Chapter 8

Offshore Wind Feasibility Study in India

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Additional information is available at the end of the chapter

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Abstract

Offshore wind provides a scalable alternative to conventional energy resources. This chapter provides an insight into various activities of Ministry of Earth Sciences for the realization of offshore wind in India. To understand the hurdles in policy frame work for offshore wind, the evolution of onshore wind policy is analyzed and suitable strategies for offshore wind are proposed. Wind resource assessment results indicated a high offshore potential at Kanyakumari, Rameshwaram, Gulf of Khambhat, and Gulf of Kutch. Commercial viability studies showed levelized cost of electricity (LCOE) of around Rs 10/kWh at identified sites for an internal rate of return (IRR) of 14%. Offshore light detection and ranging (LiDAR)-based data collection platform has been installed at Gulf of Khambhat and Kutch to obtain bankable wind data for the development of offshore wind farms. A preliminary design of substructure by exploring different concepts like monopile, jacket, and gravity-based foundations was carried out based on their suitability for site-specific environmental and soil data. The port facilities along Gujarat and Tamil Nadu coast were assessed, and installation methodology was developed considering marine spread along the Indian coast.

Keywords: offshore wind, India, wind resources, commercial viability, substructure, installation

1. Introduction

The increased environmental awareness, energy security, and depletion of land-based resources are driving the dependence on renewable energy technologies. Wind energy has gained wide acceptance across the globe and presently the focus is toward the development of offshore wind farms. The promising factors for offshore wind development are (1) powerful and consistent winds compared to onshore, (2) low sound pollution and visual intrusion, (3) best benefit to coastal areas due to less transmission cost and losses, and (4) easy transportation of larger capacity turbines.

Europe is leading the offshore wind market since the inception of its first commercial offshore wind project in 1996 with an installed capacity of more than 8 GW connected to grid as of 2014. The installed capacity of wind farms in Europe is 8.045 GW [1], while in China and Japan are 0.67 and 0.05 GW, respectively [2]. Proposals exist to expand the respective capacities to 24 GW (Europe) [3], 10 GW (China) [4], and 1 GW (Japan) [5] by 2020. Actually, more than 90% of the global offshore wind farms were located in European waters, and the contribution from various countries is shown in **Figure 1**. In 2013, the world's largest wind farm "London Array" with a capacity of 630 MW is commissioned in United Kingdom [6]. A project with 0.468 GW capacity is under construction in USA with proposals for expanding the capacity to 10 GW by 2020 [7].

Developing country like India is yet to meet the required energy demands through existing installed capacities of 259 GW [8]. During fiscal year 2013–2014, India has experienced an energy shortage of 4.2% (960 BU against a demand of 1002 BU) with a peak shortage of 4.5% (130 GW against a demand of 136 GW) [9]. The southern region has experienced a severe energy shortage of 6.8% with a peak shortage of 7.6% [9]. Tamil Nadu, Andhra Pradesh, Karnataka, and Kerala belonged to this region and have a coastline of 3100 km [10]. Offshore wind being pollution free would be an ideal solution to meet the increasing demand as these coasts were blessed with significant winds. India initiated the efforts toward the development of offshore wind in the potential locations, and policy guidelines were formulated by the Ministry of New and Renewable Energy (MNRE) to promote offshore wind projects. Prior to finalization of offshore wind policy in India, it was essential to study the key aspects such as identification of potential sites, selection of suitable wind turbines capacity, and arriving at feasible incentives to promote offshore wind, which were performed.

Various technical institutes working with MNRE and the Ministry of Earth Sciences (MoES) along with the global partners carried out offshore wind assessment studies and identified

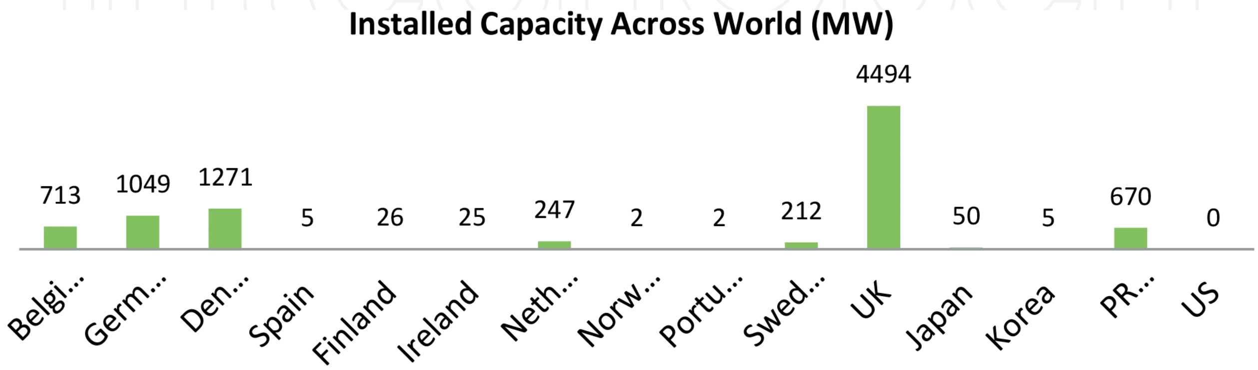

Figure 1. Installed capacity across the world (2014).

