraction, manufacturing, construction, and operation to maintenance and end-of-life disposal. In the previous LCA study [27], indicators such as Energy Payback Period (EPP), Energy Payback Ratio (EPR), avoided emissions, and fuel savings were quantified, demonstrating the environmental benefits of wind energy deployment.

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-Environmental Impact Assessment

This study further evaluated additional environmental aspects that were not fully addressed in the previous work. These include:

- Water consumption, a critical factor in arid regions.
- Noise pollution from individual turbines and cumulative farm-level noise.
- Visual impact and shadow flicker on nearby communities.
- Land use and site occupation.
- Electromagnetic interference, relevant for aviation and communication systems.

-Shadow and Noise Analysis

The shadow effect of the wind farm was assessed using SHADOWS PRO 3.5, while MATLAB was employed to calculate shadow lengths and evaluate their influence on surrounding areas. The MATLAB program was also used to compute turbine-specific noise levels and to assess the cumulative noise impact at multiple locations. All calculations were performed according to the equations described in the following section.

-Integration of Results By combining the LCA results with the assessment of water use, noise, shadow flicker, visual impact, land use, and electromagnetic interference, this study provides a comprehensive evaluation of both the environmental and social impacts of the proposed wind farm. The financial consequences of these impacts were then integrated into the economic analysis, enabling a more realistic determination of the levelized cost of energy (LCoE).

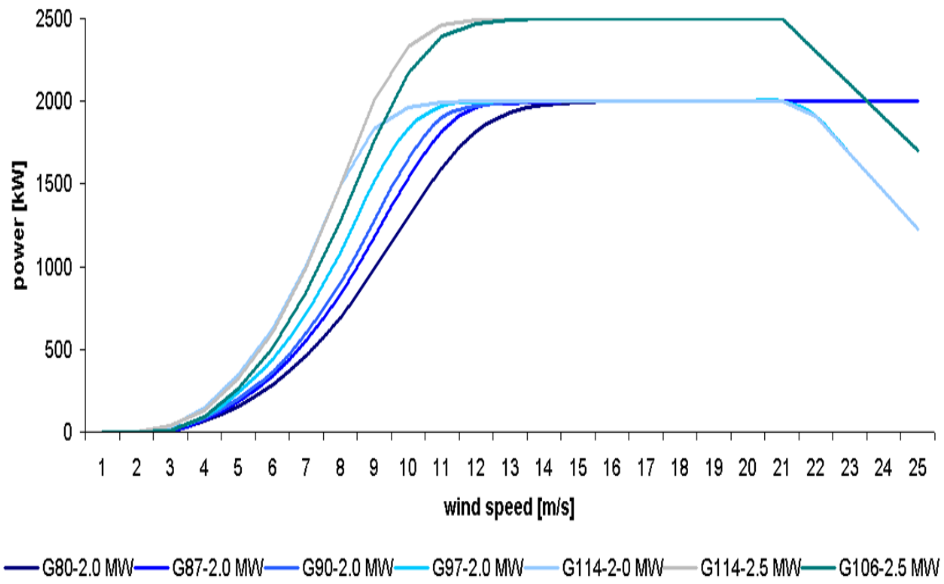

Figure 3. Power curve of the Gamesa G114-2.0/2.5 MW turbine compared with other turbine platform models [30]

Table 1. Specification of Gamesa G-114 wind turbine [30]

Rotor	
Diameter	114 m
Swept area	10207 m^2
Rotational speed	7.8 – 14.8 rpm
Blades	
Number of blades	3
Length	56 m
Airfoils	Gamesa
Tower	
Type	Modular
Height	93 m
Gear box	
Type	1 planetary stage – 2 parallel stages
Ratio	1: 128.5 (50 Hz) – 1:102.5 (60 Hz)
Generator	
Type	Doubly fed machine
Rated power	2MW
Voltage	690V AC

3.1. Wind turbine description

The Gamesa G114-2.0 MW wind turbine was selected for deployment in the proposed wind farm, as it has been identified as the most suitable configuration for the site conditions, in agreement with the recommendations of several local studies [28,29]. The planned wind farm comprises ten turbines, each with an anticipated operational lifespan of approximately 20 years. The turbine is rated at 2.0 MW and employs a three-bladed rotor design. It features a rotor diameter of 114 m, corresponding to a swept area of 10,207 m², supported by a tapered tower with a hub height of 93 m. Table 1 summaries the specification of Gamesa G-114 wind turbine [30]. The power curve of the G114, shown in Figure 3, is presented in comparison with alternative platform models [30].

3.3. Wind energy productivity

The energy generated by a specified wind turbine may be assessed as in equation 1 [31,32]:

$$E_{Wind}(t) = \begin{cases} 0 & V_Z(\mathrm{t}) \leq V_{cut-in}\ OR\ V_Z(\mathrm{t}) \geq V_{cut-off} \\ P_{rat}\left(\frac{V_Z(t) - V_{cut-in}}{V_{rat} - V_{cut-in}}\right) & V_{cut-in} < V_Z(\mathrm{t}) < V_{rat} \\ P_{rat} & V_{rat} \leq V_Z(\mathrm{t}) < V_{cut-off} \end{cases} \tag{1}$$

Where: P_{rat} is the rated power of the wind turbine at rated wind speed V_{rat}, V_{cut-in} and $V_{cut-off}$ represent the cut-in and cut-off wind speeds, respectively; and $V_Z(t)$ is the wind speed at the wind turbine hub height (h_Z) is assessed by the exponent relation as: $V_Z(t) = V_0(t)\left(\frac{h_Z}{h_0}\right)^{\sigma}$, where σ wind shear coefficient which taken as 1/7 [33,34]. Table 2 presents the main parameters of the proposed wind turbine.

Table 2. The main parameters of proposed wind turbine [35]

Metric	Value
Hub height	93.0 m
Cut-in speed	2.0 m/s
Cut-out speed	22.0 m/s
Rated speed	10.0 m/s
Rated power	2.0 MW

3.4. Assumptions, limitations and uncertainties in the results

To facilitate the analysis, the following assumptions were adopted:

1. All monetary values are expressed in US dollars ($) as of August 10, 2024.
2. Degradation of wind energy production over time is not considered.
3. The wind speed profile at the turbine hub height is assumed to follow the power law.
4. The analysis assumes no controller faults occur during operation.

