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Site feasibility for offshore wind farm development: A preliminary case study at Jakhau, Gujarat (India)

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ABSTRACT

Renewable and sustainable energy technologies have been adopted globally to meet increasing energy demands. Offshore wind farms are crucial for reducing greenhouse gas emissions and enhancing the availability of power supply. Planning offshore wind energy farm development, involves carefully considered multiple variables to identify the ideal project sites. This study assesses the feasibility of offshore wind farm development along the northern coast of Gujarat, India, which has been identified as an optimal zone for wind energy generation. This assessment was based on a long-term analysis of critical parameters, including wind speed, bathymetry and met-ocean conditions. The annual average wind speed in the study area is about 7m/s, making it feasible for offshore wind energy production. Bathymetric data show depth values ranging from 10 m to 23 m, suitable for monopile foundation structures, recommended for offshore turbines in shallow waters. The site experienced a maximum tidal fluctuation of 3 m, which affected the turbine design and placement. Wave patterns were analyzed to understand the local wave climate. This study incorporates these parameters into the site selection process, considering environmental sustainability, technical feasibility and cost-effectiveness. The results suggest that the identified location of the northern Gujarat coast provides a suitable environment for developing an offshore wind farm. This study gives valuable insights into the criteria required for the early planning stages of offshore wind projects. The findings show that the Jakhau, Gujarat has a good potential for offshore wind farm development.

Keywords: Offshore wind farm, Feasibility study, Bathymetry, Met-ocean parameters, GIS, Jakhau (Gujarat)

INTRODUCTION

Globally, fossil fuels are the most extensively utilized energy source. Historically, fossil fuels have been the primary component of energy systems in both industrialized as well as developing nations (Caetano et al., 2017). People are now forced to choose renewable energy owing to rising energy demands and the depletion of fossil fuel supplies. By the end of the 20th century, wind energy had become increasingly popular for producing electricity (Rashid and Sarkar, 2022). One of the first and most important contributions to the generation of wind energy dates back to 1941 (Kaynia, 2019). Offshore wind farms perform better than onshore wind farms because of their higher and more consistent wind speeds at the sea. India's more than 7000 km long coastline (Dimri et al., 2023), presents a significant opportunity for offshore wind energy harvesting (Rashid and Sarkar, 2022). An overview of India's offshore wind resources was provided through satellite data analysis (Nagababu et al., 2016). Subsequently, satellite data were used to assess the offshore wind potential off the western coast of India (Nagababu et al., 2017).

The feasibility of establishing offshore wind farms in the northeastern Arabian Sea was thus investigated, considering factors such as harbors, wind speed, proximity to the coast, and marine protected zones (Mani Murali et al., 2014). Soil-structure interaction (SSI) is crucial for designing wind turbines under seismic loads, influencing dynamic performance on clay with monopile foundations using p-y curves (Prowell, 2011; Bisoi and Haldar, 2014; Zuo et al., 2018). Owing to their ease of fabrication, design, and installation, monopiles are the most commonly used foundation type worldwide. Approximately 80% of the wind turbine foundations currently in use are monopiles. Other standard foundation types for offshore wind turbines include, gravity foundations, jacket foundations and floating turbine systems (IRENA, 2012). The Indian government approved Rs. 7,453 crore VGF scheme to support 1 GW offshore wind projects in Gujarat and Tamil Nadu, aiming for 37 GW capacity and long-term CO_2 reductions under the 2015 Offshore Wind Energy Policy (Press Information Bureau, 2024). Onshore wind turbines installed near the Jakhau coast in Gujarat are part of India's extensive wind-energy initiatives. This coastal region, known for its solid, steady, and consistent wind patterns, provides an ideal environment for wind energy generation. The turbines in this area contribute significantly to the state's renewable energy output, tapping into the vast wind potential of Gujarat.

The wind farms near the Jakhau coast enhances energy security and support to local economies through job creation and infrastructure development (Murthy and Atmanand, 2013), Gujarat has installed on-shore wind turbines along its coast about 5 km from the shore. As India achieves its ambitious renewable energy targets, exploring the feasibility of offshore wind farms along the Gujarat coast, becomes essential in diversifying the nation’s energy portfolio and reducing its dependence on fossil fuels.

