Case Study on Floating Offshore Wind Energy in Maharashtra, India: Feasibility, Challenges, and Future Prospects

Atharva Suhas Kulkarni[1],

[1]*atharvakulkarni642@gmail.com*

***

Abstract – *This case study examines the feasibility, implementation, and operational efficiency of a floating offshore wind farm in Maharashtra, India. The study explores key aspects, including site selection, wind resource assessment, turbine technology, energy output optimization, and challenges in grid integration. The project aims to assess the economic and environmental impact of floating offshore wind energy in India's energy transition. Additionally, it evaluates the role of government policies, financial incentives, and technological innovations to enhance offshore wind deployment. The findings provide insights into the sustainability and feasibility of offshore wind energy in Maharashtra, contributing to India's renewable energy goals.*

Key Words: **Floating Offshore Wind Energy, Maharashtra Wind Power, Renewable Energy, Offshore Wind Turbines, Wind Farm Feasibility, Grid Integration**

1.INTRODUCTION

Offshore wind energy has emerged as a key player in the global transition toward sustainable power generation [1]. With increasing energy demand and the urgency to reduce carbon emissions, offshore wind farms provide a reliable and scalable solution. Unlike onshore wind farms, offshore installations benefit from higher and more consistent wind speeds, leading to greater energy generation potential [2]. Within offshore wind technology, two primary approaches exist: fixed-bottom wind turbines, which are anchored to the seabed in shallow waters, and floating wind turbines, which are more suitable for deep waters where fixed foundations are not feasible [3].

In India, Maharashtra's Konkan region presents a viable location for offshore wind energy development due to its consistent wind speeds (6.5 – 8 m/s), proximity to urban energy demand centers (Mumbai, Pune), and access to maritime infrastructure [4].

Given the deep waters along Maharashtra's coastline, floating offshore wind technology becomes the preferred choice for energy generation in this region[5].

This case study aims to evaluate the feasibility, implementation, and challenges of developing a floating offshore wind farm in Maharashtra, addressing aspects such as wind resource potential, turbine selection, economic viability, environmental impact, and future growth prospects in India's offshore wind sector.

2. Site Selection and Wind Resource Assessment

The selection of a suitable site is a crucial step in offshore wind farm development, as it directly influences the energy output, cost-effectiveness, and environmental impact of the project. Maharashtra's Konkan region has been identified as a promising location for offshore wind deployment due to its strategic positioning along the Arabian Sea and favorable wind conditions [6].

2.1 Main Reasons for Selecting Maharashtra's Konkan Region

Maharashtra's coastal belt, stretching along the Konkan region, offers several advantages for offshore wind development. Firstly, the region is close to major urban energy demand centres such as Mumbai, Navi Mumbai, Pune, and Thane, making it an ideal location for clean energy generation. This proximity reduces transmission losses and enhances grid stability [7]. Secondly, Maharashtra is actively exploring offshore renewable energy as part of its long-term sustainability goals, aligning with India's commitment to increasing its renewable energy capacity to 500 GW by 2030 [8].

Additionally, the Konkan coastline has a mix of shallow to deep waters, allowing for the installation of floating offshore wind turbines, which are essential for harnessing wind energy in areas with water depths exceeding 50 meters. Compared to fixed-bottom wind turbines, which are limited to shallow waters, floating wind technology enables Maharashtra to utilize its deeper offshore regions efficiently [5].

2.2 Wind Speed and Direction Analysis

The effectiveness of an offshore wind farm is highly dependent on wind speeds and consistency. Studies conducted by the National Institute of Wind Energy (NIWE) indicate that Maharashtra's Konkan region experiences average wind speeds ranging from 6.5 – 8 m/s at 100 meters hub height. These speeds fall within the optimal range for efficient energy generation, particularly with large-capacity floating wind turbines like the Vestas V236-15.0 MW model selected for this study [7].

