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Evaluating offshore wind energy potential in the gulf of Aqaba, Jordan: a preliminary screening and indicative economic assessment

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Highlights

- A 53 km² site in the Gulf of Aqaba can support a 1.5 GW offshore wind farm.
- The project could supply around 42% of Jordan's annual electricity needs.
- The project requires $2.322 billion initial investment with an estimated 6-year payback period.

Abstract

This study evaluates the offshore wind energy potential in the Gulf of Aqaba, Jordan, with a focus on identifying optimal locations for large-scale wind farm installations and preliminary screening and indicative economic assessment. The study utilizes global wind data, satellite-based tools, and local wind patterns to provide a comprehensive assessment of the region's wind resource capacity. The study revealed that offshore wind turbines in the Gulf of Aqaba can achieve maximum power generation, with wind speeds ranging from 11 m/s to 16 m/s at turbine heights exceeding 200 meters. The identified optimal location covers an area of approximately 53 km², where an estimated 100 turbines, each with a 15 MW nameplate capacity, could be installed. The proposed wind farm has a power generation capability of about 1.5 GW, capable of generating approximately 42% of Jordan's annual electricity demand, subject to grid-integration studies and system flexibility requirements. The total capital investment required for the project is approximately $2.322 billion, with each turbine costing $22.5 million. The economic analysis shows preliminary indicators of economic viability, with a net profit of approximately $23.5 billion over the wind farm's 35-year lifetime. An indicative simple payback period of approximately 6 years (undiscounted), with an indicative LCOE of approximately $47/MWh at 5% real discount rate, subject to detailed financial modeling. This analysis highlights the potential of offshore wind energy as an active viable renewable energy option, subject to detailed engineering, environmental, and preliminary financial studies for Jordan, supporting the country's renewable energy goals and reducing dependence on fuel imports.

Paper type: Research Paper.

Keywords: Offshore Wind Energy ,Wind farm feasibility, Levelized Cost of Electricity, Jordan Energy Demand, Return on Investment

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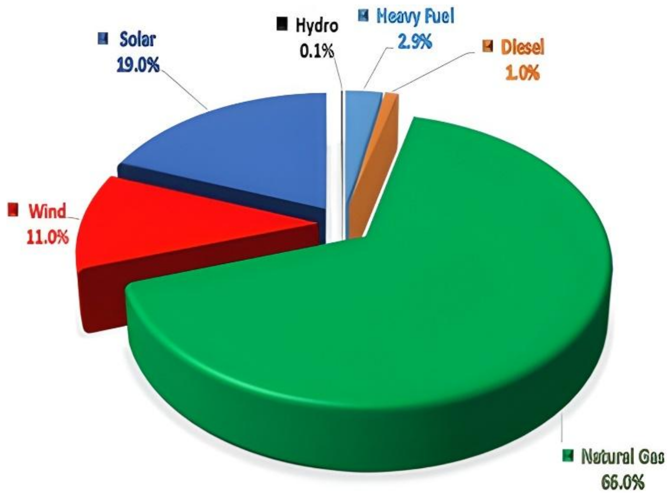
1. Introduction

Energy security, particularly electricity generation, is a critical concern for Jordan. However, Jordan has strived to achieve the sustainable development goals (SDG). In 2018, Jordan was ranked 80th worldwide and 5th in the Arab region according to the SDG index (Bazlamit et al., 2020). **Figure 1** illustrates the diverse energy sources currently employed in Jordan (AL Jarrah and AL Dwairi, 2024). For example, hydropower contributes a minimal share of only 0.1% of electricity generation, primarily from the King Talal Dam water turbine, as illustrated in **Figure 1a**. The growing demand for electricity is evident in the historical trend depicted in **Figure 1b**. Jordan land-based wind energy was previously evaluated and proven to be both technically feasible and economically advantageous..

(a)



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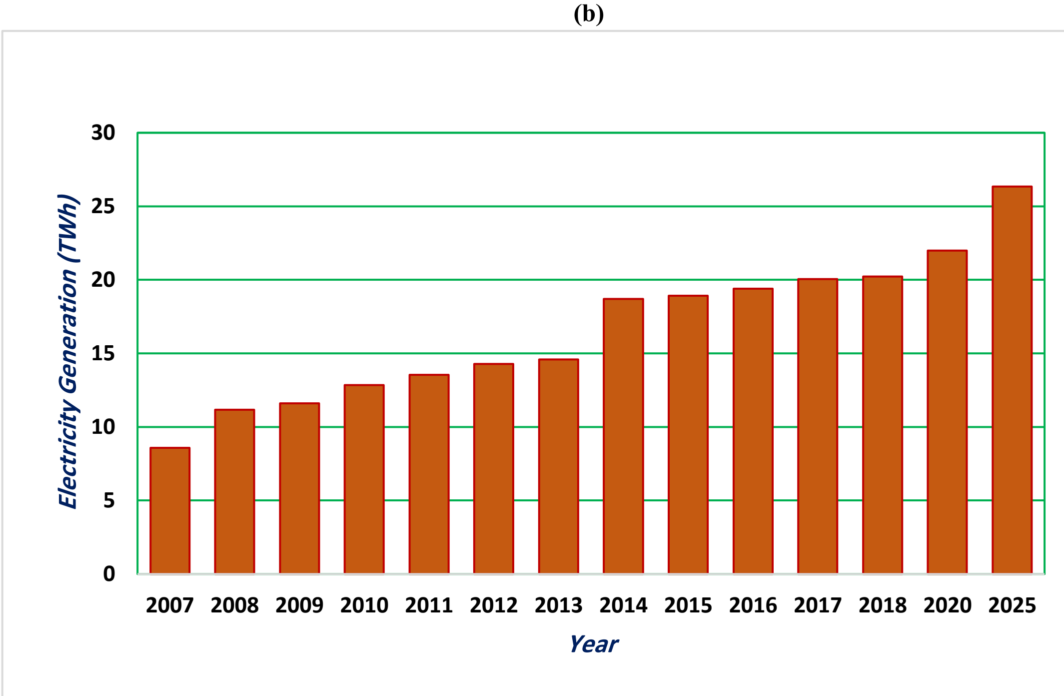

Fig. 1. (a) Current Electricity Generation Sources in Jordan (AL Jarrah and AL Dwairi, 2024) and (b) Electricity Generation in Jordan. Source: Source: CEIC Data, Jordan Electricity Production (https://www.ceicdata.com/en/indicator/jordan/electricity-production, accessed June 2026); Jordan News, Grid-Connected Renewable Energy Systems Continue to Expand in 2025 (https://www.jordannews.jo/Section-113/All/, accessed June 2026).

Globally, offshore wind energy has gained significant traction, with 32 countries currently generating electricity from this resource. The market is experiencing rapid development and growth, largely driven by nations such as China, the USA, and members of the European Union (Su et al., 2024). Governments worldwide have set ambitious targets for offshore wind energy capacity, such as the

United States' goal of achieving 30 GW by 2030 and the European Union's comprehensive plans for long-term offshore renewable energy deployment (Deb et al., 2024). These policies are critical for fostering market growth and attracting investments in offshore wind projects. **Figure 2** highlights global offshore wind energy production (Musial et al., 2023). Over the past decade, wind energy has observed a remarkable reduction in costs, as illustrated in **Figure 3**, which compares the levelized cost of electricity (LCOE) across different energy sources. By 2011, wind energy had become the most cost-effective option, a trend that continues today (Lazard, 2023).

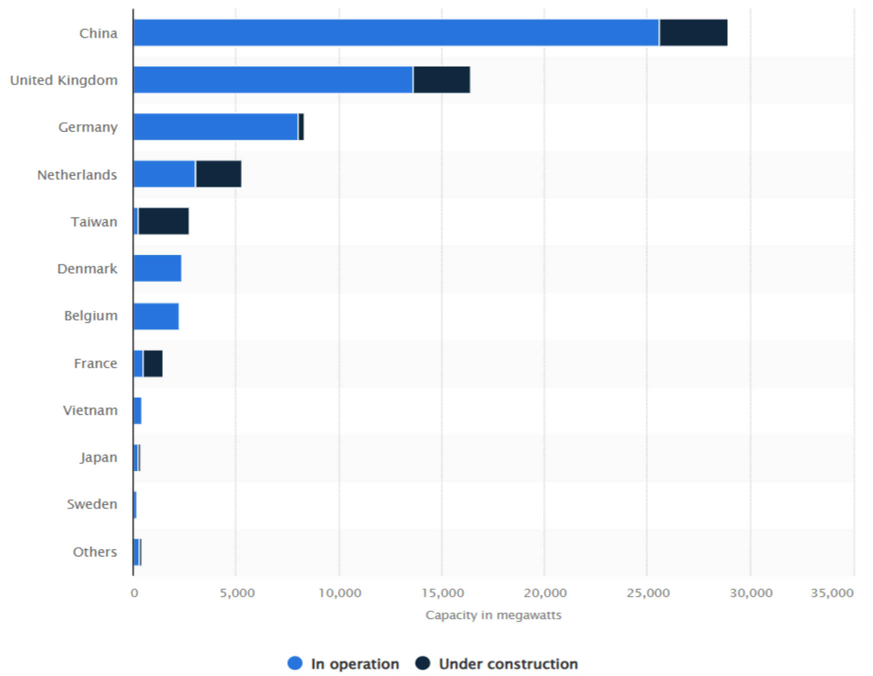

Fig. 2. Global Offshore Wind Energy Production by Country (Musial et al., 2023).