Although the methodology presented in this study is comprehensive and can, in principle, be applied to various wind turbine types and geographical locations, the present results are restricted to a single turbine model and a specific site.

The primary sources of uncertainty in this work arise from:

- The datasets employed for the monetary estimation of the social and environmental impacts of wind energy utilization, and
- The considerable variability in wind energy equipment costs reported in the literature [36].

3.4. Environmental assessment of the proposed wind farm

3.4.1. *Water consumption*

Water consumption is a key performance indicator (KPI) that quantifies the total freshwater use associated with the entire life cycle of a wind turbine. It is typically expressed as the mass of water consumed per unit of energy generated (g/kWh). The estimation is derived from the life cycle inventory (LCI) data on water use for all turbine components across different life cycle stages. Reported values for wind turbine water consumption vary considerably, ranging from 0 to 64 g/kWh over the operational lifespan [37]. For the Gamesa G114-2.0 MW turbine, the distribution of water consumption among its components is presented in Table 3 [38]. The analysis shows that the turbine's total life cycle water consumption amounts to 30.8 g/kWh. Among individual components, the tower and nacelle account for the largest shares, contributing 28.22% and 20.43%, respectively—together representing nearly half (48.65%) of the total. When combined, the principal components (nacelle, tower, rotor, and foundation) contribute 76.16% of the turbine's overall water consumption [38].The cost of purified desalinated water from seawater in Libya is approximately $6.20/m^3 [39].

3.4.2. Noise pollution

A wind turbine generates noise primarily from its mechanical and aerodynamic components.

Mechanical noise can generally be mitigated using conventional approaches. During the design stage, for example, the incorporation of acoustic insulation within the turbine casing effectively reduces noise emissions, while during operation, the use of acoustic insulation drapes and anti-vibration foundation supports can further diminish noise levels [40]. In contrast, aerodynamic noise is more complex in origin and is strongly influenced by turbulent wind flow conditions and the rotational speed of the blades. As reported by Oerlemans et al. [41], such factors significantly increase aerodynamic noise emissions. This type of noise can be mitigated through careful aerodynamic optimization of blade design [41]. The intensity of noise perceived at a receptor site (e.g., residential areas) is also affected by the distance from the source and the characteristics of the propagation path. In general, the sound pressure level decreases with increasing distance. For flat terrains without obstacles, a hemispherical propagation model is typically assumed. Additional factors, including meteorological conditions and surface roughness of the site, further influence noise propagation.

Under these assumptions, the sound pressure level L_P at a distance R from a wind turbine emitting a noise intensity of L_W can be expressed as follows [40]:

$$L_P = L_W - 10\log_{10}(2\pi R^2) - \epsilon R \tag{2}$$

where ϵ is the sound absorption coefficient. In case of broadband sound, δ may be taken as 0.005 dB(A)/m. [40].

The combined effect of noise generated (L_{AZ}) by several turbines close to a residential area can be derived from each turbine individually according to the following equation [41]:

$$L_{AZ} = 10\log\sum_{i=1}^{n} 10^{0.1L_i} \tag{3}$$

Where: L_i is the Sound pressure level for each wind turbine.

$$L_{pT} = 10\log\sum_{i=1}^{n} 10^{0.1(L_{pi}-90)}\,(\mathrm{dB}) \tag{4}$$

$$P_N = 10^{0.1(L_{pi}-90)}\,(\mathrm{W}) \tag{5}$$

Where:

L_{pT} : Total pressure level from all wind turbines

L_{pi} : Pressure level of each wind turbine

P_N : Sound power of each wind turbine.

To assess the monetary value of noise pollution, it is necessary to first estimate the A-weighted day–evening–night equivalent sound level (L_{den}), expressed in decibels (dB), which is defined as follows [42]:

$$L_{den} = 10\log\frac{1}{24}\left\{12\left(10^{\frac{L_{day}}{10}}\right) + 4\left(10^{\frac{L_{evening}+5}{10}}\right) + 8\left(10^{\frac{L_{nigth}+10}{10}}\right)\right\} \tag{6}$$

where L_{day} represents the A-weighted long-term average sound level during the daytime period (12 hours, 07:00–18:00 local time), $L_{evening}$ denotes the A-weighted long-term average sound level during the evening period (4 hours, 19:00–22:00 local time), and L_{night} corresponds to the A-weighted long-term average sound level during the nighttime period (8 hours, 23:00–06:00 local time). In this study, the monetary value of noise impact (in $) was estimated and modeled using a Standard Curves; Five-Parameter Logistic (2-Slope) equation, implemented in SigmaPlot. The model achieved a high goodness-of-fit, with an accuracy of approximately $R^2 \cong 1$, as expressed below:

$$C_N = a + \frac{(b-a)}{\left[1 + f_1\left(\frac{L_{den}}{c}\right)^{-d} + (1-f_1)\left(\frac{L_{den}}{c}\right)^{(-dg)}\right]} \tag{7}$$

Where: $f_1 = \left[1 + \left(\frac{L_{den}}{c}\right)^{f_2}\right]^{-1}$, and $f_2 = \frac{2d.g}{1+g}$; $a = 43.0261$; $b = 196.028$; $c = 64.2029$; $d = 12.5695$; and $g = 2.2533$.

According to [43], financial compensation should be provided to individuals adversely affected by noise exposure, particularly those subjected to sound pressure levels exceeding 40 dB(A). Based on this criterion, each resident living within a 700-meter radius of the wind farm is entitled to an annual compensation of USD 50.3.