The wind direction in this region is predominantly southwest during the monsoon season and northeast during the winter months, ensuring relatively steady wind flow throughout the year. This consistency enhances the capacity factor of offshore wind turbines, leading to higher energy production compared to onshore wind farms, which often experience greater seasonal fluctuations. [4]

2.3 Sealed Conditions, Water Depth, and Environmental Considerations

The offshore waters of Maharashtra, exceeding 50 meters in depth, necessitate the use of floating wind turbines. Given the seabed composition of sand, silt, and rock, semi-submersible platforms are the most viable foundation, ensuring stability in dynamic marine conditions.

To mitigate environmental and socio-economic impacts, wind farms must be strategically positioned to avoid critical fishing zones and shipping lanes. Implementing low-noise installation techniques and engaging local stakeholders will facilitate sustainable development while minimizing disruption to marine ecosystems and coastal livelihoods.

Additionally, the presence of busy shipping lanes near Mumbai poses a logistical challenge, requiring proper marine spatial planning to prevent conflicts between wind farm operations and commercial shipping routes. Collaboration with local fishing communities and port authorities is essential to ensure that offshore wind development does not negatively impact livelihoods or coastal economies.

3. Floating Wind Turbine Technology and Infrastructure

Floating wind technology enables wind turbines to be installed in deep waters where fixed-bottom foundations are impractical. These turbines are mounted on floating structures anchored to the seabed using mooring systems. This approach is essential for Maharashtra's offshore waters, which exceed 50 meters in depth, making traditional fixed foundations unsuitable.

Semi-submersible platforms are the most suitable floating foundations for this project. They distribute the turbine's weight across multiple pontoons, ensuring stability against strong ocean currents and wind forces. Their low center of gravity and dynamic positioning system make them highly effective in Maharashtra's deep-water conditions while minimizing structural stress.

3.1 Selection of Wind Turbines

The following table compares two turbine models based on key technical parameters:

Table -1: Comparison of two turbine models

Feature	**Vestas V236-15.0 MW**	**Suzlon S120-10.2 MW**
Rated Power	15.0 MW	10.2 MW
Rotor Diameter	236 m	200 m
Swept Area	43,742 m^2	31,400 m^2
Annual Energy Production (AEP)	Higher due to larger swept area	Lower compared to Vestas
Suitability for Floating Wind	Proven offshore technology	Limited offshore deployment experience

Reason for Choosing Vestas V236-15.0 MW: The Vestas V236-15.0 MW turbine is selected for this project due to its higher capacity, larger swept area, and proven offshore performance [5]. Its greater energy capture efficiency reduces the number of turbines required, optimizing both cost and maintenance efforts in deep-sea conditions [6].

3.2 Energy Components and Working of Offshore Wind Turbine

The efficiency and reliability of a floating offshore wind turbine depend on its core components, which work together to convert wind energy into electricity. The diagram below illustrates the key structural and functional elements of a floating offshore wind turbine, including the nacelle, rotor blades, gearbox, generator, and tower. Understanding these components is essential for optimizing energy production and ensuring long-term operational stability

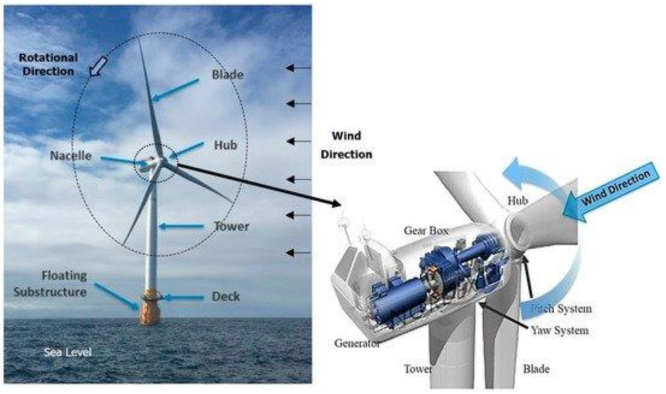

Fig -1: Structural and Functional Components of a Floating Offshore Wind Turbine

As seen in the diagram, the rotor blades capture wind energy, rotating the hub and transferring mechanical power through the gearbox to the generator housed in the nacelle. The yaw and pitch systems ensure optimal blade orientation based on wind direction, maximizing efficiency. The turbine is mounted on a floating substructure, allowing deployment in deeper waters, making it an ideal solution for Maharashtra's offshore wind energy potential. These components work together to enable sustainable and reliable power generation.