Such feasibility study encompasses various techno-economic assessments, wind resource analysis, bathymetry studies, environmental impact evaluations, and technological feasibility. This coast offers promising wind conditions, particularly in areas such as the Gulf of Khambhat and along the southern coastlines, where strong and steady winds create optimal conditions for energy generation. While the broader potential of Gujarat's coastline for offshore wind development has been acknowledged, site-specific insights, for example, wind-wave dynamics, structural feasibility, and resilience to environmental challenges remain underexplored at Jakhau. Further, several other challenges, such as complex seabed conditions, tidal variations, and potential environmental impacts on marine ecosystems and coastal communities, must also be addressed. Additionally, the study must consider logistical factors, such as the availability of port infrastructure for transporting materials and equipment, the proximity to power grid connections, and the overall installation and maintenance cost in offshore environments.

Advanced technologies, such as floating wind turbines or jacket foundations, may be required to be adapted to varying seabed depths and tidal ranges. The long-term reliability and stability of these structures under both wind and hydrodynamic forces, are vital to ensure the economic viability of the project. The present feasibility study is aimed to comprehensively understand the opportunities and challenges associated with the development of an offshore wind farm in Gujarat.

SITE DESCRIPTION

The coast of Gujarat has been favorable for wind energy projects because of its extensive coastline and steady wind conditions. The present study area, bounded between 68°19′51.13″ E, 23°11′48.76″ N and 68°36′15.35″E, 22°41′43.03″ N (Figure 1), is located off the west coast of Jakhau in Gujarat. Wind potential, bathymetry, and distance to the shoreline were considered for site selection based on the approach outlined in the Offshore Renewable Energy Conversion Platform Coordination Action [ORECCA] project (Murphy et al., 2011).

The site off the west coast near Jakhau port has been particularly chosen as the possible location for developing an offshore wind farm which experiences a tropical climate, with monsoon winds contributing to high wind energy potential. However, the region occasionally experiences extreme weather conditions, such as cyclones formed during the pre-monsoon (April-June) and post-monsoon (October-December) seasons, driven by warm ocean waters and atmospheric instability. There is already a wind farm working near Jakhau Port. The generated electricity from this wind farm is exported to Gujarat's state grid. In Turkey, such an exercise included wind potential, territorial waters, military zones, civil aviation, maritime traffic, pipelines, and underground cables (Argin and Yercy. 2015).

METHODOLOGY

The offshore wind farm development methodology, involves evaluation of critical factors. Environmental data such as water depth, wind, tide, and wave were used in this met-ocean study based on ORECCA. Long-term wind speed and direction data are analyzed to assess energy generation potential. Bathymetric studies focused on seabed depth and suitability for monopile foundations. Tidal variations are examined to account for changes in water levels and dynamic forces on the turbines. Wave patterns are analyzed to understand hydrodynamic impacts on structural stability. Geotechnical studies evaluated the seabed characteristics for foundation support. Economic assessments estimate, costs, viability and break-even periods. Logistical considerations, including proximity to Jakhau Port, are included to streamline construction, transportation, and maintenance efforts.

RESULTS AND DISCUSSION

Bathymetry

The bathymetry data was collected from GEBCO datasets (Becker et al., 2009). The bathymetry variation at the site (Figure 1), indicates a sloping seabed. This variation in depth also influences the hydrodynamic forces that act on the turbine-supporting structures, as waves, currents, and tides intensify with greater depths, pose additional challenges for installation and maintenance. Furthermore, the differing depths may suggest varying seabed sediment types, with sandy or rocky bottoms in shallower regions and softer sediments in deeper zones. These are essential factors in determining the most suitable foundation design. Understanding these bathymetric variations is necessary for optimizing the offshore wind turbine project's design, layout, and cost-effectiveness.

Wind

This site has favorable wind conditions at around 100 m above mean sea level. The wind data, spanning from 2013 to 2023, was analyzed over 11 years using hourly data on single levels to capture long-term variation and to better understand recurring patterns, which are essential for site suitability assessments. The wind rose plot for the site reveals that the predominant wind direction is from the north-northwest, which is a crucial factor when considering the placement of wind turbines to optimize energy capture. Wind speeds ranging between 7 to 15 m/s are the most frequent, occurring 40-50% of the time, which falls within the ideal operational range for modern wind turbines (Figure 2).

Additionally, wind speeds below 7 m/s occur about 20% of the time, while higher speeds above 25 m/s are relatively rare, appearing less than 2.5% of the time. These statistics indicate that extreme wind conditions, which could pose risks to turbine structures, are minimal at this location.