3.4.3. *Shadow and shadow flicker impact*

The shadow effect arises when the wind turbine tower obstructs sunlight. The resulting shadow length is a function of both the tower height and the solar position in the sky, as illustrated in Figure 4. The length and coordinates of the shadow can be determined using the following set of equations [44]:

Table 3. Water consumption for Gamesa wind turbine components [38]

Component	(ml/kWh)	%
Total life cycle	30.8	100.00%
Nacelle	6.29	20.43%
Rotor	5.15	16.75%
Tower	8.68	28.22%
Foundation	3.31	10.76%
Civil works	3.12	10.13%
Transport	0.733	2.38%
Operating	0.268	0.87%
Large correctives	0.844	2.74%
Gamesa productive processes	2.17	7.04%
End of life	0.208	0.67%

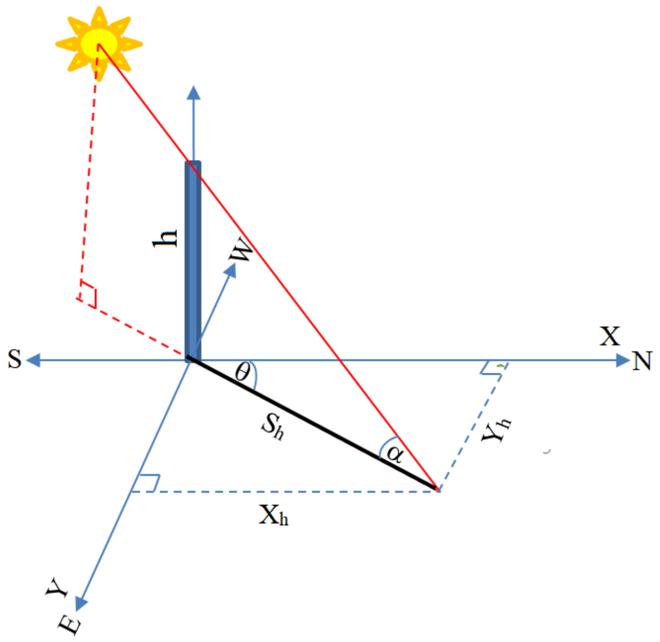

Figure 4. Derivation of the shadow coordinates of the wind turbine tower

$$S_h = h\,cot\alpha$$
$$\frac{X_h}{h} = cot\alpha\ cos\theta \qquad (8)$$
$$\frac{Y_h}{h} = cot\alpha\ sin\theta$$

Where [45]:

α is solar altitude angle;

$$\alpha = \sin^{-1}[\cos(\delta)\cos(\phi)\cos(\omega) + \sin(\phi)\sin(\delta)]$$

δ Is solar declination angle;

$$\delta = -23.45\cos\left[\frac{360}{265}(n+10)\right]$$

$\emptyset$= latitude location of the site

θ is the solar azimuth angle; $\theta = sin^{-1}\left[cos\delta\frac{sin\omega}{cos\alpha}\right]$

ω is the hour angle; $\omega = 15°(LST - 12)$

LST is local solar time.

Also, the shadow of a wind turbine can be estimated by using the Wind Turbine Shadow Calculator [46].

When the sun and rotating wind turbine generators (WTGs) are aligned at specific angles, a disruptive shadowing effect may occur. This effect is not produced by the tower itself but by the movement of the turbine blades, which creates a rhythmic alternation of light and shadow. The resulting fluctuations in brightness, typically occurring at frequencies of 0.5–3 Hz depending on the blade tip speed ratio, can become intrusive if they affect living or working spaces, potentially leading to health-related concerns [47].

Shadow flicker, defined as the intermittent shadow produced by turbine blades passing through direct sunlight, becomes a significant human impact when multiple factors coincide, such as the distance from the turbine, the duration of operation, and the angle of sunlight [48]. This phenomenon can affect individuals or buildings located within the shadow-affected zone. While shadow flicker can be observed over relatively large distances, it is limited in duration at any single location. Although it may cause annoyance and disturbance, current evidence indicates that it does not have direct adverse effects on human health.

$$Sf_m = \begin{cases} 1 & if\ \{[(\alpha - r_e)^2 + (\theta - t_a)^2] \leq (r - 0.25)^2\ and\ \alpha \geq 3\} \\ 0 & otherwise \end{cases} \tag{9}$$

Where: α and θ denote the sun's elevation and azimuth, r_e represents the rotor midpoint elevation (adjusted for the property's ground elevation and the turbine height), t_a is the turbine azimuth, and r is the rotor radius. All parameters are expressed in degrees, with solar positions calculated at one-minute intervals using standard spherical geometry relations.

In this study, shadow flicker was evaluated under the criterion that its duration at a sensitive receptor should not exceed 30 hours per year and 30 minutes per day on the most affected day [49,50].

Wind turbine generators (WTGs) may also produce other optical effects. One such effect is the emission of periodic light reflections from the rotating blades under strong sunlight, commonly referred to as the "disco-effect." Additionally, blades can cast intermittent shadows—termed "shadow flicker"—which depend on solar position, wind direction, and cloud cover. At night, WTGs may generate further visual disturbances due to aviation safety requirements, as tall turbines are equipped with aircraft warning lights. These lights, which blink rhythmically, can intrude into residential spaces and potentially disrupt sleep.

Shadow flicker has also been associated with economic impacts. Studies indicate that properties affected by this phenomenon may experience a decline in market value of up to 12%, with an additional reduction of up to 8.1% for homes most severely impacted. The extent of this effect is greater for high-capacity turbines and is influenced by turbine siting and proximity to residential areas [51].

3.4.4. *Visual impact*

The visual impact of wind farms is shaped by several technological and contextual factors, including turbine size, color, and contrast with the background, their proximity to residential areas, the occurrence of shadow flicker, the duration of operational versus idle states, and the historical presence of turbines in the local environment. Most visual impact assessments rely on Geographic Information Systems (GIS), which, combined with visibility analyses, allow researchers to identify affected areas and predict the degree of visual disturbance when a site is proposed [50,52]. Evaluating such impacts, however, remains a complex task. Thayer and Freeman's work on public perceptions of wind energy landscapes demonstrated that residents living closer to turbines, and those familiar with the original landscape, reported stronger perceptions of visual intrusion [53, 54]. Elements, *i.e.*, scenic backgrounds, regional topography, and intervening landscape features, also influence the turbines' visual perception [52,53].

In the case of the proposed wind farm, the visual impact was assessed to minimize disruption by integrating the turbines as harmoniously as possible into the landscape. Design considerations emphasized the importance of spacing, color choice, and placement so that the turbines would blend with the surrounding environment while remaining acceptable to nearby residents [54,55]. The degree of visibility was found to depend strongly on factors such as viewing distance, the number and scale of turbines, the presence of supporting infrastructure, and natural features like trees or hills, in addition to varying with time of day and weather conditions. When combined with community perception surveys, these factors provide a more comprehensive indication of the appropriateness of wind farm siting. In this context, the current study accounted for these parameters to minimize visual disturbance and achieve satisfactory outcomes. Furthermore, recent evidence indicates that visual exposure to wind turbines can extend beyond aesthetic concerns, as properties located within a turbine's viewshed have been shown to experience a measurable decline in value of about 1% [56].