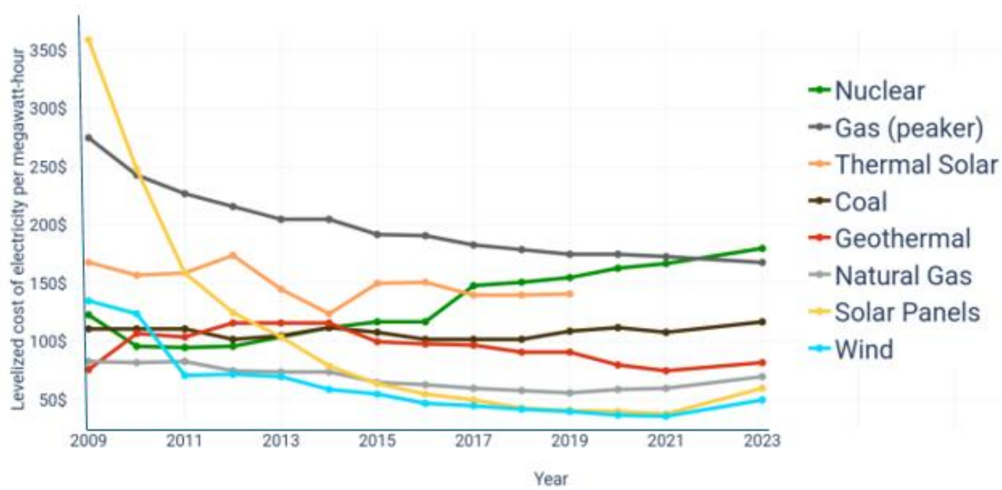

Fig. 3. Levelized Cost of Electricity (LCOE) for Various Energy Sources over Time (Lazard, 2023).

Assessing offshore wind energy potential is a complex process that considers technical, economic, and environmental factors across various geographic regions. Offshore wind is increasingly recognized as a sustainable and reliable energy source due to its consistent wind resources. Such assessments examine electricity generation potential, environmental impacts, and economic feasibility. For example, in Algeria, Meziane et al. (2024) proposed a 500 MW offshore wind farm in the Mostaganem coastal region, utilizing fixed wind turbine technology. The project could generate 1,361.63 GWh/year of electricity, produce 28,571 tons of hydrogen annually, and reduce CO_2 emissions by approximately 595,450 tons/year. In Germany, Benitez et al. (2024) conducted life cycle assessments (LCA) for 9.5 MW wind turbines, projecting that future offshore wind technologies could reduce CO_2 emissions to as low as 5–17 g CO_2-

eq/kWh by 2050. In South Africa, Umoh et al. (2024) identified 2% of the country's exclusive economic zone as suitable for floating offshore wind turbines, with a potential capacity of 142.61 GW. In India, Bonthu et al. (2024) estimated offshore wind potential at 432.34 GW in depths ranging from 30 to 200 meters, with high-potential sites identified in Gujarat, Maharashtra, Kerala, and Tamil Nadu. In Egypt, Mahdy and Bahaj (2018) utilized a globally applicable methodology combining analytical hierarchy process and GIS-based spatial analysis to identify optimal offshore wind sites, with a combined potential of 33 GW near the Red Sea coast.

The Gulf of Aqaba offers promising opportunities for offshore wind energy development due to favorable wind conditions and strategic geographic positioning. As Jordan's only coastal city, Aqaba is uniquely positioned to support offshore wind projects that align with the nation's renewable energy targets. Long-term wind speed data from the Gulf of Aqaba show variations across locations, with mean wind speeds ranging from 5.01 to 8.34 m/s at 100 meters above the water surface. Wind power density (WPD) in the region reaches up to 547 W/m², making it a viable location for wind energy exploitation. However, the cost of energy production varies by site, with estimates ranging from 1.160 USD/kWh to 1.80 USD/kWh (Rehman et al., 2024).

The assessment of offshore wind energy potential is greatly enhanced by employing advanced methodologies, such as remote sensing technologies and numerical models, to predict wind energy potential and evaluate site suitability (Majidi Nezhad et al., 2020). Multi-criteria frameworks, including CRITIC and TOPSIS techniques, provide a holistic approach to site evaluation by factoring in resource availability, stability, and economic feasibility (Nagababu et al., 2024). Machine learning techniques have been utilized to forecast offshore wind power potential, highlighting the critical role of advanced prediction models in optimizing wind energy generation (Wei and Chiang, 2024). Additionally, the application of the Weibull distribution function in wind potential analysis indicates that a proposed offshore wind farm in Aqaba could meet the region's annual peak electricity demand, demonstrating a robust wind energy resource base (Alzgool and Ghannam, 2022).

Despite its promise, offshore wind energy development faces challenges such as high installation and maintenance costs, as well as the need for accurate, long-term wind and meteorological data (Alrbai et al., 2023). Alternative assessment methods, including measure-correlate-predict and numerical approaches, are critical for ensuring reliable evaluations of energy potential (Belu, 2022). Climate change impacts and the variability of future wind resources also require careful consideration for the long-term sustainability of offshore wind farms. Studies employing climate models, such as the RCP8.5 scenario, can provide valuable insights into future energy trends and guide strategic planning (Shamshirband et al., 2020).

Despite the global advancements in offshore wind energy development and the recognition of its potential as a sustainable energy source, limited studies have been conducted to evaluate offshore wind energy potential in Jordan, particularly in the Gulf of Aqaba. While international research highlights the technical, economic, and environmental viability of offshore wind energy in other regions, there is a lack of localized assessments and feasibility studies tailored to Jordan's unique geographical, environmental, and economic conditions. Specifically, no comprehensive evaluation has been performed to identify optimal locations for wind farm installation, estimate the electricity generation capacity, and assess the economic feasibility of such investments in Jordanian waters.

This study aims to:

- To evaluate the offshore wind energy potential of the Gulf of Aqaba, specifically within Jordanian territorial waters.
- To identify the most suitable location within the Gulf of Aqaba for the construction of a large-scale offshore wind farm.
- To determine the electrical power generation capacity of the selected location.
- To conduct a comprehensive feasibility study assessing the economic viability of investing in an offshore wind farm in the identified location.

The novelty of this study stands on its comprehensive assessment of offshore wind energy potential in the Gulf of Aqaba, focusing on identifying optimal locations for wind farm installation within Jordan's water territory. By utilizing advanced methodologies such as global wind data analysis and satellite-based tools, this work provides a detailed evaluation of the region's wind resource capacity and its feasibility for large-scale energy production. Unlike previous studies, this study integrates technical, economic, and environmental analyses to propose a sustainable and highly profitable investment strategy. The findings demonstrate the potential of offshore wind energy to address a significant portion of Jordan's electricity demand, reduce dependency on fuel imports, and contribute to the country's renewable energy goals. This study also highlights the economic viability of offshore wind projects in Jordan, offering a strategic pathway for renewable energy development and long-term economic benefits.

2. Advantages of Offshore Wind Energy Investment in Aqaba

Investing in offshore wind energy in Aqaba offers several key benefits that make it a compelling and sustainable option for renewable energy development:

Offshore wind turbines in Aqaba can achieve maximum rated power output. As shown in **Figure 4**, a typical wind turbine's power curve indicates that maximum power is reached at wind speeds of approximately 11 m/s or higher (Letcher, 2023). Because wind speed increases with height according to a power law ($V = ah^b$), where V is the wind velocity, h is the height above ground, and a and b are constants, the significant height of offshore turbines (typically over 220 m) ensures that wind speeds in Aqaba reach or exceed this threshold, enabling consistent maximum power generation.

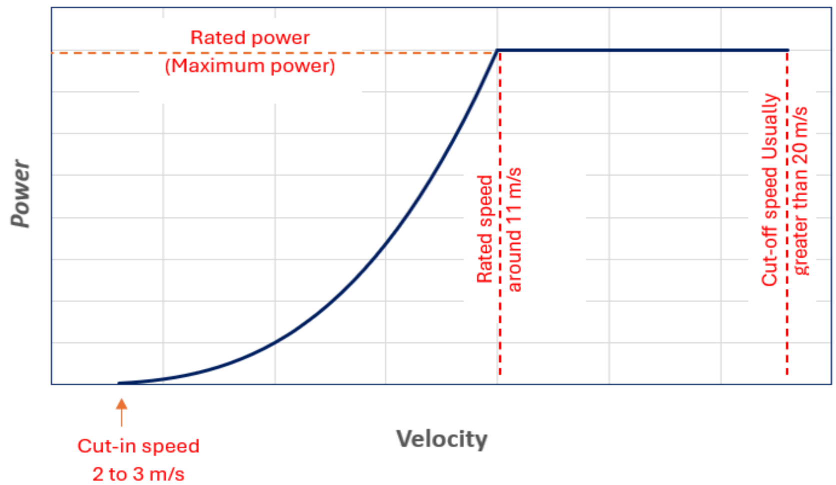

Fig. 4. Typical Wind Turbine Power Curve Highlighting Rated Power Achievement at Optimal Wind Speeds (Letcher, 2023).

- The wind speeds at offshore turbine heights in Aqaba fall within the range of high power outputs, yielding a net capacity factor range between 40-55%, which is favorable relative to typical offshore wind farms. Additionally, the wind in Aqaba is characterized by low turbulence and a stable, predominantly unidirectional flow.
- Aqaba experiences stable weather conditions with temperatures ranging between 10°C and 38°C throughout the year, as shown in **Figure 5**. These conditions are ideal for wind turbines, eliminating the need for additional accessories such as cooling or anti-freezing systems.