4. Energy Output and Grid Integration

The successful integration of a floating offshore wind farm into Maharashtra's power grid requires strategic planning to maximize energy output and ensure efficient electricity transmission.

4.1 Energy Generation Potential

A 100 MW floating offshore wind farm in Maharashtra is expected to generate approximately 400–450 GWh per year, based on:

- High-Capacity Factor (~45%) – Offshore wind turbines generate power more consistently due to stronger and steadier wind speeds.
- Advanced Turbine Efficiency – The selected Vestas V236-15.0 MW turbine is designed for optimal performance in offshore conditions.
- Minimal Land Constraints – Unlike onshore wind farms, offshore projects face no physical obstructions, enabling continuous energy production [8].

4.2 Grid Integration Challenges

While offshore wind energy offers high reliability, integrating it into Maharashtra's power grid presents several challenges:

- **Fluctuating Wind Speeds** – Variability in wind intensity can cause fluctuations in power generation, requiring a **balanced grid infrastructure**.
- **Transmission Infrastructure Costs** – Laying **subsea HVDC cables** and upgrading the existing power grid requires high capital investment.
- **Grid Stability and Demand-Supply Balance** – Offshore wind farms need to be synchronized with the grid to prevent voltage fluctuations.

4.3 Importance of HVDC Transmission

To overcome transmission challenges, **High Voltage Direct Current (HVDC) transmission** is preferred over traditional AC systems due to:

- **Lower Transmission Losses** – Offshore wind farms are located far from demand centers, making HVDC cables more efficient.
- **Higher Power Transfer Capacity** – HVDC lines can handle large amounts of power with minimal energy dissipation.
- **Improved Grid Stability** – HVDC converters regulate power flow and enhance system reliability.

The **integration of HVDC technology** ensures that offshore wind power is delivered efficiently to Maharashtra's energy grid, reducing energy losses and maximizing economic returns.

4.4 Energy Storage and Hybrid Solutions

To ensure a **consistent power supply**, offshore wind energy can be combined with energy storage and hybrid renewable solutions:

- **Battery Energy Storage Systems (BESS)** – Stores excess wind power and releases it during periods of low wind speeds.
- **Hybrid Offshore Wind-Solar Integration** – Floating solar panels alongside wind turbines optimize energy output and ensure a steady supply.
- **Grid-Connected Smart Systems** – AI-driven smart grids can predict energy demand and adjust supply accordingly.

5. Economic Viability and Performance Analysis

5.1 Investment and Cost Analysis

A floating offshore wind farm requires a substantial upfront investment due to the complexity of deep-sea installations and transmission infrastructure.

For a **100 MW floating offshore wind project in Maharashtra**, the estimated capital expenditure (**CapEx**) is **₹3,000 – ₹3,700 crore ($360M – $450M)**. The cost distribution includes:

- **Turbine Procurement & Installation** – 35%
- **Floating Platform & Anchoring System** – 30%

- **HVDC Transmission & Substation** – 25%
- **Engineering, Development & Permits** – 10%

While offshore wind has a higher initial investment compared to onshore wind or solar, it ensures greater long-term energy reliability and higher capacity factors, making it a strategic long-term investment.