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the potential sites. The wind resource assessment studies need to be reinforced with suitable data collection in the potential location not only for validation but also for obtaining bankable wind data. National Offshore Wind Energy Policy allows interested government and private agencies to indulge themselves in carrying out met ocean studies in the potential locations. MNRE-National Institute of Wind Energy (NIWE) and M/s Suzlon Energy Limited along with technical expertise from the National Institute of Ocean Technology (NIOT) have installed light detection and ranging (LiDAR)-based Offshore Data Collection Platforms at Gulf of Kambhat and Gulf of Kutch, Gujarat, during fiscal year 2017.

2. Identification of offshore wind potential sites

Wind Atlas gives good indication of the geographical distribution of the wind resource and will be useful for decision making and planning of feasibility studies. However, to meet the bankability requirements, precise measurements are required for a couple of years at the proposed site. Conventionally, Wind Atlas is generated using analytical wind measurements at a number of sites across the country. As long-term historical wind data are not available at all the terrains in India, the National Institute of Wind Energy (NIWE) has used Karlsruhe Atmospheric Mesoscale Model (KAMM)/Wind Atlas Analysis Application (WAsP) developed at Risø DTU National Laboratory and generated numerical Wind Atlas for India [11]. Verification of model results was carried out using measured wind speeds and directions from onshore NIWE metrological masts. The offshore winds till 100-km deep into ocean are also generated using the same model, and results need to be verified using measured offshore winds. The offshore Wind Atlas shows significant potential along the southern Tamil Nadu coast as shown in **Figure 2**.

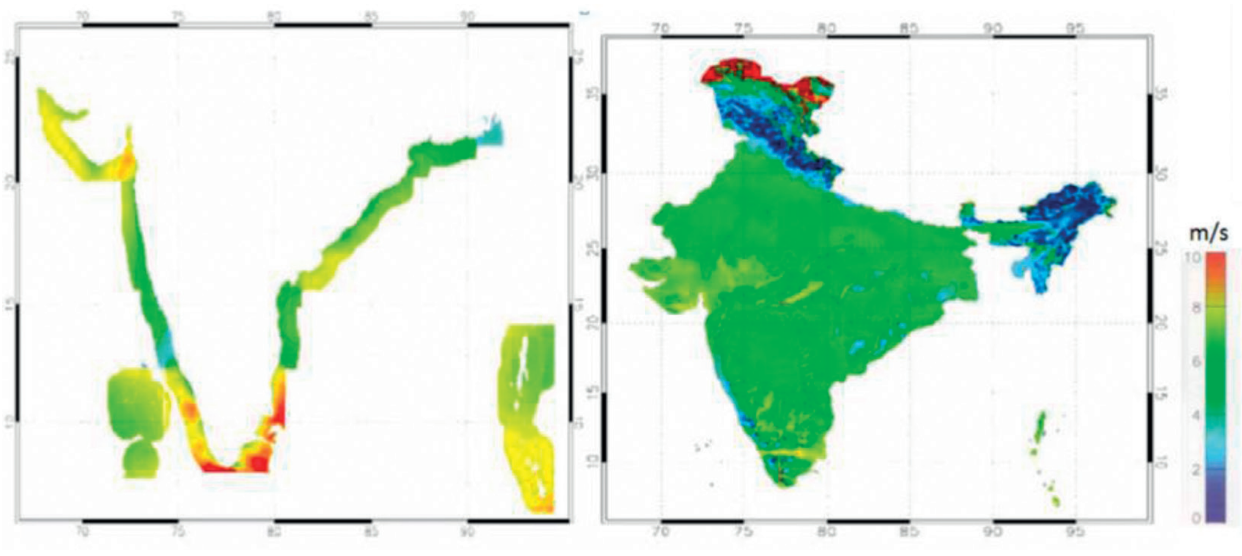

Figure 2. Numerically generated offshore and onshore wind resource maps for India by NIWE (source: Risø DTU, Indian Wind Atlas, Center for Wind Energy Technology [11]).

NIWE has commissioned a 100-m high-guyed offshore mast in the coastal line of Dhanushkodi, Rameshwaram, to understand the wind profile behavior in the region. The measurement is the first of its kind in India being conducted in a narrow strip into the sea at Dhanushkodi, which gives a close representation for offshore wind. The data have been monitored since October 2013, and the 4-year-old measured wind profile at Dhanushkodi looks promising for wind power potential with a mean wind speed of 8.5 m/s.

The European Union (EU) Delegation to India granted the Facilitating Offshore Wind in India (FOWIND) project to the consortium led by the Global Wind Energy Council (GWEC) including DNV-GL, Center for Study of Science, Technology and Policy (CSTEP) with an objective of assessing and promoting the offshore wind power development in India and aiding in facilitating India's transition toward a low carbon energy future. FOWIND reported that a number of agencies and institutions have assessed the offshore wind potential of the Indian coast including the coasts of Gujarat and Tamil Nadu. However, all of these studies are subject to various limitations with a possibility to draw various conclusions. Based on the various studies, FOWIND identified the significant offshore wind potential zones as shown in **Figure 3**. (Source: FOWIND pre-feasibility report at www.fowind.in.)