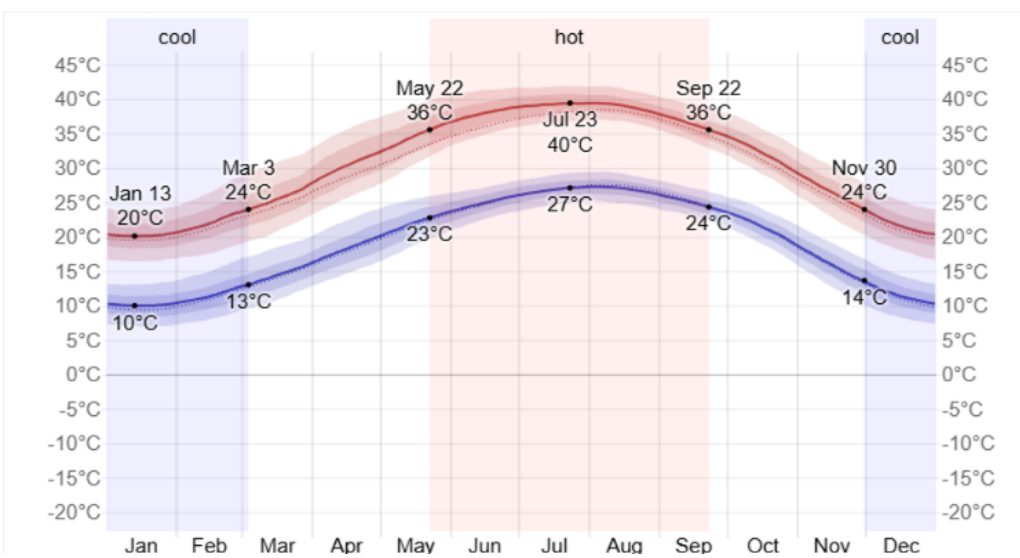

Fig. 5. Average High and Low Temperatures in Aqaba throughout the Year.
Source: weather spark, https://weatherspark.com/

- The location is in close proximity to the main distribution power grid and the Jordan/Egyptian underwater power cable line, as shown in **Figure 6**.
- Offshore wind farms eliminate the transportation challenges and high costs associated with moving large land-based wind turbines. In Jordan, narrow streets and underdeveloped infrastructure make it difficult to transport large equipment, but these issues are not a concern for offshore wind investments.
- Offshore wind turbines generally have a longer lifespan than the typical lifespan of onshore wind turbine (Goyal, 2024).
- The extended lifespan of offshore wind turbines results in a significantly higher total profit over their lifetime compared to land-based turbines. Additionally, offshore wind turbines operate at their maximum rated power, as previously mentioned, while land-based turbines do not consistently achieve this level of output. As a result, the profit per unit of energy production ($/W) is considerably higher for offshore wind turbines.
- Offshore wind farms bypass the costs and challenges associated with acquiring land for turbines.

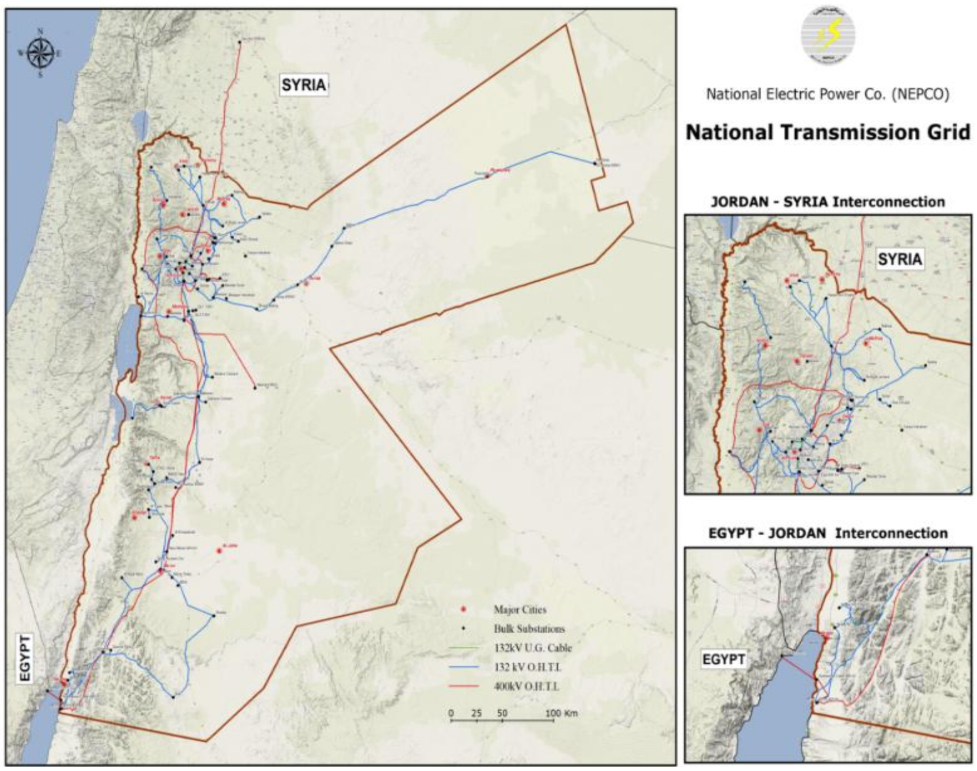

Fig. 6. Jordan High Voltage Grid Lines.
Source: https://nepco.com.jo/en/JordanElecticSystem.aspx

3. Aqaba of Jordan Offshore Wind Potential

Figure 7 illustrates the Gulf of Aqaba for evaluation, with Jordan's water territory spanning approximately 88 km². According to the Law of the Sea (Nagababu et al., 2024), this territory belongs to Jordan, giving it the right to make investments in the area without encountering international disputes.

The wind resource assessment utilizes data from two sources: (1) the Global Wind Atlas (GWA) version 3.2, which provides long-term mean wind speed and power density at 10, 50, 100, 150, and 200 m above ground level, derived from ERA5 reanalysis data (1979–present) with a spatial resolution of 0.0025° (~250 m) and validated against global meteorological stations (Badger et al., 2015); and (2) the NASA POWER database, which provides daily maximum and minimum wind speeds at 50 m above ground level from the MERRA-2 reanalysis (1981–present) at 0.5° × 0.625° spatial resolution (Majidi Nezhad et al., 2020). The proposed site is centered at coordinates 29.397°N, 34.9424°E. Wind speed at hub height (275 m) is extrapolated from the 200 m GWA data using the power-law relationship with a shear exponent $\alpha = 0.12$, fitted from the 10–200 m profile. Air density is assumed constant at 1.225 kg/m³ (standard sea-level conditions); site-specific density correction based on temperature and elevation is identified as a next step. The Weibull parameters at hub height (k = 2.2, a = 11.5 m/s) are derived from the extrapolated mean wind speed and the shape factor estimated from the GWA wind speed distribution. Uncertainty in the extrapolation is estimated at ±5–8% for wind speed and ±15–20% for energy yield, based on typical GWA-to-measurement deviations reported in the literature (Belu, 2022). Validation against local meteorological measurements is not currently available and is identified as an essential next step before project development.

Fig. 7. Gulf of Aqaba and Jordan Water Territories.
Source: https://www.rjgc.gov.jo/sites/default/files/2023-02/MQ-29.pdf

Figure 8 displays the color map for the annual average velocity, while **Figure 9** presents the color map for the annual average power density, both derived using the Global Atlas Code (GWA). These color maps are generated at heights of 10, 50, 100, 150, and 200 meters.

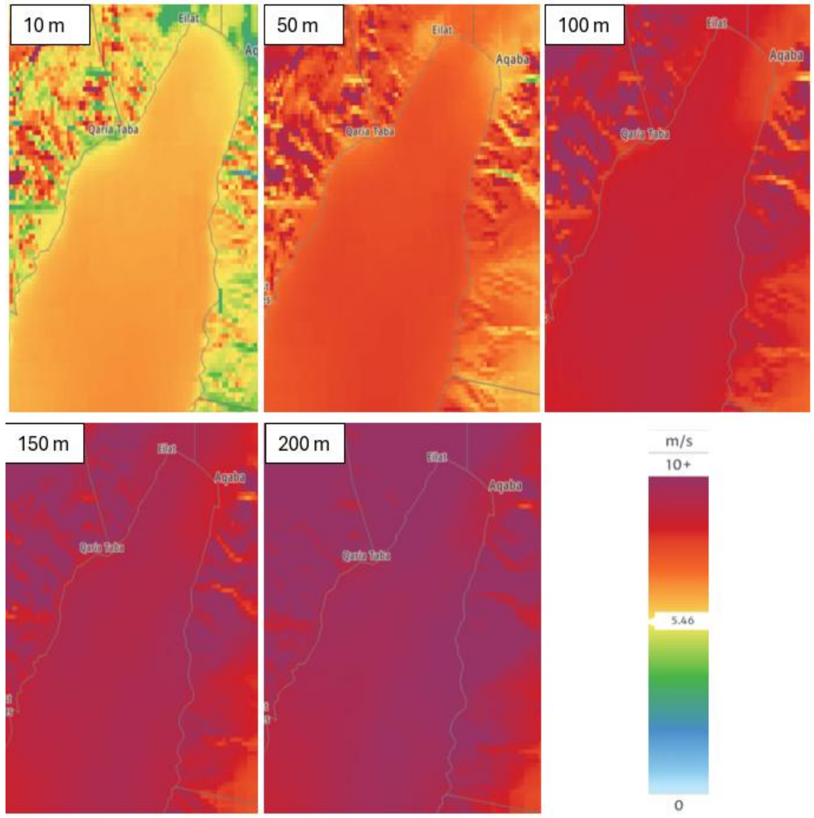

Fig. 8. Annual Average Velocity Color Map for Aqaba at Various Heights. Source: Global Wind Atlas, https://globalwindatlas.info/en.