5.2 Revenue and Payback Analysis

The financial sustainability of offshore wind energy depends on its generation capacity and market pricing. The projected revenue and cost breakdown are as follows:

- **Annual Energy Output**: **400 – 450 GWh** (45% capacity factor)
- **Tariff per kWh**: **₹6.5 ($78/MWh)**
- **Annual Revenue**: **₹260 – ₹292 crore ($31M – $35M)**
- **Operational Costs (O&M)**: **₹80 – ₹110 crore ($10M – $13M) per year**
- **Net Annual Profit**: **₹180 – ₹210 crore ($21M – $25M)**
- **Break-even Period**: **12 – 16 years**
- **Total Net Profit Over 30 Years**: **₹1,800 – ₹2,200 crore ($215M – $260M)**

Due to **higher efficiency and predictable wind conditions offshore**, this investment is financially viable, especially when supported by **government incentives, tax credits, and long-term Power Purchase Agreements (PPAs).**

5.3 Performance and Reliability: Offshore Wind vs. Solar

To evaluate **long-term stability and energy reliability**, offshore wind and solar power generation are compared over **30 years** [6]:

Table -2: Comparison of Offshore Wind and Solar

Factor	Offshore Wind (100 MW)	Solar (100 MW)
Capacity Factor	~45%	~20%
Annual Generation	400 – 450 GWh	180 – 220 GWh
Degradation Rate	0.3% per year	0.8% per year
Lifespan	25 – 30 years	20 – 25 years
Break-even Period	12 – 16 years	5 – 7 years
Total Net Profit (30 yrs)	₹1,800 – ₹2,200 crore ($215M – $260M)	₹3,700 crore ($450M)

The efficiency of a renewable energy source depends on its long-term performance. This graph compares the power generation decline of a **100 MW offshore wind farm (45% CF)** and a **100 MW solar farm (20% CF) over 30 years**, highlighting their reliability over time.

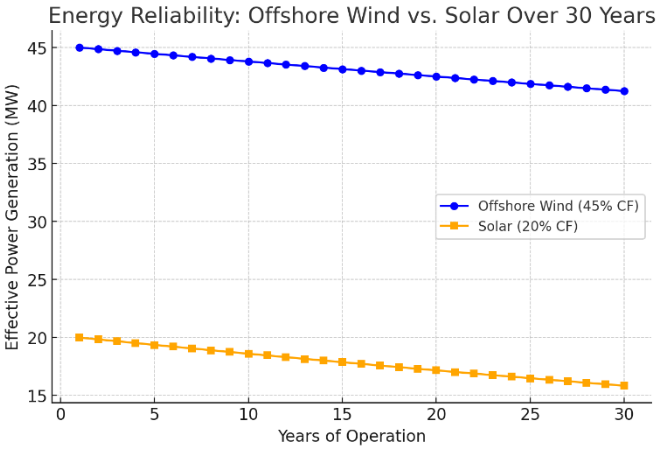

Fig- 2: Energy Reliability – Offshore Wind vs. Solar Over 30 Years

Offshore wind retains higher efficiency over 30 years, with only 0.3% annual degradation, whereas solar degrades at 0.8% per year. This makes offshore wind a more reliable and stable energy source for Maharashtra's long-term energy security.

5.4 Key Financial and Operational Insights

Offshore wind ensures long-term stability, with lower degradation (0.3% per year) compared to solar over a 30-year period.

Solar has a faster payback period (5–7 years) but degrades more quickly, reducing its long-term efficiency.

Offshore wind has a higher upfront investment but produces more power consistently due to its higher capacity factor (45%).

Hybrid models (Offshore Wind + Solar + Battery Storage) are preferred for balancing cost efficiency and grid stability.

Government incentives (Viability Gap Funding, Tax Benefits) can improve offshore wind financial viability and reduce the break-even time.

Despite a higher initial investment, offshore wind ensures consistent energy production, even during nighttime and monsoon seasons, where solar output is minimal.

6. Challenges and Solutions

The deployment of a **floating offshore wind farm in Maharashtra** presents several challenges, ranging from technical complexities to financial constraints, environmental concerns, and regulatory hurdles. Addressing these challenges effectively is crucial for the project's success. This section outlines key challenges and provides strategic solutions to overcome them.