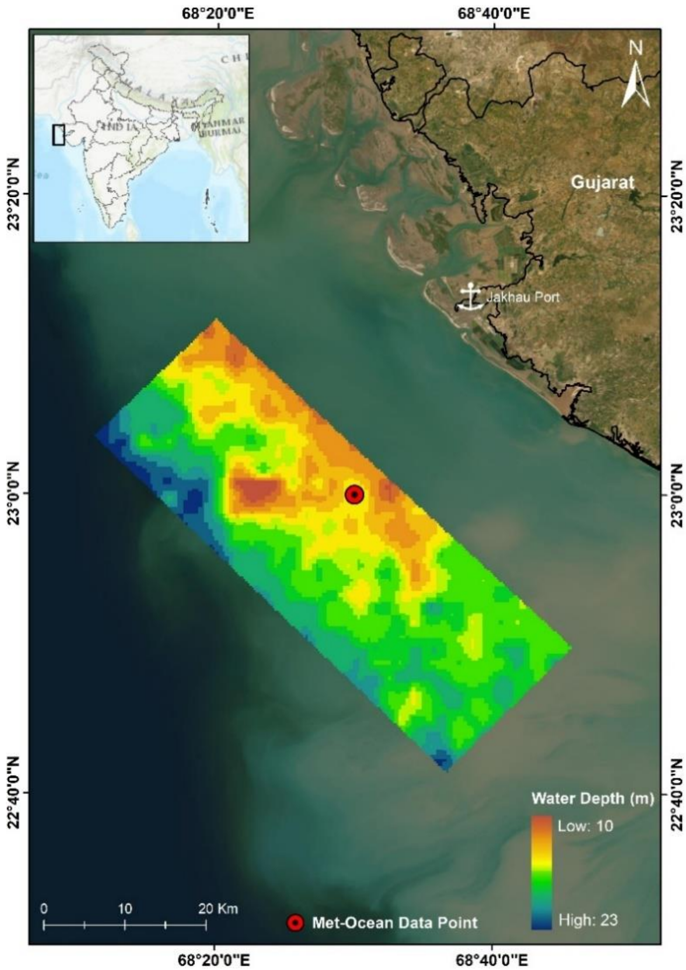

Figure 1. Site location and bathymetry variation off Jakhau coast, Gujarat (India).

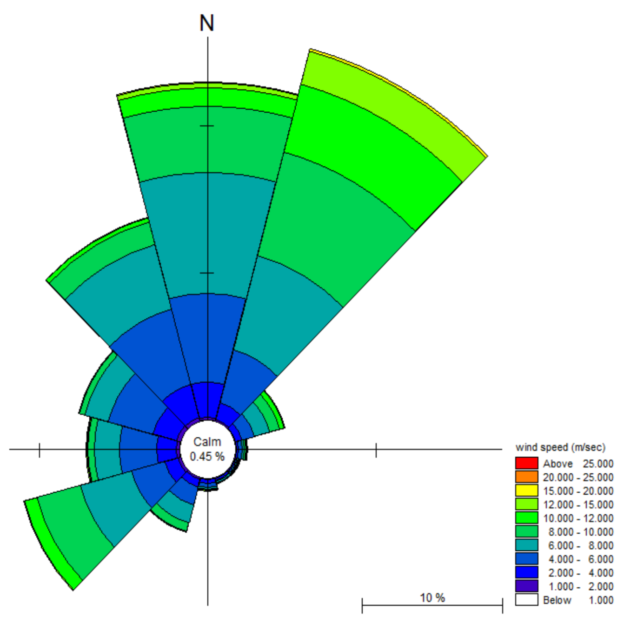

Figure 2. Wind rose plot in off Jakhau, Gujarat

Overall, the consistent presence of moderate wind speeds and the dominance of wind from a specific direction make this site an attractive candidate for offshore wind energy development. With favorable conditions occurring during a significant part of the time, this site holds considerable potential for generating a reliable and substantial amount of offshore wind energy. Studies on environmental impacts and technical factors would further confirm its feasibility for this purpose.

Tide

The tidal variation at the offshore site is based on data from a global tide model (Hart-Davis et al., 2021) for 23°N and 68.5°E, located close to Gujarat, India. Significant fluctuations in tidal elevation (-1.5 m to +1.5 m) with time, relative to the Mean Sea Level (MSL), can be seen here (Figure 3). For the present study, the data for over 18 years, spanning from 2005 to 2023, were analyzed in order to capture long-term tidal variation and recurring patterns.

The consistent variation reveals semi-diurnal tidal patterns with multiple peaks and troughs each day. This tidal range is crucial for the offshore wind turbine site study as it impacts the design of the turbine's supporting structure. The foundation must be capable of withstanding extreme tidal levels and dynamic water depths, ensuring stability during both high and low tides. Additionally, the tidal data was used to assess the hydrodynamic forces acting on the structure, which directly influences wave heights, currents, and loading conditions, including soil erosions/deposition in foundations. Understanding of the long-term tidal pattern is vital for optimizing the turbine's design, ensuring structural integrity and minimizing operational risks.