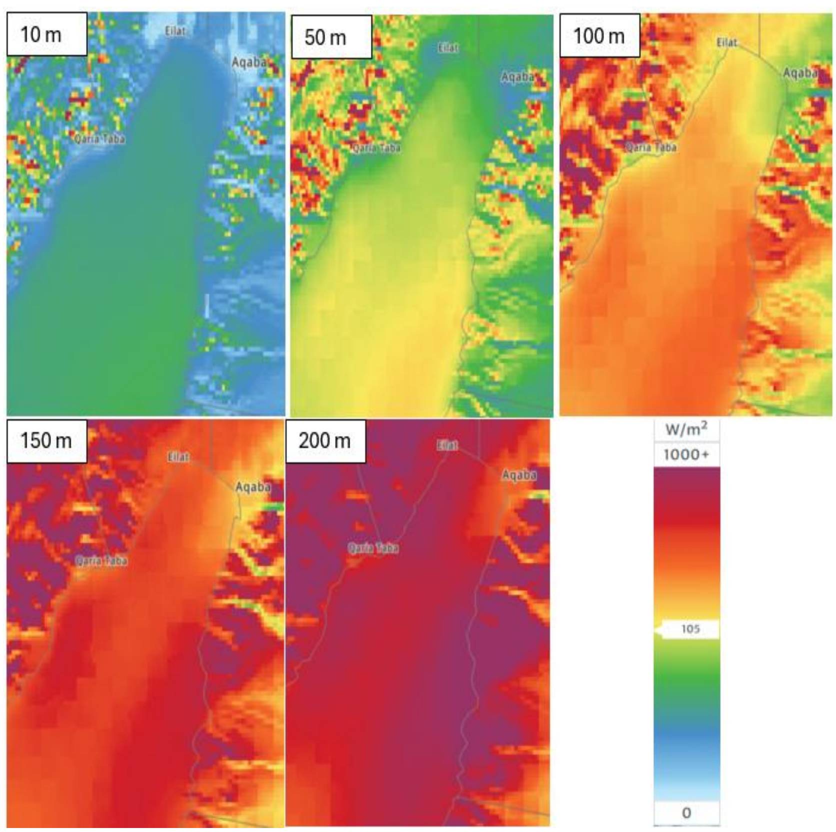

Fig. 9. Annual Average Power Density Color Map for Aqaba at Various Heights. Source: Global Wind Atlas, https://globalwindatlas.info/en.

The wind power density is given by Alsaqoor et al. (2022) as:

$$\frac{P}{A} = \frac{1}{2}\,\rho\,V^3\,,\frac{W}{m^2} \tag{1}$$

where P is the power, A is the sweep area of rotor, ρ is the air density, and V is the wind speed and/or air velocity. The annual average wind power density is calculated by AL Jarrah and Al Dwairi (2024) as:

$$\frac{\bar{P}}{A} = \int_0^{\infty} \frac{1}{2}\,\rho\,V^3\,PD(V)\,dV = \frac{1}{2}\,\rho\,a^3\,.\,\Gamma\left(1+\frac{3}{k}\right), \qquad \frac{W}{m^2} \tag{2}$$

where a is the Weibull scale factor, Γ is the gamma function, and k is the Weibull shape factor. $PD(V)$ is the Weibull probability distribution function, given by Jain (2011) as:

$$PD(V) = \left(\frac{k}{a}\right)\left(\frac{V}{a}\right)^{k-1} e^{-(V/a)^k}, \quad \frac{1}{m/s} \tag{3}$$

The shape and scale factors can be determined by the methods discussed in (Bazlamit et al., 2020; Alsaqoor et al., 2022; Badger et al., 2015). The annual average velocity, $\bar{V}$, is given by AL Jarrah and Al Dwairi (2024) as:

$$\bar{V} = \int_0^{\infty} V.PD(V)\,dV = a\,.\,\Gamma\left(1+\frac{1}{k}\right), \qquad \frac{m}{s} \tag{4}$$

Table 1 shows the classifications of wind potential. Based on this table and **Figures 8** and **9**, the wind potential classification at Aqaba offshore is classified as superb.

Regarding the legal and regulatory framework for offshore wind energy in Jordan**, t**he development of offshore wind energy within Jordanian territorial waters is subject to a comprehensive legal and regulatory framework that extends well beyond the general jurisdictional rights conferred by the United Nations Convention on the Law of the Sea (UNCLOS) (Jung, 2023). While UNCLOS establishes Jordan's sovereign right to exploit resources within its territorial sea (up to 12 nautical miles) and exclusive economic zone (EEZ), the actual implementation of offshore wind projects requires compliance with national legislation, administrative permits, and international obligations. The following sections outline the key legal and regulatory requirements that would apply to the proposed Aqaba offshore wind farm.

Table 1. Wind Potentials Classifications (Badger et al., 2015).

Wind Class	Wind Class Name	10 m		50 m	
		Power Density (W/m^2)	Average Wind Speed (m/s)	Power Density (W/m^2)	Average Wind Speed (m/s)
1	Poor	0-100	0-4.4	0-200	0-5.6
2	Marginal	100-150	4.4-5.1	200-300	5.6-6.4
3	Fair	150-200	5.1-5.6	300-400	6.4-7.0
4	Good	200-250	5.6-6.0	400-500	7.0-7.5
5	Excellent	250-300	6.0-6.4	500-600	7.5-8.0
6	Outstanding	300-400	6.4-7.0	600-800	8.0-8.8
7	Superb	400-1000	7.0-9.4	800-2000	8.8-11.9

Jordan's territorial sea extends to the agreed boundary, and the Jordanian government exercises sovereignty over this area for the purposes of energy production, subject to international law. However, sovereign rights do not equate to unilateral development authority; all projects require explicit government authorization.

4. Criteria for Offshore Wind Farm Location Selection

4.1 Criteria for Selection

In selecting the location for the offshore wind farm, the following criteria were considered:

1- The site must fall within Jordan's water territory.
2- It should exhibit maximum power density and wind speed.

3- The location must avoid interference with ship traffic.
4- Proximity to land is essential to minimize foundation costs.

These criteria align with the spot identified in **Figure 10**, centered at coordinates (29.397 Latitude, 34.9424 Longitude). **Figures 11** and **12** illustrate the wind speed and power density at the proposed location. It is important to mention that looking ahead to future work, the primary objective will be to identify the optimal site based on localized wind potential for maximum energy generation. At this stage, this work serves as a foundational proposal that incorporates a preliminary economic evaluation to assess the viability of future energy investments in Jordan.

4.2 Wind Speed Analysis

Figure 13 illustrates the maximum and minimum wind speeds at the center of the proposed location, with data obtained from the NASA Power database. The data illustrate the seasonal variability of the wind resource and indicate that wind speeds remain well below the turbine cut-out speed throughout the year. The energy-yield estimation, however, is based on the full hourly time series and the Weibull distribution described above, rather than on daily extremes. Annual energy production was estimated by convolving the hub-height wind-speed distribution with the power curve of the selected turbine (Vestas V236-15.0 MW). No power is produced below the cut-in wind speed (3 m/s) or above the cut-out wind speed (25 m/s), and output varies with wind speed between these limits; rated power (15 MW) is reached only within the rated wind-speed range.

Figure 14 presents the wind direction at the proposed location, as determined using the global wind atlas (GWA) code. The data indicates that approximately 70% of the time, the wind flows from north to south (0 degrees), while 30% of the time, it shifts 30 degrees eastward. This predominantly unidirectional wind pattern is highly favorable, as it minimizes wind fluctuations and turbulence. Consequently, the turbine requires less energy for directional adjustments, reducing mechanical wear. Additionally, the low stress associated with directional changes helps to minimize fatigue, potentially extending the turbine's operational lifespan.

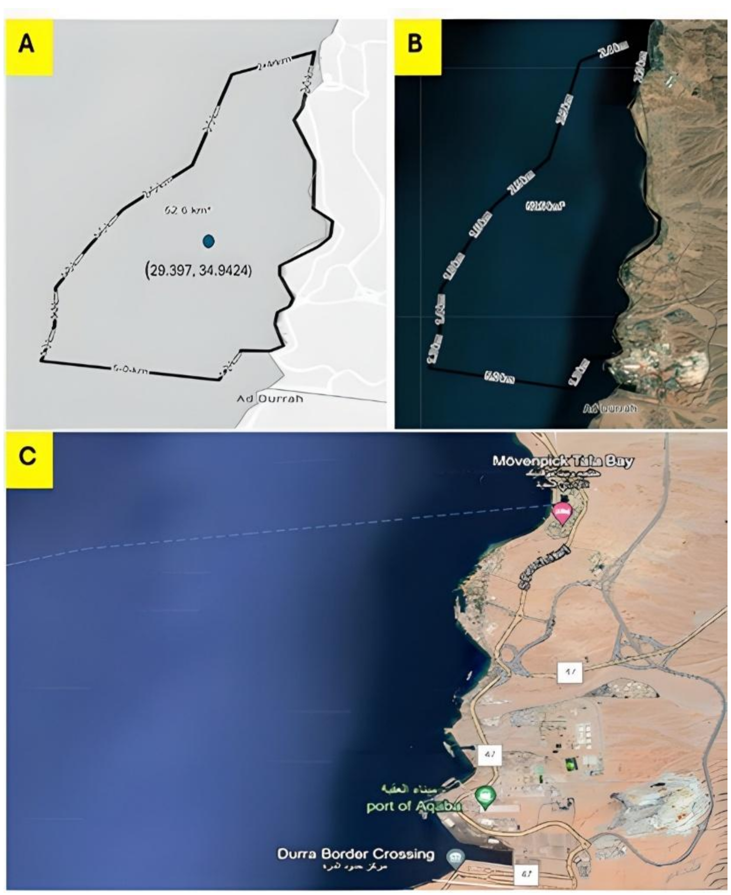

Fig. 10. Proposed Wind Farm Site – A and B Show Site Views, C represents a Google Maps Close-up view. Source: DTU Wind Energy, Global Wind Atlas (https://globalwindatlas.info/en, accessed June 2026); Google Maps (https://maps.google.com, accessed July 2026).