The Indian National Centre for Ocean Information Services (INCOIS) has developed wind potential maps based on satellite winds from QuickSCAT as shown in **Figure 4** [12]. These satellite-derived winds were validated and calibrated using in situ winds from five moored buoys deployed by the National Institute of Ocean Technology (NIOT) along the Indian coast. The wind potential maps generated by these institutes indicate significant potential along Tamil Nadu and Gujarat coast. It is observed that winds of magnitude 6 m/s or more persist for more than 300 days and 8 m/s or more persists for about 200 days along the southern coasts of Tamil Nadu. The wind potential maps generated by both the institutes indicate Rameshwaram and Kanyakumari along the Tamil Nadu as suitable sites for setting offshore wind farms.

Figure 3. Offshore wind potential zones identified by FOWIND.

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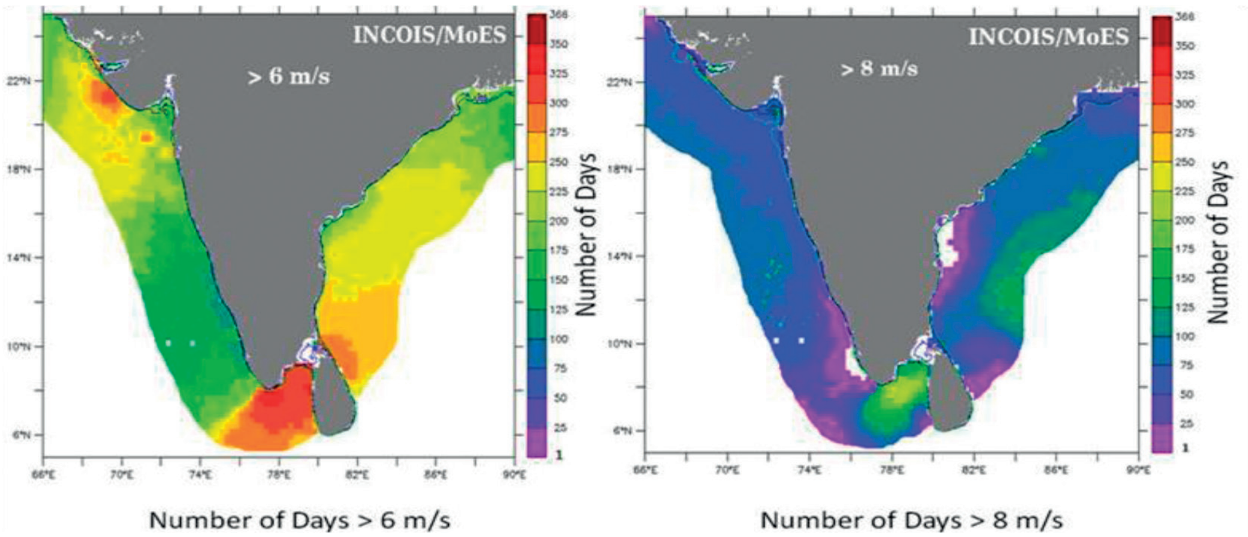

Figure 4. Offshore wind potential maps for Indian coast by Earth System Science Organization (ESSO)-INCOIS.

To study the wind characteristics, the wind speeds along Rameshwaram, Kanyakumari, and Jakhau were obtained from INCOIS at a 10-m elevation and extrapolated to 80 m using power law with a shear coefficient of 0.14 [13]. The mean wind speeds at Rameshwaram, Kanyakumari, and Jakhau for derived winds at an 80-m elevation are 8.5, 9.1, and 7.3 m/s, respectively.

A suitability analysis for these three potential sites along the Indian coast was carried out by Earth System Science Organization (ESSO)-NIOT based on the wind data obtained from ESSO-INCOIS. The properties of various class II wind turbines available in the market, in the range of 2–7 MW, were considered to identify suitable turbine. The uncertainties due to measurement scheme, futuristic wind prediction, and wind shear for measured wind speeds were considered, and the plant load factors at various probabilistic levels like 50 (P50), 75 (P75), and 90% (P90) were arrived at. It is observed that Repower 3.4-MW turbine performs well at both the locations. The power production from wind turbine after accounting for various losses like turbine unavailability (3%), Wake effects losses (8%), and electrical losses (5%) for Repower 3.4 MW turbine is given in **Table 1**.