Wave

The hourly wave data from ERA5 (Hersbach et al., 2023) for over 11 years, spanning from 2013 to 2023, was analyzed to capture long-term variation and recurring patterns. Based on this data, the wave rose diagram represents the wave climate at a specific offshore wind turbine site. The dominant wave direction is southwest (SW), with wave heights primarily ranging between 2.0 and 3.5 m (Figure 4), make it the most frequent and consistent direction. Though less frequent, waves also approach from the west-southwest (WSW) and north-northeast (NNE). SW waves reach 3.5 to 4.5 m occasionally, but extreme waves above 4.5 m are rare. Calm conditions, with wave heights below 0.3 m, are infrequent, indicating that the site rarely experiences still seas. The SW direction not only produces the highest wave heights, but also the highest frequency of occurrence, dominating the wave climate. WSW and NNE waves have lesser effect on the supporting structure. The wave climate is characterized by consistent moderate wave activity with infrequent calm periods.

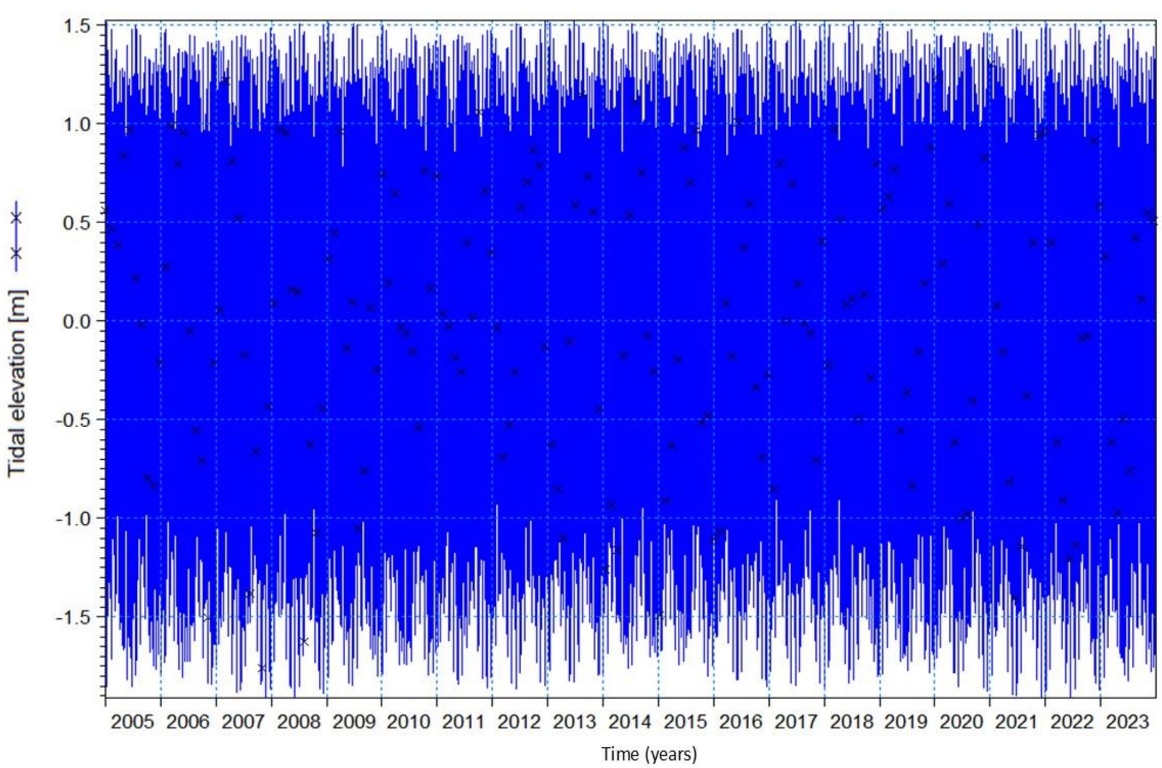

Figure 3. Tidal variation off Jakhau coast in Gujarat (India)