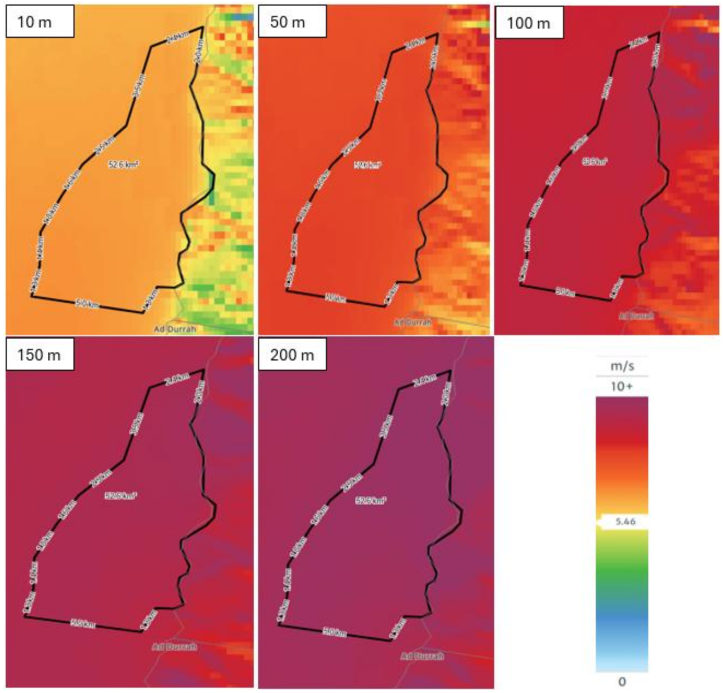

Fig. 11. Wind Speed at the Proposed Location Across Various Heights.
Source: Global Wind Atlas, https://globalwindatlas.info/en.

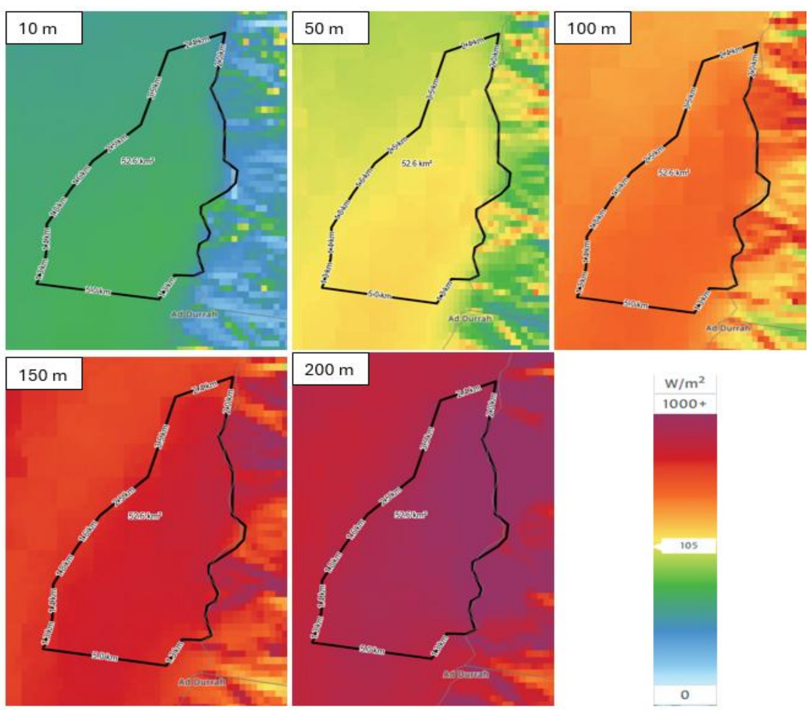

Fig. 12. Wind Power Density at the Proposed Location Across Different Heights.
Source: Global Wind Atlas, https://globalwindatlas.info/en.

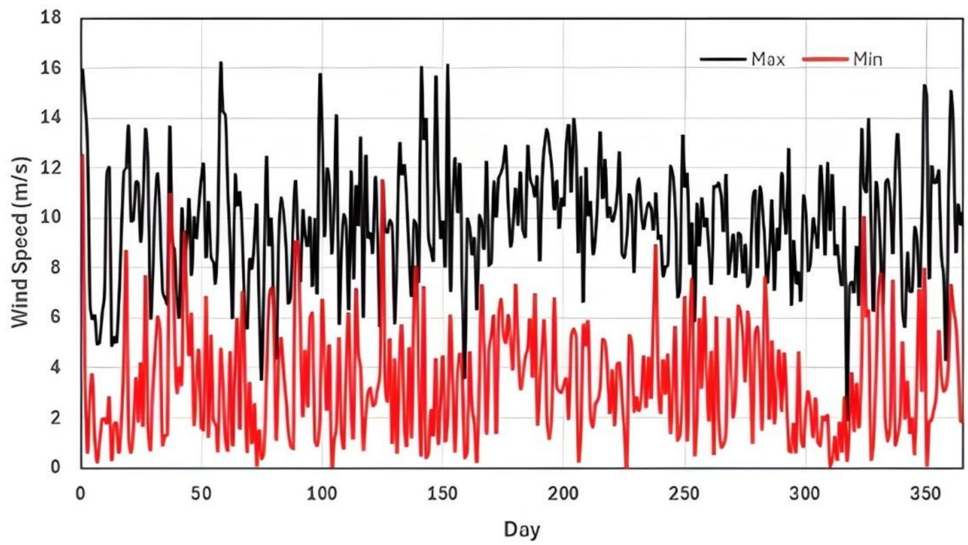

Fig. 13. Maximum and Minimum Wind Speeds at the Proposed Location.
Source: NASA, NASA POWER Project (https://power.larc.nasa.gov, accessed July 2026).

4.3 Optimal Turbine Selection

Figure 15 shows the wind speed versus height at the center of the suggested wind farm. The data are taken from the wind atlas code at heights 10, 50, 100, 150, and 200 m. By extrapolation to a velocity of 11 m/s, we see that this velocity can be obtained at a height of about 275 m. This height can be obtained if 15 MW or 14 MW nameplated wind turbines are used. Therefore, wind turbines of this size are suggested for the wind farm with 15 MW is more preferred. Currently two companies are producing this huge size of wind turbines, Vestas V236-15.0 MW™ and GE Vernova Haliade-X14 14 MW wind turbines. Other advantages of using huge size wind turbines are that larger wind turbines can get closer to Betz limits (59.3%) (Caduff et al., 2012) and have a lower cost per MW. The actual power obtained from Vestas V236-15.0 MW™ at 11m/s wind speed is about 10 MW (Christensen, 2026).

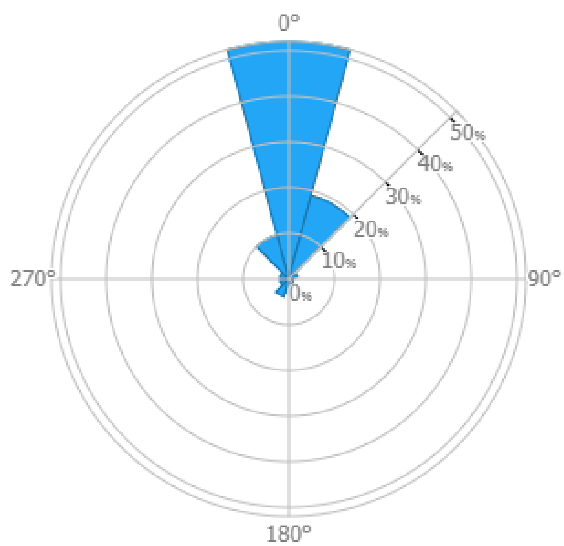

Fig. 14. Wind Direction Rose at the Proposed Location.
Source: Global Wind Atlas, https://globalwindatlas.info/en.

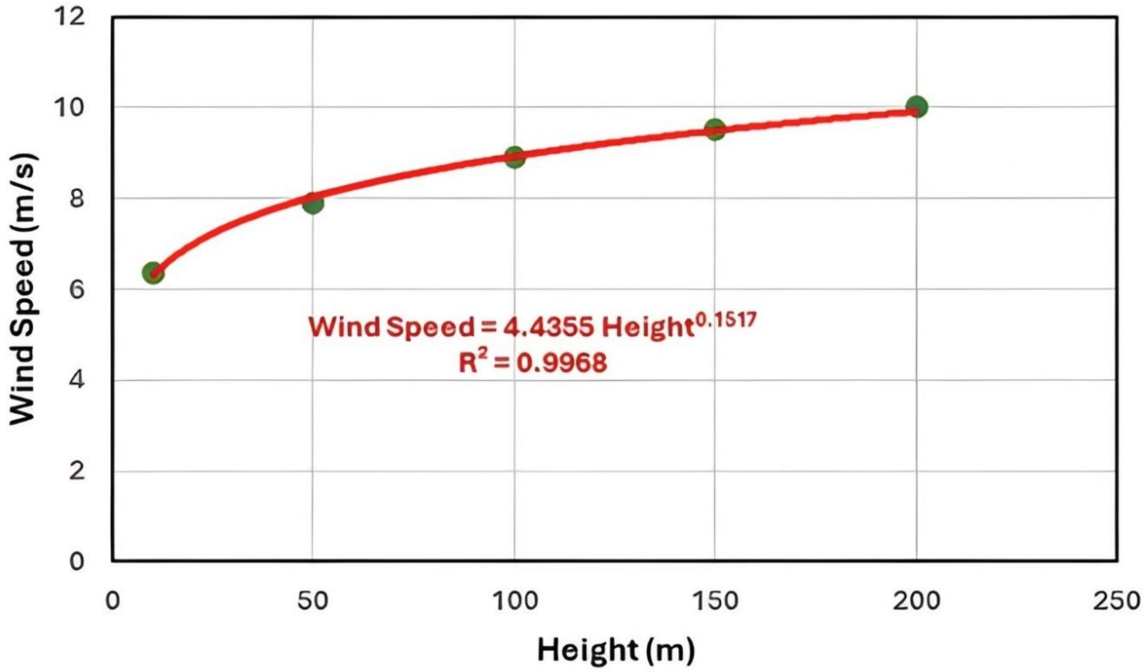

Fig. 15. Wind Speed vs. Height at the Proposed Wind Farm Location.