S. no.	Company	Capacity (MW)	Kanyakumari			Rameshwaram		
			(P90)	(P75)	(P50)	(P90)	(P75)	(P50)
1	Suzlon	2.1	0.43	0.45	0.47	0.37	0.38	0.40
2	Repower	3.2	0.40	0.42	0.44	0.33	0.34	0.36
3	Repower	3.4	0.51	0.53	0.55	0.43	0.45	0.46
4	Repower	5.0	0.39	0.40	0.42	0.33	0.34	0.35
5	Repower	6.2	0.31	0.33	0.34	0.30	0.31	0.32
Plant load factors after incorporating losses in power production								
1	Repower	3.4	0.43	0.45	0.46	0.37	0.38	0.39

Table 1. Performance of wind turbines at potential sites (plant load factor).

Figure 5. Installed LiDAR at Gulf of Khambhat for MNRE-NIWE.

The wind resource assessment is proposed to be validated with LiDAR-based data collection platform. These platforms were designed and successfully installed with the technical support of the National Institute of Ocean Technology (NIOT) at Gulf of Khambhat for M/s NIWE and Gulf of Kutch for M/s Suzlon to obtain wind velocities along with profiles. The platforms at Gulf of Khambhat and Gulf of Kutch have been installed in high tidal currents and poor soil conditions (**Figure 5**). The substructure (monopile) shown in **Figure 5** supports the data collection equipment/wind turbine by absorbing the environmental loads acting on it. The monopile is fabricated using the steel plates and mobilized using barges and installed at the site.

3. Commercial viability studies

Commercial viability studies are important to attract the investors for expensive offshore systems. Offshore development in general and wind projects in particular are complex, capital-intensive engineering endeavors, and a large number of factors influence development. The design, logistics, vessel requirements, and physical infrastructure of each offshore farm are unique but a number of similarities exist between projects. The environmental conditions, the level of competition, and government support are regional and country-specific and they play a key role in offshore wind viability studies.

The capital cost of offshore wind turbine systems is significantly higher than land-based systems because of the higher cost in foundations, installation, operation and maintenance, and complex logistics. The offshore environment is significantly more uncertain and difficult than onshore and thus more costly and risky. The offshore environment involves personnel traveling to and from offshore turbines, and this increases equipment and time costs as well as insurance costs due to increased risks. Offshore work involves increased risks of strong winds which affect the amount of time available for maintenance and installation which in turn influence capital and operation costs. Offshore environments are corrosive to electrical and structural equipment and require turbines to be marinized with cathodic and humidity protection. Capital expenditures for offshore wind projects depend on marine vessel day rates which are uncertain, and offshore foundations require more steel for jackets and pilings than onshore foundations. The components that affect the capital cost of wind turbine are (1) wind turbine and its installation, (2) substructure and its installation, and (3) electrical systems and its installation (inner array cables, export cables, and substation).

The capital cost is modeled with hypothetical 170-MW wind farm composed of 50, 3.4-MW turbines. The turbine data available in open source are considered (Repower) for this study. The farm considered in shallow water of 10–15-m water depth with a 5-m diameter monopile with 100-mm thick and 30-m penetration into seabed. The cost of various components, operation and maintenance cost, is considered as per existing wind farms and modified to Indian conditions, which is explained in detail in subsequent sections.

The primary capital cost for onshore wind projects is the turbine; installation costs make up about 14% of the total capital costs. For offshore wind projects, the cost of installation is higher, approximately 20% of the total costs, and the costs of building the foundations account for another 20% of capital costs. For offshore wind, operation and maintenance costs make up a larger proportion of the overall components of the COE. This is likely due to the costs of accessing offshore wind farms and maintaining turbines in operating condition. The components considered are substructure, transition piece, wind turbine, installation of the above three components, inner array and export cables laying, and offshore substation installation [1, 14–19].

3.1. Substructure and transition piece

One of the most significant challenges facing offshore wind engineers is the effective and cost-efficient fixing of the turbine tower to the seabed. To date, this has typically been achieved via a monopile foundation which constitutes approximately 20–25% of the total capital expenditure in offshore wind farm construction. In this study, monopile- and gravity-based foundations are considered for capital cost estimation. For substructure and transition piece fabrication, Rs. 200/− per kg is considered based on the market studies for monopile and Rs. 25,000/− per cubic meter for gravity foundation (including concrete reinforcement and handling).

3.2. Wind turbine

The wind turbine itself is the most important cost component of an offshore wind project constituting from 30 to 40% of the total capex. Here, the turbine cost is considered based on interaction with the Original Equipment Manufacturers (OEMs). A range of interacting drivers will affect costs into the future, like increasing competition, competing markets, innovation, scale effects, and standardization before drawing conclusions about the overall scale and trajectory of change to turbine costs.

3.3. Installation

Foundation, turbine, substation, and cable installation together comprise approximately 20% of overall capex. At present, no offshore wind projects have been developed or are under construction in India, and since there is no direct Indian experience to draw upon, a comparative statistical assessment is used in the analysis. In this study, the installation methodology used in European offshore projects is reviewed; the costing of marine spread is accounted for considering the availability in India and nearby countries like Singapore, Middle East, and Korea.