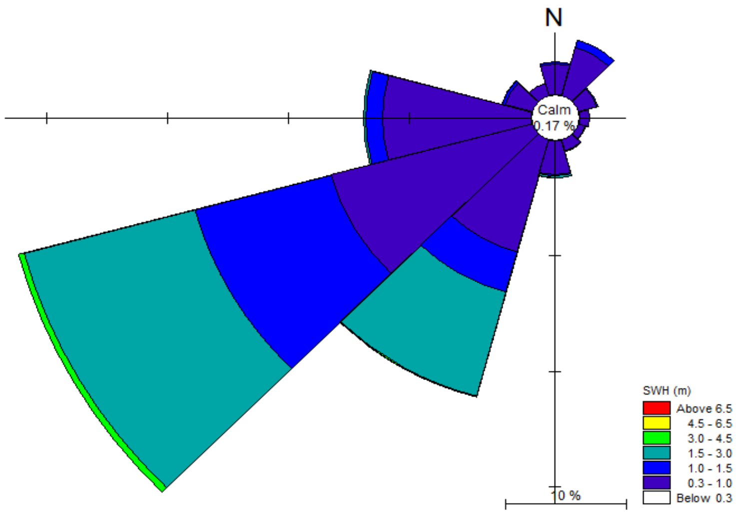

Figure 4. Significant wave height wave rose diagram off Jakhau coast, Gujarat (India)

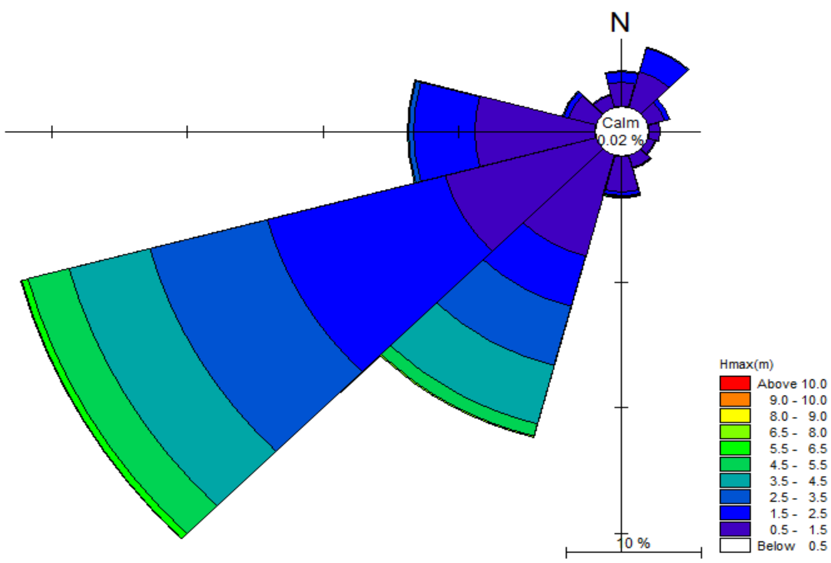

Figure 5. H_{max} wave rose diagram in off Jakhau coast, Gujarat (India)

The rose diagram (Figure 5), illustrates the maximum wave heights (H_{max}) and their corresponding mean wave direction (MWD) for an offshore wind turbine site. The dominant wave direction is southwest (SW), with additional contributions from the west-southwest (WSW) and north-northeast (NNE) directions. Most maximum wave heights range from 1.5 to 4.5 m, particularly from the SW, with occasional waves between 5.5 and 6.5 m. Calm conditions, with waves below 0.5 m, are rare. The SW direction consistently produces the highest wave activity, making it critical for wind turbine design to account for these forces. While the site experiences moderate to high-energy waves, extreme events above 10 m wave heights, are not observed, indicating that, although the site faces occasional large waves, it is not subjected to the most extreme conditions.

This wave climate analysis is essential for ensuring the structural resilience and long-term operational efficiency of offshore wind turbines. Decoupling of local winds from distant swell waves, is frequently the cause of opposing wind and wave orientations in offshore environments (Lyu et al., 2019). This phenomenon is impacted by several elements, including area meteorology, swell propagation, monsoon and geographic features (Li et al., 2023).

Site suitability analysis

The offshore wind power project site, located 37 km from Jakhau Port, Gujarat, exhibits promising conditions for wind turbine development. The wind speed at 100 m above mean sea level averages 7 m/s, which is suitable for harnessing wind energy effectively. The water depth ranges from 10 to 23 m, making it feasible to install fixed-bottom offshore wind turbines, which are cost-effective and widely used in similar depths. Additionally, the site's proximity to the Jakhau Port facilitates an advantage in logistics. With a total area of 1,284 km², this location offers ample space for large-scale wind farm development (Table 1). The short distance to Jakhau Port (37 km) further supports operational efficiency apart from ease of power evacuation, enabling convenient access for construction, transportation, and future maintenance activities.