6.1 Technical Challenges and Solutions

6.1.1 Floating Turbine Stability in Deep Waters

Challenge: Floating offshore wind turbines must withstand **harsh ocean conditions, strong currents, and high waves**, making stability a critical issue.

Solution:

- Implement **semi-submersible floating platforms** to enhance stability.
- Utilize **dynamic mooring systems and AI-based stability control** for real-time adjustments.
- Conduct **continuous monitoring and predictive maintenance** to prevent structural failures.

6.1.2 Grid Integration and Power Transmission

- **Challenge:** Offshore wind farms require **high-voltage subsea transmission**, and fluctuating wind speeds can lead to **grid instability**.
- **Solution:**
    - Use **HVDC subsea cables** to minimize transmission losses and increase efficiency.
    - Develop a **hybrid wind-solar-storage system** for enhanced grid stability.
    - Implement **smart grid technologies** to balance energy supply and demand in real-time.

6.1.3 Operations and Maintenance (O&M) Complexity

- **Challenge:** Conducting **repairs and routine inspections** in deep-sea environments is costly and logistically challenging.
- **Solution:**
    - Deploy **AI-driven predictive maintenance systems** to detect issues before failures occur.
    - Utilize **autonomous underwater drones and robotic repair units** for inspections.
    - Establish **dedicated offshore O&M service vessels** for quick response and maintenance operations.

6.2 Financial and Investment Challenges

6.2.1 High Initial Capital Investment

- **Challenge:** The project requires **₹3,000 – ₹3,700 crore ($360M – $450M)** in upfront investment, making it less attractive for private investors.
- **Solution:**
    - Implement **Viability Gap Funding (VGF)** to reduce financial risks.
    - Offer **Green Bonds and Offshore Wind Investment Tax Credits** to attract investors.
    - Establish **long-term Power Purchase Agreements (PPAs)** to ensure stable revenue.

6.3 Environmental and Social Considerations

6.3.1 Impact on Marine Biodiversity

- **Challenge:** Offshore wind projects can affect **marine ecosystems, fish populations, and seabird migration.**
- **Solution:**
    - Conduct **detailed Environmental Impact Assessments (EIA)** before deployment.
    - Implement **eco-friendly turbine foundations** to promote marine habitat protection.
    - Use **low-noise installation techniques** to minimize disturbance to marine life.

6.3.2 Fishermen and Local Community Concerns

- **Challenge:** Offshore wind farms may interfere with **traditional fishing zones**, causing economic concerns for local communities.
- **Solution:**
    - Develop **compensation and benefit-sharing models** for affected fishermen.

- Establish **fishermen co-management programs** that allow sustainable fishing alongside offshore wind operations.
- Conduct **public consultations and stakeholder engagement** to build local support.

7. Future Outlook and Recommendations

The successful deployment of a **floating offshore wind farm in Maharashtra** has the potential to pave the way for large-scale offshore wind development in India.

7.1 Future Growth of Offshore Wind in India

India has set ambitious renewable energy targets, and offshore wind is expected to play a crucial role in achieving them. The projected growth for offshore wind capacity includes:

Table -3: Offshore Wind Growth in India (2025–2050)

Year	**Installed Capacity**	**Key Milestone**
2025	50-100MW	Pilot projects in Maharashtra & Gujarat
2030	5GW	Offshore wind auctions, first large-scale farms
2040	20-30 GW	Hybrid models (wind + solar + battery storage)
2050	30-50 GW	Offshore wind becomes a major contributor to India’s grid

7.2 Technological Innovations and Cost Reductions

Continuous technological advancements will drive offshore wind adoption by making it **more efficient and cost-effective**. Key innovations include:

Next-generation floating wind turbines with larger rotor diameters and higher efficiency.

Smart grid integration and AI-based predictive maintenance to optimize energy output and reduce O&M costs.

Advanced HVDC transmission systems to ensure minimal power losses over long distances.