3.3.1. Foundation installation

Monopile foundations consist of a large cylindrical steel pile and a steel structure (transition piece) placed over and grouted onto the monopile. Monopiles may be transported to the site by the installation vessel (considered in this study); they may be barged to the site, they may be transported by a feeder vessel, or they may be capped and wet-towed. The pile is upended by a crane and/or a specialized pile-gripping device, and a hydraulic hammer drives the pile into the seabed to a predetermined depth. The time to drive the piles depends on the soil type, diameter and thickness of the piles, burial depth, and the weight of the hammer. A rocky subsurface may prevent driving operations, in which case a drill will be inserted into the pile to drill through the substrate. After the monopile is secured, a transition piece is grouted onto the pile. The transition piece is typically installed immediately after piling by the same vessel that drove the pile, but if two vessels are employed in installation, a separate vessel may follow behind the foundation installation. The area around the monopile may need to be protected with rocks to guard against erosion (scour protection).

All these activities need to be performed in a highly dynamic offshore environment, and hence expensive vessels are required for safe installation. Presently, such barges are available in countries like Europe, Chain, Japan, and Korea only. Based on the ease of transportation, Korean vessels are considered for cost estimation with day rates as per market rates. The cost of bringing the vessels from Korea (4000 nm), the travel time of 60 days (for both ways) at a speed of 6 knots, the installation rate of 3.1 days per unit [14], and hiring rates of 140,000 USD/day all inclusive are considered along with the tug.

3.3.2. Turbine

There are a large number of options for turbine installation. The method used to install turbines is determined by available vessels, the turbine model, and the desire to minimize the number of offshore lifts. If the number of lifts is minimum, it is noted that crane capacity will increase accordingly.

As mentioned in Section 3.3.1, these vessels also should be obtained from the same countries. Based on the ease of transportation, Korean vessels are considered for cost estimation with day rates as per literature and market. The cost of bringing the vessel from the Korea (4000 nm), the travel time of 36 days (for both ways) at a speed of 10 knots, the installation rate of 4.0 days per unit, and the hiring rates of 200,000 USD/day are all inclusive.

3.3.3. Electrical infrastructure

The electrical infrastructure at an offshore wind farm includes inner-array cables which connect turbines together in series, export cable which transmits electricity to shore, and, potentially, one or more electrical substations to increase voltage prior to export. Offshore wind power cable is usually buried in the seafloor. There are several methods for installation, but in most cases, cable is simultaneously laid and buried by either an underwater plow or a remotely operated vehicle (ROV). Presently, such barges are available in countries like Singapore and Malaysia nearer to India. Hence, the cost of bringing the vessel from Singapore or Malaysia (1600 nm), the travel time of 10 days (for both ways) at a speed of 15 knots, the installation rate of 0.7 km/day, and the hiring rates of 125,000 USD/day for export cable and 50,000 USD for in-array cables are all inclusive.

The grid infrastructure is a concern for renewable energy in India and will be facing challenges for offshore wind developments due to large-scale variable generation technology. These challenges include grid strengthening, grid/code balance at national scale, and so on. Technical Standard for Grid Connectivity such as Grid Code (IEGC 2010) and GEGC-2004 can be updated.

The capital cost is estimated for three cases comprising different scenarios, and the summary is provided in **Table 2**.

Case 1: Considering the present scenario in India, with most of the marine spread from nearby countries and using average installation rates per unit-based existing wind farms [14].

Case 2: Assuming the required marine spread to be available in India and using optimistic installation rates per unit based on existing wind farms [14].

Case 3: Considering innovative gravity-based foundation for Rameshwaram based on site-specific soil stratum in addition to Case 2.

A study was conducted to check the commercial viability of offshore wind farms along Tamil Nadu coast. The general cash flow for a wind turbine is shown in **Figure 6**. The capital cost for setting up a wind turbine is raised by an investor with certain equity and the rest as debited from bank at an interest rate during loan tenure. In India, Indian Renewable Energy Development Agency Limited (IREDA) provides soft loans for 70% of capital cost with an interest rate of 11.90–12.50% based on grade for a tenure of 10–15 years. However, if the tenure is more than 12 years, an additional interest rate will be charged. In this study, an interest

S. no.	Component	Cost in Indian rupees (crores)		
		Case 1	Case 2	Case 3
1	Foundation (material and fabrication)	9.81	9.81	1.5
2	Transition piece (material and fabrication)	3.67	3.67	3.67
3	Installation of substructure and transition piece	4.25	1.48	0.07
4	Turbine	23.8	23.8	23.8
5	Installation of wind turbine	6.40	1.90	1.90
6	Electrical infrastructure (material and installation)	10.68	8.84	8.84
7	Port-handling charges and project development	2.17	1.89	3.25
	Total	60.78	51.40	43.05

Table 2. Capital cost summary for hypothetical 170-MW wind farm consisting of 50 numbers of 3.4 MW turbines.