Geotechnical study

Based on offshore subsurface information, between depths of 40 to 60 meters, the soil transitions from clay to sand, which has a submerged unit weight of 10 kN/m³. Although specific shear strength and friction angle data for the sand layer are not provided, sand typically offers higher bearing capacity and better drainage, making it an excellent base for monopile foundation support. The combined soil profile, with clay in the upper layer and the soil profile at the proposed offshore wind turbine site in Gujarat, with a monopile foundation, indicates favorable conditions for such installations. The upper 0-40 m of the seabed consists predominantly of clay, with a submerged unit weight of 7.5 kN/m³. The shear strength of the clay layer varies between 5 and 50 kPa, providing adequate resistance to lateral loads, essential for ensuring the monopile's stability (Table 2). The friction angle of 30° further supports soil-structure interaction, supporting the resistance to sliding forces. Beneath the sand at greater depths creates a balanced foundation condition for monopile installation, ensuring structural stability and efficient load distribution for the offshore wind turbines (FOWIND, 2018).

Wind resource assessment and cost estimation

The wind speeds observed at Jakhau, as depicted in the wind rose diagram, predominantly range between 7-15 m/s, with occasional higher speeds of 15-20 m/s and a small fraction below 7 m/s. This wind profile aligns effectively with the rated power range of the Siemens Gamesa 3.4-145 turbine, which achieves its maximum output of 3.4 MW at a rated wind speed of 12 m/s that operates efficiently within a wind speed range of 3-25 m/s (Figure 6). The turbine's rated power curve demonstrates a gradual increase in power output starting from the cut-in speed of 3 m/s, reaching full rated capacity at 12 m/s, and maintaining maximum power output up to the cut-out speed of 25 m/s. This performance characteristic ensures the turbine can consistently harness the available wind energy at Jakhau, where the most frequent wind speeds fall within this operational range.

3.4 MW offshore wind turbine has been taken into consideration for cost estimation based on the site's available wind potential. As a comprehensive concept, capital expenditure (CAPEX) includes direct investment costs and the financing, development and operational capital necessary to complete the project. In this study, CAPEX estimations have been made by the reported values of currently operating offshore wind farms, consistent with the methodologies suggested by Dicorato et al. (2011). The estimated cost for a 3.4 MW offshore wind turbine is Rs. 80.784 crores per turbine, which translates to a unit cost of Rs. 23.76 crores per MW.

Table 1. Parameters of the offshore site considered in for feasibility study

Average wind speed at 100 m elevation (m/s)	Water depth variation (m)	Distance to nearest coast (km)	Distance to nearest port (km)	Area (km^2)
7	10-23	34.5	37	1284

Table 2. Gujarat soil profile for spatial analysis

Depth	Soil type	Submerged unit weight (kN/m^3)	Shear strength (kPa)	Friction angle (degree)
0 - 40 m	Clay	7.5	5-50	30
40 - 60 m	Sand	10	-	-

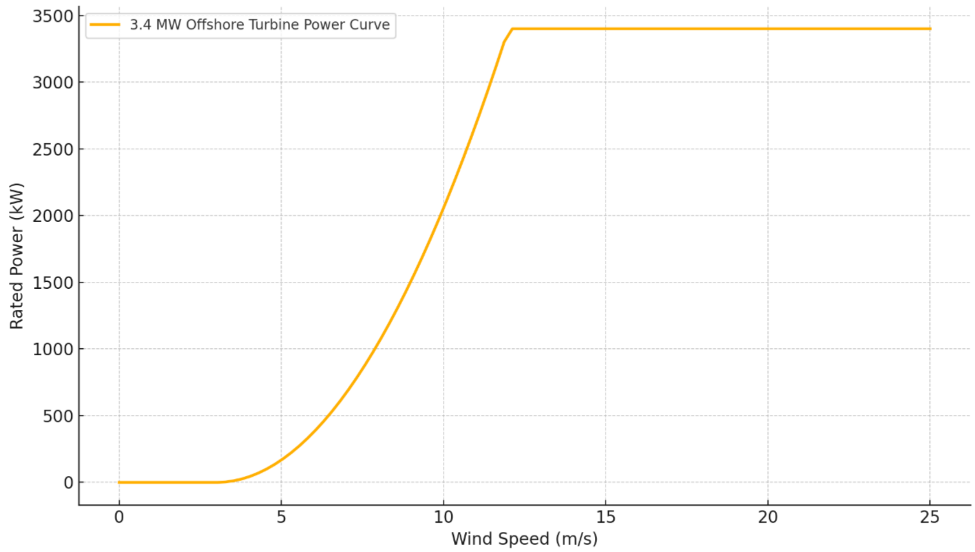

Figure 6. Typical 3.4 MW Offshore wind turbine rated power curve

Table 3. Cost estimation of a 3.4 MW capacity offshore wind turbine for a hypothetical 340 MW capacity offshore wind farm development