3.4.5. *Bird mortality risk*

When avian fatalities are normalized per unit of electricity generated, wind energy proves considerably safer than both conventional and nuclear energy sources. Mortality rates are estimated at 0.269 birds/GWh for wind power, compared to 0.3–0.4/GWh for nuclear power and 5.2/GWh for fossil-fuel-based power plants [57–59]. The number of bird deaths associated with wind farms varies substantially depending on site location, turbine design, size, and hub height, ranging from zero fatalities in certain installations to as many as 9.33 birds per turbine annually [57–59]. To minimize potential risks to avifauna at the proposed site, patterns of local wildlife activity were carefully assessed. The economic valuation of bird mortality linked to wind turbines has been estimated at approximately $18,238 per GWh [60].

Figure 5. Paths of the Birds migration
[Source:
https://storymaps.arcgis.com/stories/b6e8946a0d56477eb46d22581591cbe2]

The suitability of the Zawia wind farm site was evaluated with reference to both bird migration routes and site-specific ecological conditions. As shown in Figure 5, which maps the location of the proposed wind farm relative to major migratory flyways between South Africa and Europe, the selected site does not intersect with critical migration pathways. Consequently, the project is not expected to exert significant adverse impacts on bird populations.

The figure indicates that major bird migration routes do not traverse the Libyan coast and remain distant from the proposed wind farm site. This substantially reduces the potential risk to migratory bird species. Furthermore, the site is characterized by the absence of trees or vegetation that could serve as nesting, roosting, or foraging habitats for birds or other wildlife. Owing to its unused and barren nature, the location can therefore be considered suitable for wind farm development without posing significant adverse effects on local or migratory fauna.

3.4.6. *Interference with telecommunication signals*

The impact of wind turbines on electromagnetic waves associated with air navigation and communication signals is generally negligible. Potential interference with navigation systems can be effectively mitigated by careful site selection and precise micro-siting of turbines. Electromagnetic interference (EMI) from wind turbines typically arises through three main mechanisms: direct interaction with signals, near-field effects, and diffraction or reflection phenomena. Diffraction occurs when an object simultaneously reflects and absorbs portions of a signal, leading to potential distortions. Although the exact minimum distance required to avoid interference between a wind turbine and a radar installation cannot be universally defined, predictive equations can be applied to approximate the conditions under which interference is likely to occur. As described by Boundless [61], radio waves are electromagnetic (EM) waves characterized by specific wavelength ranges that determine their susceptibility to such interactions.

$$r = \frac{c\,\eta\,A}{\lambda\,m_o} \tag{10}$$

where:

A: Wind turbine rotor swept area (m^2)
η: Retorted reflection blades (metal blades = 0.7 and fiberglass blades= 0.3)
c: Constant expresses the site.
λ: wavelength (m)
m_o: Signal density = 0.15

Watson [62] examined the economic implications of wind farm development near radar installations, noting that the associated radar data costs could amount to approximately $0.07 /hectare/year or around $20,000 /MW of installed capacity.

3.4.7. *Carbon footprint during the life cycle of wind turbines*

Wind energy is widely recognized as a key contributor to addressing environmental challenges and represents an essential bridge in the global clean energy transition. As one of the most promising renewable energy sources, it has the potential to mitigate many of the social and environmental impacts associated with conventional fossil-based energy systems. Nonetheless, wind power cannot be considered entirely emission-free, since carbon emissions are generated across all stages of the turbine life cycle, including manufacturing, transportation, installation, operation and maintenance, as well as decommissioning and either landfilling or recycling of turbine components. Nassar et al. [27] conducted a carbon footprint and life cycle energy assessment of the wind energy industry in Libya for several prospective sites and turbine types, including Gamesa models, reporting greenhouse gas (GHG) emission factors ranging between 32 and 70 gCO_2/kWh depending on site productivity, with an estimated value of 45.45 gCO_2/kWh for Zawia city.

The economic implications of these emissions are closely tied to global carbon pricing mechanisms. Under the European Union Emissions Trading System, established in 2005 as a market-based tool to reduce carbon emissions, the carbon price is projected to range between €65 and €78 per ton by the end of 2024, with further increases expected to reach approximately €130 per ton by 2040. Regionally, Egypt has set the carbon price at around $80 per ton for 2023, while Canada announced a trajectory that will raise its carbon price to CAD 170 ($214) per ton by 2030. In the United States, carbon pricing has shifted with political administrations: the Obama administration estimated the global social cost of carbon at $43/ton, the Trump administration reduced the valuation to $3–5/ton by considering only domestic impacts, and the Biden administration reinstated a global estimate of $51/ton, later supported by a 2022 U.S. Environmental Protection Agency proposal suggesting an increase to $190/ton [63]. At the global level, carbon pricing programs currently cover only about one-fifth of total emissions, with the average global carbon price at just $3/ton. The International Monetary Fund (IMF) has recommended differentiated minimum carbon prices by 2030, namely $70/ton for advanced economies, $50/ton for high-income emerging economies such as China, and $25/ton for lower-income emerging markets such as India. In contrast, Libya currently lacks any carbon pricing scheme (to the best of the authors' knowledge). For the purposes of this study, a value of $43/ton CO_2 is adopted [64], which translates into an estimated annual carbon-related cost of approximately $3.15/MWh for the proposed wind farm.