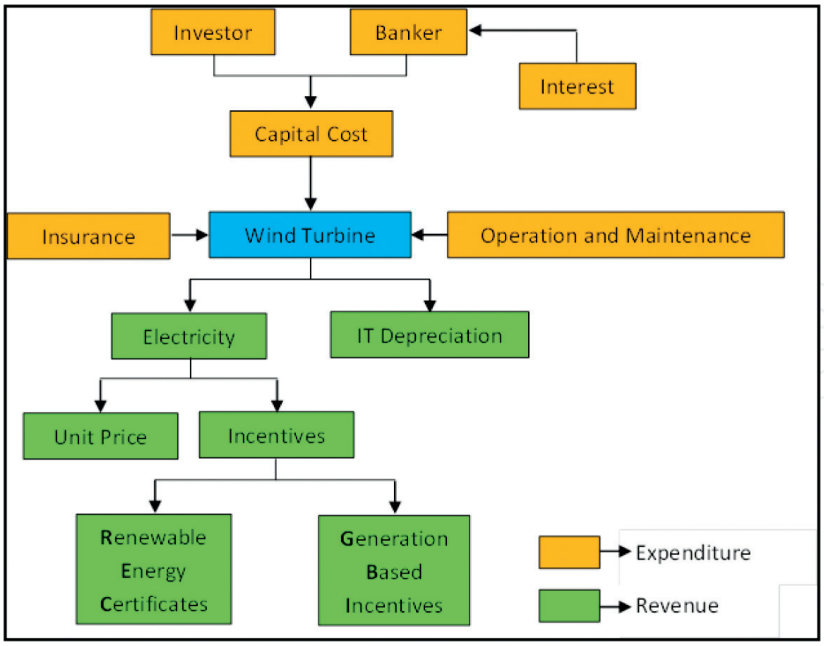

Figure 6. Cash flow for wind turbine project.

rate of 12.5% for a tenure of 12 years is considered. After commissioning of wind farm, the components that contribute for cash-out flow are insurance (0.1% of initial cost) and operation and maintenance charges. The returns include unit price paid for electricity produced, fiscal incentives, and income tax depreciation. The main incentives provided by the Indian government for wind energy are generation-based intensive (GBI) and renewable energy certificates (RECs). GBI of Rs. 0.50/kWh will be provided with a cap of Rs. 1 crore/MW for a period of 10 years through IREDA. The Central Electricity Regulatory Commission (CERC) has notified that the floor and ceiling prices will range from Rs. 1.5 to 3.9 per unit (for non-solar RECs) [17]. In this study, RECs of Rs. 1.5/kWh is considered. The accelerated depreciation of 80% in the first year is reinitiated in 2014. All these incentives are considered in this study.

Developers should structure the repayments which will give the lenders a comfortable zone and aim for higher debt-service coverage ratios. For banks to finance a wind farm, an average DSCR of 1.3 is required. The unit prices of electricity for three different scenarios are listed in **Table 3** for a DSCR of 1.3 at P50 PLF level.

	Kanyakumari		**Rameshwaram**	
	LCOE with no incentives (Rs.)	**Unit price with existing incentives (Rs.)**	**LCOE with no incentives (Rs.)**	**Unit price with existing incentives (Rs.)**
Case 1	8.23	4.71	9.38	5.52
Case 2	7.24	3.98	8.21	4.66
Case 3	—	—	7.17	3.89

Table 3. Unit pricing with and without incentives.

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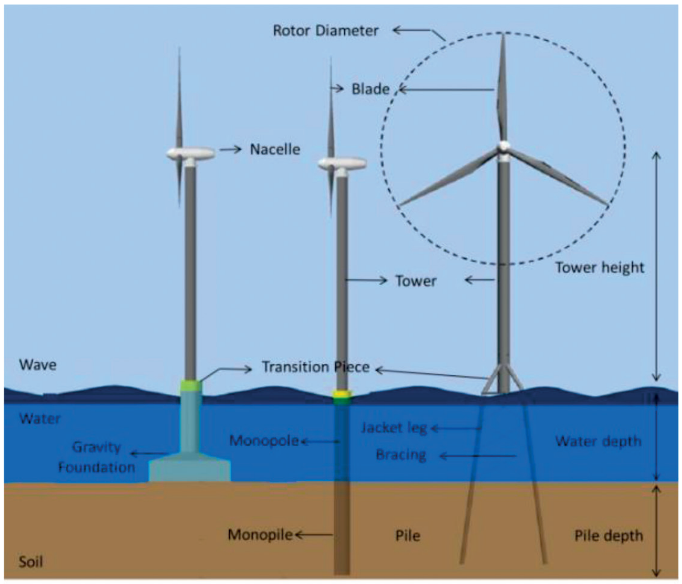
4. Development of substructures for offshore wind

The support platform costs about 24% [20] of the total system cost and needs to be optimized to increase the commercial viability of offshore wind projects. The substructure concepts used to support offshore wind turbine include monopiles, gravity-based structures, jackets, tripods, tripiles, and floating platforms [21]. The choice of foundation depends on water depth, environmental, and geotechnical conditions. Monopiles and gravity-based foundations are generally adopted for shallow water depth below 30 m. As the water depths increase, these foundations yield larger lateral deflection and rotations at a nacelle level. Therefore, a braced frame structure like jacket and tripod is used at a transition water depth of 30–50 m. In ultra-deep water (>50 m), floating compliant structures are adopted [22].