S. No	Category	Cost per MW (in crores)
1	Development and project management	1
2	Turbine cost	8.0
3	Balance of plant	5.5
4	Installation and commissioning	6.0
5	Operation, maintenance, and services per year	0.76
6	Decommissioning	2.5
7	Total cost	23.76
Estimated total cost for 3.4 MW offshore wind turbine = 23.76 x 3.4 = 80.784 crores/turbine		

This estimation includes several key cost components: Rs. 1 crore/MW for development and project management, Rs. 8.0 crores/MW for the turbine, Rs. 5.5 crores/MW for the balance of the plant, Rs. 6.0 crores/MW for installation and commissioning, and Rs. 2.5 crores/MW for decommissioning. Operational expenditure (OPEX), which covers operation, maintenance, and other ongoing operational expenses, is often under-reported, resulting in high uncertainty (Table 3). However, it is generally accepted that operation and maintenance (O&M) costs can account for 14–30% of the total lifecycle costs, representing around 50% of OPEX. For this analysis, an annual O&M cost of Rs. 0.76 crores/MW has been assumed based on the correlation developed by Möller et al. (2012). The economic analysis is conducted with an interest rate of 10%, a moderate value consistent with actual rates reported in the literature, and a project lifespan of 20 years, which is the consensus in wind turbine studies. These cost estimates provide a detailed financial framework, crucial for assessing the feasibility and economic sustainability of the offshore wind energy project.

The development of a 340 MW offshore wind farm using 3.4 MW turbines involves the installation of 100 turbines arranged to optimize energy capture and operational efficiency. Following industry standards, turbine spacing is approximately 8-10 times the rotor diameter (10D) along the prevailing wind direction and 3-5 times the rotor diameter (5D) in the perpendicular direction. This spacing minimizes wake effects between turbines, ensuring consistent wind flow and maximizing energy generation.

Economic analysis

The economic viability of the project, such as the installation of the 3.4 MW turbine, is strongly influenced by historical cost trends and current financial metrics like the Levelized Cost of Electricity/Energy (LCOE). The provided chart offers valuable insight into the global trend of LCOE for offshore wind energy from 2000 to 2022, measured in 2022 USD/kWh. The graph shows a clear downward trend in LCOE over the past two decades, reflecting technological advancements, increased scale of deployment, and improved project management practices in offshore wind energy. The cost reductions have been particularly significant since 2014, when the LCOE dropped sharply, making offshore wind increasingly competitive with other forms of energy generation (Figure 7).

From 2018 to 2022, the LCOE for offshore wind energy has stabilized at around \$0.08 to \$0.10 per kWh. This downward trend aligns with the economic analysis of a 3.4 MW offshore wind turbine in Gujarat, where the LCOE is estimated at Rs. 8.03 per kWh (Table 4). This cost is competitive within the global market, especially considering the complex logistics and environmental challenges associated with offshore wind installations.

The historical data shown in the graph further supports the economic feasibility of offshore wind projects by illustrating that as the industry matures, costs continue to decline, making such investments more attractive. This trend is a crucial factor in the long-term planning and financial forecasting for new offshore wind energy projects in Gujarat or anywhere else. The economic analysis of offshore wind energy must consider both the current LCOE estimates and the historical cost trends, as depicted in the graph, to provide a comprehensive understanding of the financial landscape of offshore wind investments.

Global perspective on offshore wind energy

Offshore wind energy roadmap (IRENA) gives significant growth ambitions, with plans to rapidly scale capacity over the following decades. The Global Wind Energy Council (GWEC) forecasts a rise in offshore wind capacity to 487 GW by 2033, driven by annual growth rates of 24%. Countries like the U.S., U.K. and China, are key players in this expansion. The United States administration has set a target of 30 GW of offshore wind by 2030, with long-term plans for 110 GW or more by 2050 (U.S. Department of the Interior). The global focus is to enhance efficiency, fast permitting processes, improving grid integration, and innovating floating wind technology to tap wind over deeper water (IRENA, 2024). In India, the government has laid a roadmap to install 30 GW of offshore wind capacity by 2030, focusing initially on Gujarat and Tamil Nadu coasts, which have significant wind potential of 36 GW and 35 GW respectively.