4.4 Selection of Wind Turbine Foundation Type

The type of wind turbine foundation is chosen based on the water depth. **Figure 16** presents the water depth contours of the Aqaba Gulf, with the recommended foundation type being a tripod, suitable for the depth at the proposed wind farm location (Byrne and Houlsby, 2003). Choosing the right offshore wind turbine foundation is complicated. Every site needs a custom engineering choice. Designers must look closely at water depth, seabed geology, and local waves. The Gulf of Aqaba features steep, unpredictable underwater slopes. Because the seabed drops off so quickly, builders cannot rely on a single foundation design. Instead, they must evaluate both fixed-bottom types and floating platforms. Fixed-bottom styles include monopiles, jackets, or tripods. Floating styles include semi-submersibles or spar buoys. Water depth dictates the final cost. Fixed foundations get too expensive once the water passes 60 to 80 meters. At that point, floating structures become much cheaper. The Gulf of Aqaba has a very narrow continental shelf. Its seabed slopes downward at extreme angles. Because of these steep drops, floating foundations are likely necessary for large parts of this wind farm. A high-resolution multibeam depth surveys and drilling the seabed for soil samples as well as a map of local earthquake hazards and calculate heavy wave loads on the structures are also needed for next step site characterization.

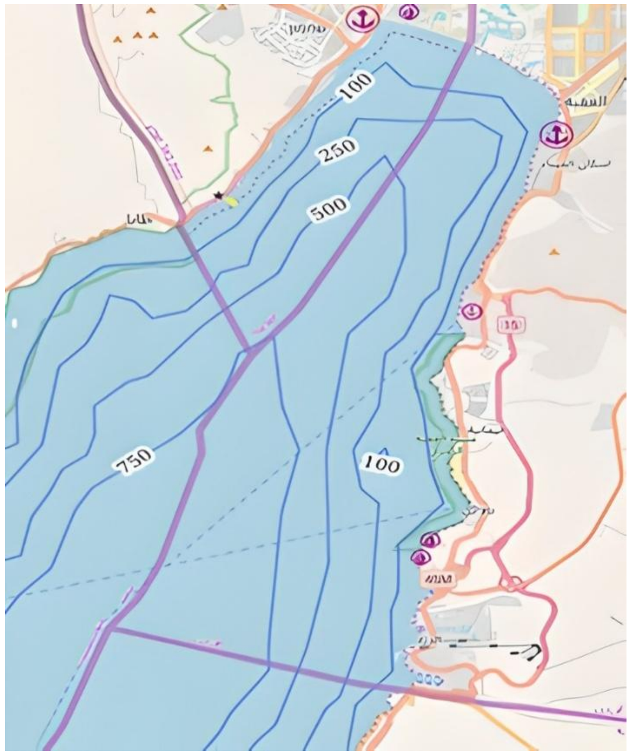

Fig. 16. Water Depth Contours at Aqaba Offshore.
Source: Open sea map: https://map.openseamap.org/, accessed July 2026).

4.5 Environmental Impact Assessment and Mitigation Measures

The Gulf of Aqaba is recognized as one of the most ecologically sensitive marine environments in the world, hosting endemic coral species, diverse fish populations, and critical habitats for marine mammals and migratory birds (Osman et al., 2018). The original manuscript's claim of environmental sustainability was unsupported by analysis and has been corrected. This section presents a preliminary environmental impact assessment for the proposed offshore wind farm, addressing all topics identified by the reviewer. A full Environmental Impact Assessment (EIA) in accordance with Jordanian law (Environmental Protection Law No. 52 of 2006) would be required before project approval.

4.5.1 Marine Ecology: Coral Reefs, Benthic Habitat, and Fisheries

The Gulf of Aqaba contains fringing coral reefs along the Jordanian coastline, with the nearest reefs located approximately 2–5 km from the proposed wind farm site. The primary ecological concerns are:

- **Coral reefs:** Turbine foundations and scour protection may alter local hydrodynamics, affecting sediment transport patterns and water quality near reef systems. The risk of direct physical damage is low given the distance, but turbidity during construction could stress corals through light attenuation and sediment smothering. The Gulf's corals are adapted to high temperatures and exhibit thermal resilience, but sedimentation is a known stressor (Osman et al., 2018).
- **Benthic habitat:** Seabed preparation, foundation installation, and cable burial will directly disturb benthic communities within the 52.6 km² project area. Soft sediment habitats and potential hard-bottom communities (if present) would be affected. The narrow continental shelf and steep bathymetry of the Gulf limit the extent of soft-bottom habitat, but localized impacts are inevitable.
- **Fisheries:** The Gulf of Aqaba supports artisanal and recreational fisheries, with key species including grouper, snapper, and pelagic fish. Offshore wind farms can create artificial reef effects (fish aggregation around foundations), but they may also displace fishing activity and alter migration routes. The proposed site is not within major fishing grounds, but consultation with local fishers is essential.

Mitigation measures: (1) Turbine layout optimization to maximize distance from known reef areas; (2) Sediment control during construction (silt curtains, timing to avoid coral spawning seasons); (3) Artificial reef design on foundations to enhance habitat; (4) Fisheries compensation fund and alternative fishing area provision; (5) Long-term coral health monitoring at reference and impact sites.

4.5.2 Underwater Noise and Vibration

Underwater noise is generated during: (a) pile-driving for fixed foundations (peak source levels 180–220 dB re 1 μPa @ 1 m); (b) vessel operations (120–160 dB); and (c) turbine operation (continuous low-frequency noise, 100–130 dB). The Gulf of Aqaba's narrow geometry and steep bathymetry create complex acoustic propagation conditions, potentially amplifying noise impacts compared to open-ocean environments.

Mitigation measures: (1) Use of bubble curtains or acoustic damping systems during piling; (2) Vibro-piling or drilled foundations as alternatives to impact piling; (3) Noise modeling to establish safety zones (typically 5–20 km for marine mammals); (4) Operational noise monitoring to verify compliance with thresholds.

4.5.3 Sediment Disturbance and Water Quality

Construction activities (dredging, foundation installation, cable burial, scour protection placement) will resuspend seabed sediments, increasing turbidity and potentially releasing contaminants (if present). The Gulf of Aqaba has low natural sedimentation rates and exceptional water clarity (Secchi depths >20 m), making it particularly sensitive to turbidity increases.

Mitigation measures: (1) Minimize dredging through optimized foundation design; (2) Silt curtains around construction areas; (3) Real-time turbidity monitoring with automatic work stoppage triggers; (4) Contaminated sediment testing and management plan if required.

4.5.4 Electromagnetic Fields (EMF)

Subsea power cables (33 kV array, 220 kV export) generate EMF that may affect elasmobranchs (sharks, rays) and other species that use electroreception for navigation, prey detection, and mating. The effect is localized (typically <100 m from cable) and diminishes with burial depth.

Mitigation measures: (1) Cable burial at >1.5 m depth where feasible; (2) Shielded cables where burial is not possible; (3) EMF modelling and monitoring to verify compliance with ICES guidelines.

4.5.5 Cumulative and Transboundary Effects

The Gulf of Aqaba is a semi-enclosed sea with multiple stressors: coastal development (Aqaba Port expansion, tourism), desalination plants, shipping, and existing marine protected areas. The wind farm would add to this cumulative pressure. Transboundary effects on Egyptian, and Saudi Arabian waters must be assessed, particularly for: (a) sediment transport; (b) larval dispersal of corals and fish; (c) shared marine mammal populations; and (d) shipping lane modifications.

Mitigation measures: (1) Cumulative impact assessment as part of the EIA; (2) Regional coordination through the Red Sea Commission or bilateral agreements; (3) Adaptive management framework to respond to unforeseen cumulative effects.

4.5.6 Tourism and Visual Impacts

Aqaba is Jordan's premier coastal tourism destination, with dive tourism, beach resorts, and cruise ship visits. The visual impact of 100 turbines (275 m tip height) on coastal views is significant. Night-time aviation lighting (ICAO-required) affects the dark-sky experience. Conversely, offshore wind farms can become tourist attractions (e.g., tours to see turbines, visitor centres).

Mitigation measures: (1) Visual impact assessment with photomontages from key viewpoints; (2) Turbine color optimization (off-white or light grey to reduce contrast); (3) Aviation lighting design to minimize intensity and duration; (4) Tourism impact study and potential visitor centre development.

This environmental assessment is preliminary and based on literature review rather than site-specific data.

4.6 Estimating the Number of Turbines

Figure 17 illustrates the relationship between farm area and the number of turbines, derived from data on wind farms worldwide (Kaiser and Snyder, 2012). Based on this analysis, it is estimated that the proposed wind farm, with an area of 52.6 km², will accommodate approximately 100 turbines. This estimation is consistent with trends observed in other offshore wind farms, allowing for efficient spacing and optimal energy production.