Innovations in floating platforms, making offshore wind feasible in deeper waters at lower costs.

7.3 Policy and Regulatory Enhancements

To accelerate offshore wind deployment, India must establish **strong policy frameworks** and regulatory mechanisms. Key policy improvements include:

- **Long-term offshore wind auctions** to provide financial security for investors.
- **Viability Gap Funding (VGF) and Green Bonds** to attract private sector investment.
- **Clear environmental permitting guidelines** to streamline approval processes.
- **Incentives for local manufacturing of offshore wind components**, reducing reliance on imports.

8. CONCLUSIONS

This case study has demonstrated the feasibility, challenges, and future potential of developing a **100 MW floating offshore wind farm in Maharashtra, India.** The findings indicate that **floating offshore wind technology** presents a viable solution for harnessing **India’s vast offshore wind resources**, offering **higher capacity factors, long-term energy reliability, and reduced land dependency** compared to other renewable energy sources.

Despite challenges related to **high capital costs, grid integration complexities, and environmental concerns**, this study highlights key strategic solutions, including **Viability Gap Funding (VGF), advanced HVDC transmission, hybrid wind-solar integration, and enhanced policy frameworks**. These measures can **mitigate financial risks, improve grid stability, and ensure sustainable project deployment.**

Furthermore, projections suggest that **India’s offshore wind capacity could grow from 100 MW (pilot stage) to 50 GW by 2050**, positioning Maharashtra as a **critical hub for offshore wind energy expansion.**

With the right **policy instruments, technological innovations, and investment strategies**, Maharashtra’s offshore wind sector can serve as a model for sustainable energy development, contributing significantly to India's clean energy transition and climate commitments.

REFERENCES

[1] [1] M. Arshad and B. C. O'Kelly, "Offshore wind-turbine structures: A review," *Proceedings of the Institution of Civil Engineers Energy*, vol. 166, no. EN4, Nov. 2013. Available: https://www.researchgate.net/publication/260424553_Offshore_wind-turbine_structures_A_review.

[2] H. Almansoori, "Offshore Wind Farms Research Paper," *ResearchGate*, Aug. 2020. Available: https://www.researchgate.net/publication/343878559_Offshore_Wind_Farms_Research_Paper.

[3] B. Desalegn, D. Gebeyehu, B. Tamrat, T. Tadiwose, and A. Lata, "Onshore versus offshore wind power trends and recent study practices in modeling of wind turbines' life-cycle impact assessments," *Cleaner Technologies and Environmental Policy*, Nov. 2023, doi:10.1016/j.clet.2023.100691.

[4] L. Alhmoud and H. Al-Zoubi, "IoT Applications in Wind Energy Conversion Systems," *Engineering Review*, vol. 39, no. 6, Nov. 2019, doi:10.1515/eng-2019-0061.

[5] B. Desalegn, D. Gebeyehu, and B. Tamrat, "Wind energy conversion technologies and engineering approaches to enhancing wind power generation: A review," *Heliyon*, vol. 8, no. 11, Nov. 2022, doi:10.1016/j.heliyon.2022.e11263.

[6] A. Fernández-Guillamón, K. Das, N. A. Cutululis, and Á. Molina-García, "Offshore Wind Power Integration into Future Power Systems: Overview and Trends," *Journal of Marine Science and Engineering*, vol. 7, no. 11, Nov. 2019, doi:10.3390/jmse7110399.

[7] A. M.-Z. Gao, C.-H. Huang, J.-C. Lin, and W.-N. Su, "Review of recent offshore wind power strategy in Taiwan: Onshore wind power comparison," *Energy Strategy Reviews*, vol. 38, 2021, doi:10.1016/j.esr.2021.100747.

[8] P. Hevia-Koch and H. K. Jacobsen, "Comparing offshore and onshore wind development considering acceptance costs," *Energy Policy*, vol. 125, Feb. 2019, doi:10.1016/j.enpol.2018.10.019.