3.5. Economic and environmental analysis

The Levelized Cost of Energy (*LCoE*) is widely regarded as a key metric in the economic evaluation of energy systems. It represents the cost per unit of electricity generated over the lifetime of a project. Conventionally, *LCoE* is expressed as the ratio of the total annualized costs to the annual energy output (*E*), and can be formulated as follows [65–68]:

$$LCoE = \frac{\frac{i(1-i)^n}{(1-i)^n - 1} C_{Cap} + C_{\mathrm{O\&M}}}{E} \qquad (11)$$

Including the cost of environmental damage (C_C) in economic assessments ensures fair competition for clean and environmentally sustainable energy systems and enhances their market competitiveness [69]. Accordingly, the levelized cost of energy (*LCoE*) can be expressed as follows [70–73].

$$LCoE = \frac{\frac{i(1-i)^n}{(1-i)^n - 1} C_{Cap} + C_{\mathrm{O\&M}} - C_C}{E} \qquad (12)$$

Previous studies have incorporated the carbon life cycle footprint cost in Eq. (12) [74]. In the present study, a new parameter is introduced into the *LCoE* formulation, namely the carbon footprint cost of the wind energy industry (C_{Fp}). Consequently, the modified *LCoE* can be expressed as follows:

$$LCoE = \frac{\frac{i(1-i)^n}{(1-i)^n - 1} C_{Cap} + \left[C_{\mathrm{O\&M}} + C_{Fp}\right] - C_C}{E} \qquad (13)$$

The present approach enhances competition within the energy sector, extending it to account for the environmental performance of manufacturing processes, even for technologies of the same type. In this context, C_{Cap} represents the capital expenditures of the wind energy system ($1,968 per kWp) [75], including the costs of turbines, site preparation, installation, and grid connection, while $C_{O\&M}$ denotes the operation and maintenance costs ($10–25/MWh/year or $60/kW/year). *E* is the annual energy production (MWh/year), *n* is the turbine lifetime (25 years), and *i* is the interest rate (8.0%). The cost of environmental damage (C_{CO2}) associated with CO_2 emissions can be calculated using the following equation [76,77].

$$\mathrm{C}_{\mathrm{CO2}} = EF_{CO2} \times E \times \emptyset_{CO2}$$

where EF_{CO2} denotes the CO_2 emission factor of the electricity generation system (0.875 kg CO_2/MWh) [5,78,79], and $\emptyset_{CO2}$ represents the social cost of carbon ($/ton CO_2), which is assumed to be $43/ton CO_2.

4. Results and Discussion

4.1. Wind farm design and the energy yield

In this study, the SAM software was employed to simulate a 20 MW wind farm located in Zawia city. Figure 6 presents the eight-year (2015–2022) hourly time-series averages of wind speed alongside the corresponding power generation from the wind farm [26]. The wind speed data were supplied by the Libyan Center for Solar Energy Research and Studies, which oversees the measurement station at the University of Zawia.

The wind rose of the region is used to identify the prevailing wind direction. To achieve maximum energy yield, the wind farm should be oriented to face the incoming wind directly, ensuring that the wind flows perpendicular to the turbine rows, as illustrated in Figure 7.The design of the proposed wind farm was optimized to maximize energy output [80]. Considering environmental conditions and land availability, the turbines were positioned accordingly. The most suitable layout, based on the characteristics and specifications of the G-114 wind turbine, covers an area of 2 km² (0.5 km north–south by 4 km east–west), as illustrated in Figure 7. The estimated annual energy production of the 20 MW wind farm is 104,240.6 MWh.

4.3. Environmental impacts of the proposed wind farm

4.3.1. *Noise emission from proposed farm*

The noise emissions from the Gamesa G-114 turbines fall within the standard levels observed in the wind energy industry. It is also important to note that wind farms are typically situated in uninhabited areas, at distances exceeding 300 m from settlements, where noise levels are significantly reduced and generally considered negligible. In this study, noise levels at various distances within the proposed farm were evaluated. The farm consists of ten Gamesa G-114 turbines, each producing a sound power level of 105 ±2 dB(A). The turbines were arranged in a single east–west row, representing the optimal configuration in terms of minimizing noise within the farm boundaries and reducing potential impacts on residents located near the southern edge of the site. Figure 8 illustrates the turbine layout, where the spacing between units is set at 3D (342 m). Noise levels were calculated using MATLAB, applying both equations (5) and (6) to assess turbine-specific emissions as well as the cumulative impact of the farm at several locations. The results presented in Table 4 illustrate the noise levels within the proposed wind farm at varying distances. The combined noise effect of the turbines was calculated using equations (3)–(5), with L_{AZ} determined at 50 m. Additional calculations were performed at increasing distances of 100 m, 150 m, 200 m, and beyond. The results show a gradual decline in noise intensity, reaching an acceptable threshold at 300 m, where the sound level falls below 50 dB—a level considered environmentally compliant for nearby residential areas. Due to the land characteristics in this region, very few houses are located within a 300 m radius. The southern boundary of the proposed farm extends 500 m inland from the coast, where noise levels are further reduced to approximately 45 dB, a value regarded as negligible in terms of human auditory impact. As illustrated in Figure 9, the noise level at 50 m (highlighted in red) is approximately 60 dB. Sound intensity decreases progressively with distance, dropping below 50 dB at around 350 m (blue). This attenuation forms an arc-shaped distribution, with noise levels lower at the farm's corners compared to the central area. The calculated noise values derived using MATLAB are summarized in Table 4.

4.3.2. *Shadow impact of the proposed farm*

The results in Figure 10 illustrate the wind turbine shadow ratio length in both W–E and N–S directions at the proposed farm site. At sunrise, the shadow is extremely long (approximately 11,189 m) and oriented southwest at an angle of about 15°, making it practically imperceptible due to its excessive length. After one hour from sunrise, the shadow shifts westward, with a reduced length of about 681 m. At this stage, its influence outside the farm boundaries is minimal. As the day progresses, the shadow moves northward toward the sea, where it has no significant effect. During the final hour before sunset, the shadow reappears toward the southeast, again at an angle of about 15° from east, extending to nearly 11,189 m. Like sunrise, this long shadow has negligible impact. Overall, shading within the farm becomes noticeable only within limited durations, with significant reduction beyond 300–350 m, as depicted across different exposure thresholds (>1 h, >10 h, >100 h, and >1000 h) in Figure 10.