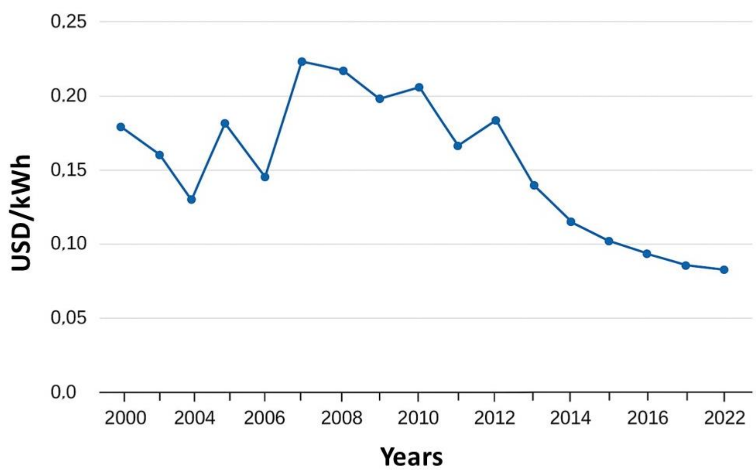

Figure 7. Weighted-average levelized cost of offshore wind generated power from 2000-2022 (IRENA, 2024)

Table 4. Levelized cost of electricity from offshore wind turbines and break-even point

S. No	Description	Value
1	Capital cost	20.50 Crores/MW
2	F O&M	0.76 Crores/MW
3	Time	20 years
4	Number of hours in a year	8760 hours
5	Capacity factor	0.45
6	Interest rate	10%
7	Tariff rate	7 Rs/kWh
LCOE		8.03 Rs/kWh
Break-even point (in years)		10.25 years

India’s phased approach includes pilot projects and collaboration with international partners to enhance technical and regulatory frameworks (IRENA, 2024). Floating offshore wind technology is crucial to harness the country's deeper waters, where favorable conditions can vary based on seafloor morphology and project location. According to IRENA’s latest data and analysis, in 2022, global offshore wind capacity grew to 63.2 GW, which is a positive development considering the impact that the COVID-19 pandemic had on sectoral activity. However, to comply with a 1.5˚C scenario, the global offshore wind capacity would need to increase to 494 GW by 2030 and 2465 GW by 2050, a target that will not be met with the current pace of sectoral development as well as supply chain constraints the industry has been experiencing. It is also essential to recognize that offshore wind developments have been concentrated in Europe and China. For a just and inclusive energy transition, other emerging economies must also increase their involvement in exploring offshore wind development.

CONCLUSIONS

The present study presents a comprehensive assessment of the feasibility and economic viability of offshore wind farm, developed off the west coast of Jakhau, Gujarat. Critical factors such as bathymetry, wind, tidal, wave conditions, and geotechnical characteristics were thoroughly analyzed to optimize future design and ensure structural integrity. Water depths ranging from 10 to 23 m, combined with hydrodynamic forces, highlight the need for a robust foundation design. Wind and wave analyses indicate favorable conditions for wind energy generation, with consistent wind speeds and moderate wave activity contributing to reliable and efficient power production. Wind speeds between 7 to 15 m/s, occurring 40–50% of the time, fall within the ideal operational range for modern turbines. Tidal studies emphasize the importance of designing turbines to withstand dynamic tidal forces, with fluctuations ranging from -1.5 m to +1.5 m relative to the mean sea level. Wave heights typically range from 2.0 to 3.5 m, with the southwest (SW) direction being the most frequent. The site is 34.5 km from the nearest coast and 37 km from the nearest port, offering logistical advantages. The on-site feasibility analysis confirms that an offshore wind farm at this location is viable. A conceptualized 340 MW offshore wind farm with 100 turbines spaced to industry standards, ensures optimal energy capture and operational efficiency while minimizing wake effects. Financially, the project is promising with an estimated Levelized Cost of Electricity (LCOE) at Rs.8.03 per kWh, in line with global cost-reduction trends. Break-even analysis shows that at a Rs.7 per kWh tariff, the project can break-even in 10.25 years. Given India’s rising energy demand and focus on sustainable solutions, this timeline is favorable. With suitable environmental conditions and strong economic prospects, the project represents a key opportunity to support India’s renewable energy goals.

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Author Credit Statement

E. Sathish Kumar: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review and editing; I. S. Judha Benhur: Conceptualization, Formal analysis, Investigation, Writing – review and editing; G. Dhinesh: Investigation, Project administration, Resources, Supervision, Validation, Visualization, Writing – review and editing; K.Mullai Vendhan: Investigation, Project administration, Resources, Supervision, Validation, Visualization; S. V. S. Phani Kumar: Project administration, Resources, Validation, Visualization.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors upon reasonable request.

Compliance with ethical standards

This article does not contain any studies with human participants or animals performed by any of the authors. The authors have followed the ethical norms of publishing. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors adhere to copyright norms.

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