The preliminary analysis of site and environmental conditions indicate the suitability of monopile along Gulfs of Gujarat due to shallow water depths, gravity-based foundations at Rameshwaram due to shallow water depths and moderated soil conditions, and jackets at Kanyakumari due to moderate depths and soil conditions. Therefore, the preliminary design of three substructure concepts, monopile, gravity, and jacket, based on static and earthquake loadings was taken up. The typical configurations of three substructure configurations considered are shown in **Figure 7**.

4.1. Methodology

The optimum substructure configuration for offshore wind turbine can be arrived only by considering the in-place behavior of structure along with suitable installation methodology.



Wind Turbine	
Rated power, MW	5
Turbine Type	NREL 5MW Turbine
Gravity Based Foundation	
Water Depth	10
Outer Shaft Diameter, m	20
Outer Shaft Height, m	6
Inner Shaft Diameter, m	6
Inner Shaft Height, m	13
Monopile	
Water Depth, m	10
Monopile Diameter, m	6
Monopile Thickness, m	0.06
Monopile Length, m	30
Jacket	
Water Depth, m	30
No. Jacket Legs	4
No. of Braces	3
Slope of Jacket Legs	1 in 10
Jacket Leg Diameter, m	1.8
Jacket Pile Diameter, m	1.6
Pile /Leg Thickness, m	0.05

Figure 7. Gravity, monopile and jacket substructure configurations.

The structure has to be analyzed for combined aerodynamic and hydrodynamic forces to understand the in-place behavior. Then, the structure should be designed for safely transferring the forces into the soil by satisfying serviceability and strength aspects. The detailed design methodology is given in **Figure 8**.

The aerodynamic loads are estimated using open-source tool "FAST" based on Blade element momentum theory. The wave kinematics is obtained using a suitable wave theory, and the hydrodynamic forces are estimated using Morison's equation. The soil interaction is modeled as springs with a suitable stiffness. The structural behavior of the entire system is analyzed using finite element method and members are designed. The gravity-based foundation is checked against stability due to sliding, overturning, and bearing. It is proposed to transport the gravity foundation through flotation and ballast at the proposed location. The draft of foundation is estimated using static stability conditions, and the response amplitude operators are estimated for dynamic stability.

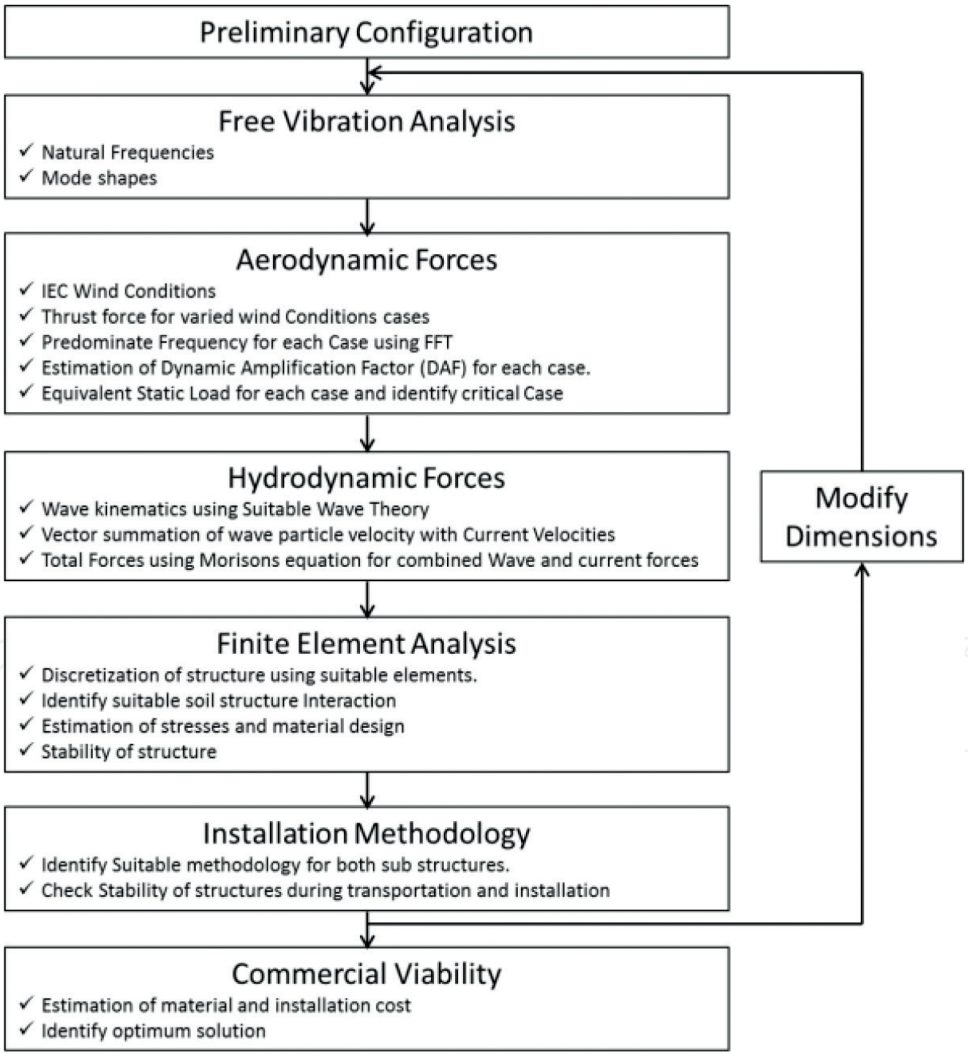


Figure 8. Methodology for substructure development.