Table 4. Noise Levels at the wind turbine area

distance	Tur A	Tur B	Tur C	Tur D	Tur E	Tur F	Tur G	Tur H	Tur I	Tur J
50m	58.831	59.062	59.102	59.114	59.117	59.117	59.114	59.102	59.062	58.831
100m	55.398	55.841	55.922	55.946	55.953	55.953	55.946	55.922	55.841	55.398
150m	53.037	53.862	53.808	53.846	53.858	53.858	53.846	53.808	53.862	53.037
200m	51.243	52.052	52.224	52.276	52.293	52.293	52.276	52.224	52.052	51.243
250m	49.783	50.717	50.933	51.001	51.023	51.023	51.001	50.933	50.717	49.783
300m	48.541	49.562	49.820	49.904	49.931	49.931	49.904	49.820	49.562	48.541
350m	47.446	48.526	48.825	48.924	48.957	48.957	48.924	48.825	48.526	47.446
400m	46.459	47.577	47.913	48.029	48.067	4.067	48.029	47.913	47.577	46.459
450m	45.554	46.695	47.065	47.197	47.241	47.241	47.197	47.065	46.695	45.554
500m	44.714	45.867	46.267	46.415	46.466	46.466	46.415	46.267	45.867	44.714

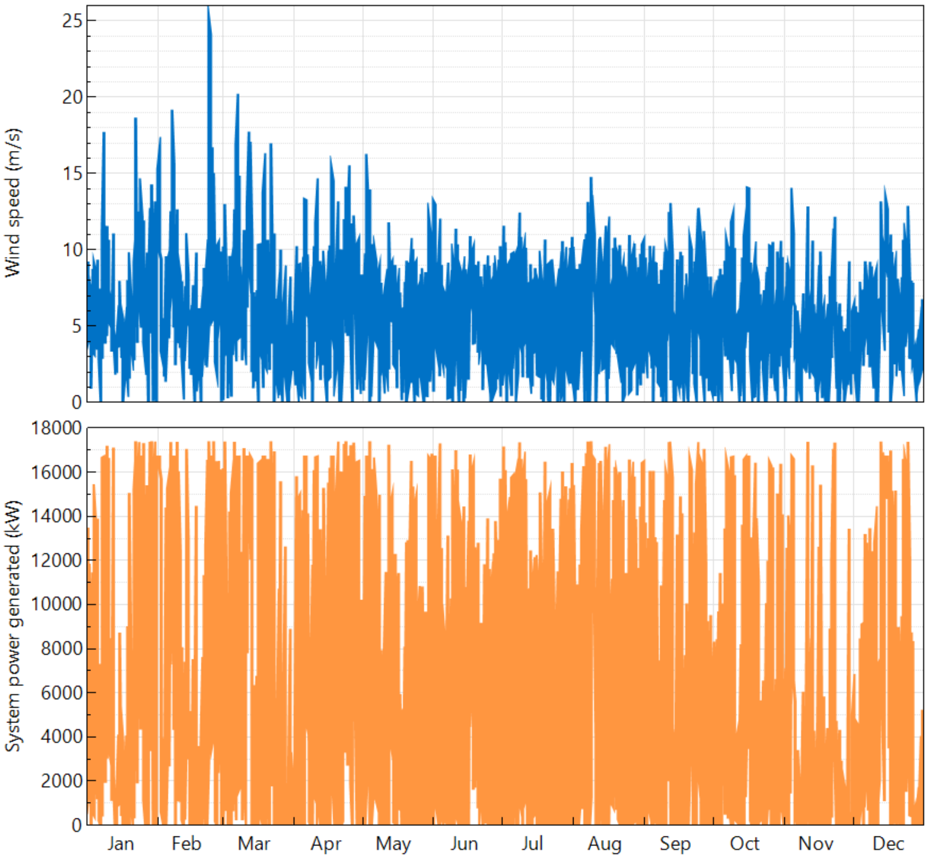

Figure 6. The average hourly wind speed and the corresponding wind farm power generation [26]

Figure 7. wind rose of the proposed wind farm

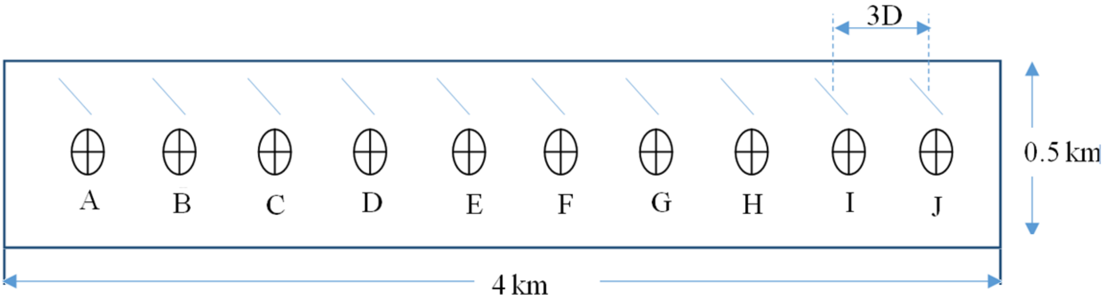

Figure 8. Position of the turbines on the farm

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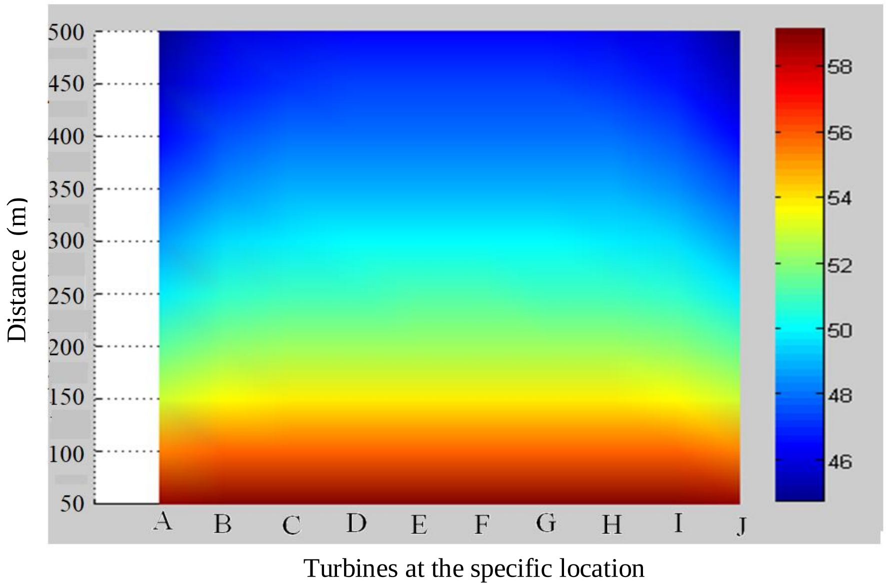
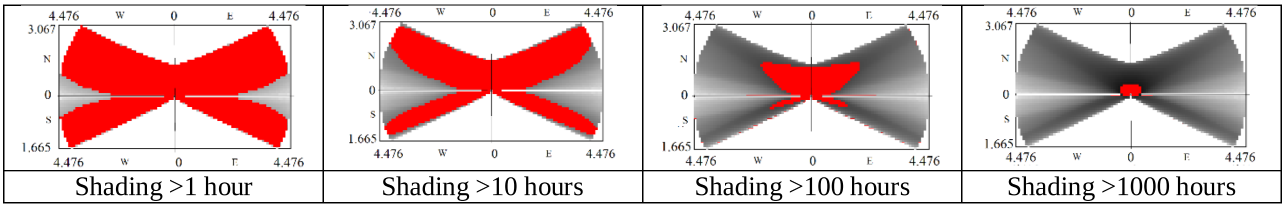