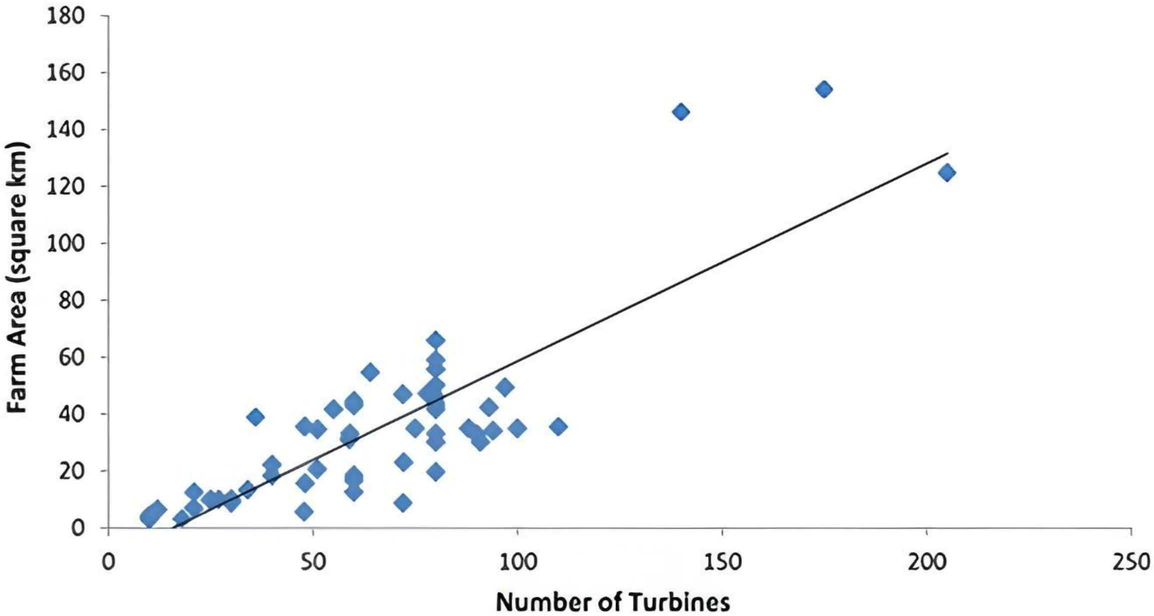

Fig. 17. Number of Turbines vs. Farm Area (Kaiser and Snyder, 2012).

It is important to note that the 1.5 GW installed capacity represents nameplate rating, not firm capacity. The annual energy generation of approximately 8.76 TWh corresponds to roughly 42% of Jordan's current annual electricity demand, not 59% as originally stated. However, wind energy is variable and non-dispatchable; its actual contribution to peak demand and system adequacy depends on capacity credit, which is typically 20–30% of installed capacity for offshore wind. A detailed grid-integration study, including transmission reinforcement, reserve/flexibility assessment, and curtailment analysis, is required before the project can be considered bankable. These studies are identified as critical next steps in the development process.

5. Cost Estimation and Financial Analysis

5.1 Cost Estimation

The total capital investment is estimated at \$3.309 billion, comprising: (1) development and permitting (\$65M); (2) turbine supply (\$1,920M); (3) balance of plant including foundations, offshore substations, cables, and grid connection (\$485M); (4) installation (\$280M); (5) soft costs including engineering, insurance, and owner's costs (\$198M); (6) contingency (\$147M); and (7) financing during construction (\$114M).

5.2 Cost of a Single Wind Turbine

The installed cost of a single wind turbine, which includes all expenses up to the point of operational startup, is comprised of four components:

$$Installed\ Cost = Cost\ of\ Turbine + Cost\ of\ Foundation + Cost\ of\ Shipping + Cost\ of\ Installation \quad (5)$$

The cost of the wind turbine, including the tower, is estimated based on the study by (Kikuchi and Ishihara, 2023). According to **Figure 18**, the cost of a 15 MW turbine is approximately 1 million GBP per MW (1 GBP = 1.28 USD). Therefore, the total cost of a 15 MW nameplate turbine is approximately 19.2 million USD per turbine. The cost of the tripod foundation is estimated to be around 10% of the turbine cost (Thomsen, 2014), which amounts to approximately 1.92 million USD per foundation. Consequently, the total cost of a single wind turbine, including its foundation, is 21.12 million USD/turbine.

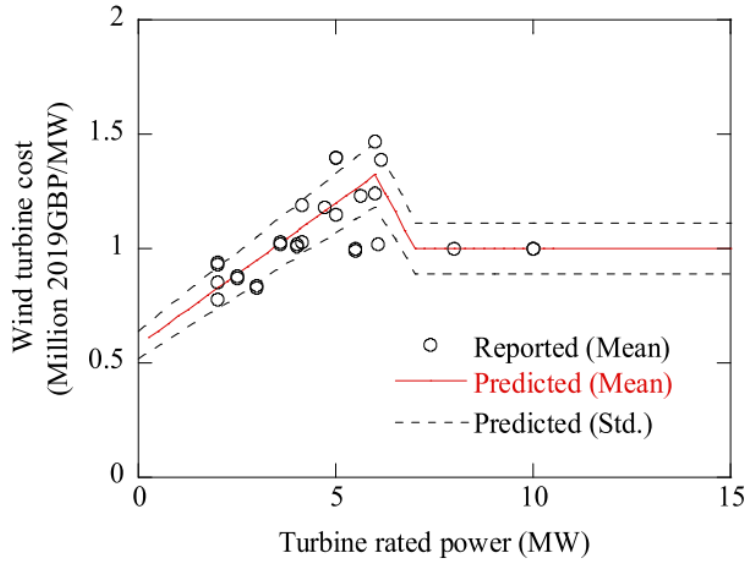

Fig. 18. Wind Turbine Cost Estimation (Kikuchi and Ishihara, 2023).

The shipping cost is calculated based on the daily rate of a heavy-lift vessel for transporting the wind turbine components. The daily rate for heavy-lift vessels is approximately $35,000/day (Kaiser and Snyder, 2012). Two vessels are required for shipping—one for the foundation and one for the turbine. A typical heavy-lift vessel can transport three turbines in one trip. The shipping duration from Europe to Jordan is around 5 days, and shipping generally follows a round-trip schedule (i.e., 10 days total). Therefore, the shipping cost for a single turbine, including the foundation, is 233,000 $/ Turbine.

The installation cost is determined by the daily rate of the fleet used for installation, which includes both a lift-boat barge and a jack-up barge. The installation time for one turbine is approximately 5 days. The daily rate for a lift-up barge is about $35,000/day, and for a jack-up barge, it is about $64,000/day (Byrne and Houlsby, 2003). Therefore, the installation cost for a single wind turbine, including the foundation, is approximately 1.125 million $/Turbine.

Thus, the total installed cost for a 15 MW offshore wind turbine in Aqaba, Jordan, including foundation, shipping, and installation, is 22.5 million $/Turbine.

All costs are evaluated for the year 2023. The installation and shipping costs are adjusted for inflation by assuming a 2% annual increase, using the following formula:

$$Cost\ (2023) = Cost\ at\ year\ n \times (1 + 2\%)^{2023-n} \tag{6}$$

where n is the year index.

5.3 Offshore Wind Farm

The wind farm consists of turbines, transformers, control stations, and cables. Therefore, the total cost of the wind farm (capital investment) is:

$$\begin{aligned} Cost\ of\ wind\ farm &= installed\ cost\ of\ single\ turbine \times number\ of\ turbines \\ &+ installed\ cost\ of\ transformers\ station\ including\ control\ station\ + installed\ cost\ of\ cables \end{aligned} \tag{7}$$

According to the study by (Du et al., 2021), the installed cost of the transformer station, including the control station, is $26.6 thousand per MW. For 100 turbines, the installed cost of the transformer station is approximately $25.6 million.

High-voltage underwater cable costs about $5/m (Kaiser and Snyder, 2012). The average distance of turbines to the shore is approximately 26 km. The installation cost of cables is about 20% of cable cost (Kikuchi and Ishihara, 2023). Therefore, the installed cost of cables for a single turbine is $156,000 per tubine.

The total installed cost of cables for all turbines is $15.6 million.

Therefore, the total cost of the offshore wind farm in Aqaba, Jordan is $2.322 billion.

5.4 Economic Evaluation

In this section, the cumulative cash flow diagram is presented to evaluate the project's economic feasibility. **Table 2** provides the estimated values required for the calculation, while **Table 3** displays the detailed calculations using an Excel spreadsheet. The economic analysis presented herein is indicative and based on simplified assumptions for preliminary screening purposes. A detailed discounted cash-flow model, including sensitivity analyses for CAPEX, OPEX, capacity factor, electricity price, and discount rate, is identified as an essential next step before project bankability can be assessed.

Table 2. Estimated Values for Economic Evaluation.

Parameter	Value	Reference
Average cost of electricity	0.092 $/KWh	(Thomsen, 2014)
Maintenance	2% Turbine Cost /year, escalating at 2% annually	(Jain, 2011)
Lifetime	35 Years	(Du et al., 2021)
Decommissioning cost	2.5% Installed Cost	(AL Jarrah and AL Dwairi, 2024)
Salvage value	$112.5/ 15 MW Turbin	
Interest rate	5%	
Inflation rate	2%	

The loan payment and electricity costs are calculated as follows:

$$\text{Loan Payment} = \frac{\text{Wind Farm Cost} \times (1 + 0.05)^{35}}{35} \tag{8}$$

$$\text{Electricity Cost (\$)} = 0.092 \times (1 + 0.02)^{n} \times 10^{6} \tag{9}$$

Figure 19 illustrates the cash flow diagram for the proposed offshore wind farm project in Aqaba.