Figure 9. The noise level (dB) at the wind farm area using MATLAB program



Shading >1 hour | Shading >10 hours | Shading >100 hours | Shading >1000 hours

Figure 10. Wind turbine shadow ratio length in W-E and N-S directions at the proposed farm location

4.3.4. Bird mortality risk in the selected location

4.3.5. *Interference of wind turbine Gamesa-114 with radio and radar signal*

Tall structures can interfere with wireless communication services. Research indicates that the rotating blades and tall towers of wind turbines may affect Radio Frequency (RF) signals through diffraction, also referred to as the shadowing effect. This interference becomes significant when a turbine is located directly between the transmitter and receiver, whereas if the turbine is outside the line-of-sight path of radio or radar, the effect can be considered negligible. To assess the potential influence of wind turbine blades on radio and radar signal propagation, equation 10 was applied, which incorporates both the signal wavelength and the rotor area of the turbine. The corresponding wavelength values for land-based and marine telecommunications are presented in Table 5.

The radius of radar signal interference was calculated using equation 10 for the two wavelength values provided in Table 5, as follows:

For λ=1 m;

$$r = \frac{c\,\eta\,A}{\lambda\,m_o} = \frac{0.3 \times 0.7X10207}{0.15 \times 1} = 40828\,m$$

Where, $A = \pi(114/2)^2 = 10207\ m^2$; η= 0.7; c=0.3; m_o = 0.15.

And for λ=10 m; r =1428.985 m

The full radiation pattern of the radar antenna must be considered in the analysis, as this factor is critical when planning a wind farm to ensure compatibility and minimize potential radar interference. For the proposed site, the use of the large Gamesa-114 turbine, with a rotor area of 10,207 m², results in a radar signal interference radius of approximately 41 km for λ=1m; and 1.4 km for λ=10 m.

4.4. Social Environmental Impact Monetary

Wind energy is recognized for its low water consumption, making it an attractive alternative to conventional power plants for water-efficient energy solutions. The proposed wind farm is expected to consume 3,210.6 tons of water annually, which corresponds to an estimated monetary value of $19,905.72.

The wind farm will be located along the coastal strip of Zawia in a sparsely populated area, covering approximately 500 m × 4,000 m. Considering the noise impact radius of 700 m, the total area affected by noise will expand to 1,200 m × 5,400 m. Approximately 1,500

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people, including local residents and farm workers, live within this zone. At a rate of \$50.3 per person per year, the total monetary value of the noise impact is estimated at \$75,450.

The area affected by shadow and shadow flicker is projected to extend 460 m north and 250 m south, and 2,672 m in the east–west direction, covering a total area of 1,335,700 m² southward, as the sea lies to the north of the farm. This zone contains no houses or buildings, so shadow-related impacts will be disregarded. Visual impacts are also considered negligible.

The estimated monetary value of bird mortality due to wind turbines is approximately \$18.238 per GWh, amounting to \$1,900 annually.Annual payments for potential interference with telecommunications signals are estimated at \$400,000, and the annual cost associated with carbon emissions is projected to be \$328,358. Table 6 provides a summary of all these monetary values.
The total annual impact of the wind energy farm is estimated at \$805,708. This amount should be incorporated into the economic analysis of the wind project. The Levelized Cost of Energy (LCoE) has been calculated using Equations (11)–(13), based on the values presented in Table 7.

The Levelized Cost of Energy (LCoE) is calculated as \$86.8, \$49.4, and \$57.3 per MWh using Equations (11), (12), and (13), respectively. It should be noted that the Libyan Electricity Company purchases electricity from investors at a rate of \$100 per MWh [2,10,81].

Figure 11 presents a sensitivity analysis of the LCoE with respect to all parameters included in Eqns (11)–(13).

The influence and relative importance of each parameter on the LCoE are clearly illustrated in Figure 11. Increases in the interest rate, capital expenditures, operation and maintenance costs, and social and environmental impacts all lead to higher LCoE values, with capital expenditure having the most significant effect. Conversely, increases in the carbon footprint and CO_2 emission factor have a mitigating effect, as higher values reduce the LCoE.

Among all these factors, two are expected to strongly enhance the competitiveness of wind energy in the market. First, NREL forecasts a reduction in wind energy equipment costs of over 51% by 2030 [82]. Second, international efforts to increase the carbon price to \$214 per ton of CO_2 by the end of 2030 will further lower the LCoE, potentially even resulting in negative values. A similar situation occurred in Germany on April 22, 2019, when electricity prices reached €-52.75/MWh [83]. In the present case study, the LCOE at $C_c = \$214/\mathrm{ton\ CO_2}$ would be \$-95.77/MWh.

Table 5. Radio and radar waves

Wave type	Wavelength	Signal
Very high frequency	30 - 300 MHz (1m – 10 m)	FM radio, television Broadcasting, communication
	30 - 300 MHz	air navigation

Table 6. The footprint and the corresponding monetary value

Footprint	Value; \$/year
Water stress	19,906
Noise pollutions	75,450
Shadow and Shadow flicker	Nil
Visual impact	Nil
Bird mortality risk	1,900
Interference with telecommunication signals	400,000
Carbon footprint	328,358
The annual total footprint (\$/year)	825,614
The total footprint (\$/MWh)	7.920

Table 7. The values of parameters used in LCOE estimation by equations (11)-(13)

Parameter	Value
Wind farm capacity; MW	20
Annual wind farm productivity; MWh/year	104,240.6
Lifespan; year	25
Interest rate; %	8
Capital cost; \$/kW	1968
Operation and maintenance expenditure; \$/MWh	25
Social and environmental footprint expenditure; \$/MWh	7.92
CO_2 emission factor of Power generation in Libya; ton/MWh	0.875
Cost of CO_2; \$/ton	43

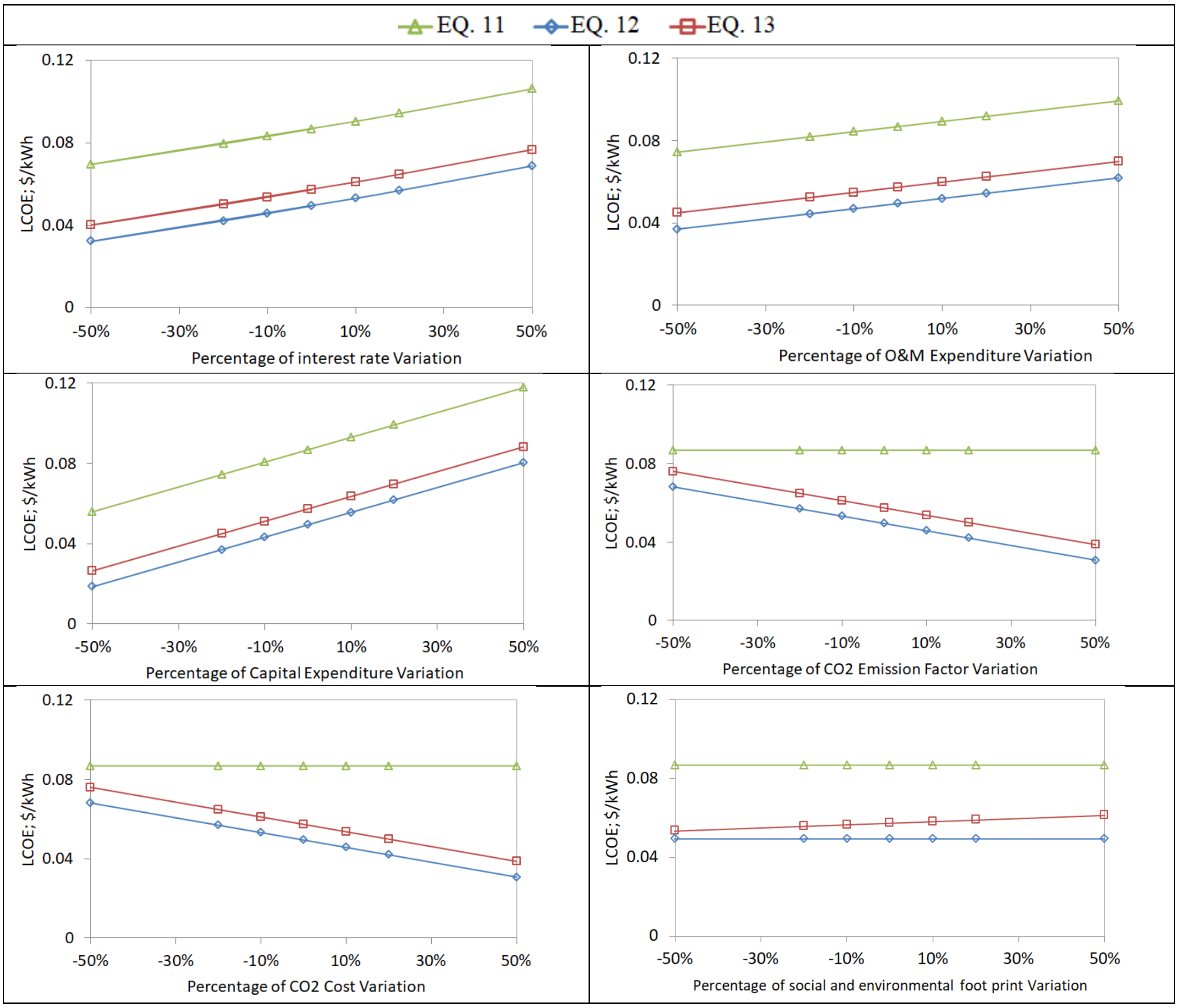

Figure 11. Sensitivity analysis of the LCoE for interest rate, operation and maintenance expenditure, capital expenditure, CO_2 emission factor, and the CO_2 cost

5. Conclusions

This study assessed the main environmental impacts of the proposed wind farm, including noise, visual effects, shadow flicker, land use, and electromagnetic interference. Water consumption was also evaluated, which is particularly critical in arid regions. Compared to fossil fuel–based systems, water use was found to be minimal. The shadow effect of the proposed wind farm was analyzed using the SHADOWS PRO 3.5 program, while MATLAB was employed to determine the duration of shadows and their impact on surrounding areas. Since June 21 experiences the greatest shadow dispersion, shadow values were assessed at various angles for that day. MATLAB was also used to calculate turbine noise levels and the impact of the planned farm at different locations. Results indicated that the overall noise level gradually decreased to 50 dB at a distance of 300 m, which is considered acceptable for the environment and nearby residences. At 350 m, noise levels were found to be below 50 dB. The site's wildlife was also studied to evaluate potential effects on birds and other species. The location was deemed suitable for wind farm construction with minimal impact on animals. Furthermore, radar signal interference was found to drop significantly beyond approximately 40 km, confirming the site's appropriateness and safety from radar conflicts.

Further studies are recommended to address additional environmental aspects, including socio-economic impacts, land-use changes, and the effects of local vegetation on wildlife habitats.

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Authors Contribution
Amhimmid and Salem: Data collection, analysis and software; El-Osta: Conception, investigation and writing- original; Nassar and El-Khozondar: Analysis, writing- review and editing. All authors read and approved the final manuscript.

Availability of data and materials
Data are available on request.

Conflict of interests
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