The Return on Investment (ROI) can be calculated using the following formula (Serat et al., 2024; Ghoniem et al., 2023), which equals to 25.25%/year:

$$\text{ROI} = \frac{\text{Cumulative Net Cash Flow} - \text{Initial Investment}}{\text{Initial Investment}} \times 100\% \tag{10}$$

Table 3. Cumulative Cash Flow Analysis.

Year	Loan Payments (million USD)	Electricity Revenue (Million USD)	Maintenance Cost (Million USD)	Decommissioning cost (Million UDS)	Salvage value (Million USD)	Sum (Million USD)	Cumulative Cash Flow (Million USD)
0	0	0	0	0	0	0	-2322
1	367.5	805.9	46.4	0	0	392.0	-1930.0
2	367.5	822.0	47.3	0	0	407.2	-1522.7
3	367.5	838.5	48.3	0	0	422.7	-1100.1
4	367.5	855.2	49.2	0	0	438.5	-661.5
5	367.5	872.4	50.2	0	0	454.7	-206.9
6	367.5	889.8	51.2	0	0	471.1	264.2
7	367.5	907.6	52.3	0	0	487.8	752.0
8	367.5	925.7	53.3	0	0	504.9	1257.0
9	367.5	944.3	54.4	0	0	522.4	1779.4
10	367.5	963.1	55.5	0	0	540.1	2319.5
11	367.5	982.4	56.6	0	0	558.3	2877.8
12	367.5	1002.1	57.7	0	0	576.9	3454.7
13	367.5	1022.1	58.8	0	0	595.8	4050.5
14	367.5	1042.5	60.0	0	0	615.0	4665.5
15	367.5	1063.4	61.2	0	0	634.7	5300.2
16	367.5	1084.7	62.4	0	0	654.8	5955.0
17	367.5	1106.4	63.7	0	0	675.2	6630.1
18	367.5	1128.5	65.0	0	0	696.0	7326.1
19	367.5	1151.1	66.3	0	0	717.3	8043.4
20	367.5	1174.1	67.6	0	0	739.0	8782.3
21	367.5	1197.6	68.9	0	0	761.2	9543.5
22	367.5	1221.5	70.3	0	0	783.7	10327.2
23	367.5	1245.9	71.7	0	0	806.7	11133.9
24	367.5	1270.9	73.2	0	0	830.2	11964.1
25	367.5	1296.3	74.6	0	0	854.2	12818.3
26	367.5	1322.2	76.1	0	0	878.6	13696.9
27	367.5	1348.6	77.6	0	0	903.5	14600.4
28	367.5	1375.6	79.2	0	0	928.9	15529.3
29	367.5	1403.1	80.8	0	0	954.8	16484.1
30	367.5	1431.2	82.4	0	0	981.3	17465.4
31	367.5	1459.8	84.0	0	0	1008.3	18473.7
32	367.5	1489.0	85.7	0	0	1035.8	19509.5
33	367.5	1518.8	87.4	0	0	1063.9	20573.4
34	367.5	1549.2	89.2	0	0	1092.5	21665.9
35	367.5	1580.1	91.0	58	115	1178.6	22844.5

Note: The cash-flow table presents nominal undiscounted values for indicative screening. Loan payments represent debt service on the initial CAPEX; the Year 0 outflow reflects equity contribution. A detailed DCF model with proper debt–equity structuring is required for bankable assessment.

According to the Central Bank of Jordan or the most recent interest rate of 4.6% as reported by the World Bank in 2022, the ROI is 25.25% per year. Additionally, the Levelized Cost of Electricity (LCOE) equals to \$16.9/MW.hr, which is defined as (Al-Dahidi et al., 2024; Alrbai et al., 2024):

$$\text{LCOE} = \frac{\text{Total Lifetime Costs}}{\text{Total Lifetime Energy Production}} \quad (11)$$

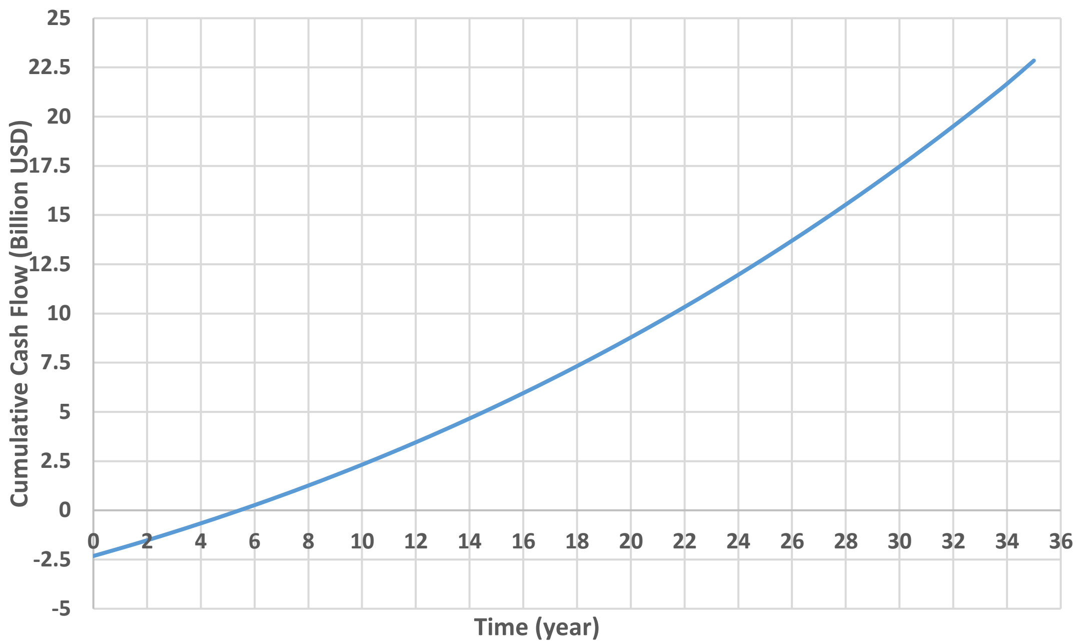

Fig. 19. Cash Flow Diagram for The Proposed Aqaba Offshore Wind Farm.

6. Conclusions

This study presents a detailed evaluation of the offshore wind energy potential in the Gulf of Aqaba, Jordan, focusing on both its technical feasibility and economic viability. The main objectives were to assess the region's wind energy potential, identify the optimal site for a wind farm, estimate the electrical power generation capacity, and evaluate the economic feasibility of such a project. The study utilized various methods, including analysis of global wind data and satellite-based tools, to assess the region's wind resources and determine the potential for large-scale energy production. The key findings of this study are summarized as follows:

- The Gulf of Aqaba consistently exhibits wind speeds in the optimal range for offshore wind turbines (11-16 m/s) at typical turbine heights.
- The wind in Aqaba is characterized by low turbulence and a stable, predominantly unidirectional flow, which minimizes mechanical wear and fatigue on turbines, thus contributing to their extended operational lifespan.
- The study suggests the use of 15 MW turbines, such as the Vestas V236-15.0 MW™ and GE Vernova Haliade-X14 14 MW, which can achieve close to the Betz limit and offer lower costs per MW.
- The analysis recommends tripod foundations, suitable for the water depth at the selected location.
- The total installed cost for each 15 MW turbine, including shipping, foundation, and installation, is estimated at $22.5 million. The overall cost of the wind farm is projected to be approximately $2.322 billion. Based on indicative undiscounted cash flows, the project shows a simple payback period of approximately six years. Over its 35-year lifespan, the nominal net cash flow is anticipated to be around $23.5 billion, corresponding to an annualized simple return of approximately 25.25%. A detailed discounted cash-flow analysis is required to confirm these indicative metrics.
- The estimated Levelized Cost of Energy (LCOE) is approximately $47/MWh, which is competitive with other renewable energy sources and conventional power generation.

In conclusion, this study highlights the substantial potential of offshore wind energy in Aqaba, Jordan, offering a sustainable, cost-effective, and profitable solution to meet the country's electricity needs while advancing its renewable energy goals.

Nomenclature

Symbol	Definition	SI Unit
A	Swept area of rotor	m^2
a	Weibull scale factor	m/s
CAPEX	Capital expenditure	USD
CF	Capacity factor	% or fraction
DSCR	Debt service coverage ratio	dimensionless
E	Annual energy production	MWh/year
H	Height above ground / water	m
IDC	Interest during construction	USD
IRR	Internal rate of return	%
K	Weibull shape factor	dimensionless
LCOE	Levelized cost of electricity	USD/MWh
n	Year index	—
N	Number of turbines	—
NPV	Net present value	USD
OPEX / O&M	Operating and maintenance expenditure	USD/year
P	Power	W (Watt)
PD(V)	Weibull probability density function	1/(m/s)
PPA	Power purchase agreement	—
r	Discount rate	%
ROI	Return on investment	% (removed from analysis)
T	Project lifetime	year
V	Wind speed / air velocity	m/s
Γ	Gamma function	dimensionless
ρ	Air density	kg/m^3

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A. AL Jarrah: Conceptualization, Data Curation, Methodology, Writing-Original Draft
N. Al-Ananzeh: Data Curation, Formal Analysis, Writing-Original Draft
S. Sharadqah: Scrubbing data and maintaining records,
M. Al-Mahasne: Data Curation, Scrubbing data and maintaining records, Formal Analysis, Writing-Original Draft, Writing- Review and Edit
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