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4.2. Structural analysis and design of substructure

4.2.1. Aerodynamic loads on turbine

The behavior of NREL 5-MW turbine has to be studied under various design conditions like power production, power production plus occurrence of fault, start up, normal shut down, emergency shutdown, parked, parked with fault conditions, transport, assembly, maintenance, and repair. The International Electrotechnical Commission [24, 25] has provided models for the wind conditions during these design conditions, and these models have to be established for various wind speeds as per IEC code. The obtained wind time history from these models can be converted to thrust force on turbine using open-source tool FAST. This tool works under beam element momentum theory, which is a combination of Blade element theory and momentum theory. The Blade element theory assumes the rotor blade sections as infinitesimally small thickness like a two-dimensional aerofoil. Aerodynamic forces for each segment are estimated considering local flow conditions, and the overall forces are obtained by integrating all the sections. The momentum theory assumes the loss of momentum due to work done by airflow through the rotor plane on the blade elements. The induced velocities are calculated from the momentum lost in the flow in the axial and tangential directions. These induced velocities from momentum theory are used by Blade element theory for the calculation of thrust forces on turbine.

The thrust force time history obtained from FAST is converted to equivalent static load for all the load conditions. The equivalent static load can be obtained by multiplying the maximum dynamic load in time history with the dynamic amplification factor. The dynamic amplification factor depends on the spacing of the natural frequency of structure and the dominant frequency of force time history and estimated using the DAF Eq. (1). The natural frequency of the structure is obtained using eigen value analysis, and the dominant frequency of force is obtained using Fast Fourier Transform. The damping in the structure is considered as 2%. It is observed that the maximum aerodynamic load of 1.6 MN was obtained for extreme operating gust case, and this is used for the design of sub-structure

$$\mathrm{DAF} = \frac{1}{\sqrt{(1 - r^2)^2 + (2\zeta r)^2}} \tag{1}$$

where r is the ratio of forcing frequency to the natural frequency of structure and ζ is the damping ratio.

4.2.2. Hydrodynamic loads on substructure

The substructure has to be designed for a designed wave height of 4 m and a period of 12 s. The hydrodynamic forces for this wave conditions are estimated using Morison's equation, which is applicable for members with a diameter smaller than 0.2 times of wavelength [26]. Considering the general dimensions of substructure for fixed offshore wind turbines, Morison's expression is commonly used. It is a semi-empirical formula which assumes the total force as a sum of inertia component due to the fluid acceleration and a drag component due to fluid velocity. The wave kinematics such as velocity and acceleration required by Morison's equation can be obtained from various wave theories like linear/airy wave theory, Stokes wave theory (up to fifth-order approximations), stream function wave theory (up to 22nd-order approximations), and cnoidal wave theory. The choice of wave theory depends on wave height (H), wave period (T), and water depth (d). A chart based on experimental results is available to guide the use of wave theory based on two non-dimensional parameters (H/gT2) and (d/gT2). Based on this chart, Stokes second-order [27] wave theory is used.

The currents mostly exist in the same direction of wave, and it will be the critical case for design. A surface current of 1.5 m/s with one-seventh power profile [28] variation is considered for the design of substructure. The current velocity exerts drag force on the structure and cannot be algebraically added to wave forces because of nonlinear term in the Morison's drag equation. Therefore, the total drag force due to wave and current is obtained by considering the vector sum of current velocity and water particle velocity. The combined drag and inertia force (including wave and current) vary with time and will be maximum only at one occasion. In order to find the maximum force, phase angle is varied from 0 to 360° with an increment of 10° and the base shear for each case is estimated. It is observed that the maximum base shear is at 300° phase angle, and this case is used for the design of substructure.

4.2.3. Earthquake loads

Wind turbines are slender structures with a large mass at the top. The slender and relative long first natural periods may reduce the seismic forces but the high top mass may induce increased inertia force [29]. The structure is discretized into beam elements of 1 m and the masses at each nodal level are lumped accordingly (the turbine mass is lumped at the top of the tower). The free vibration analysis is carried out, and the natural frequencies are given in **Table 4**.

Response spectral method is used for the estimation of earthquake forces for both the substructure concepts. In this method, earthquake acceleration is obtained by combining the acceleration coefficients of different mode shapes. For each mode, the acceleration coefficient is obtained from the design spectrum of IS 1893:2002 [30] and combined using complete quadratic combination (CQC) modal [31]. The parameters considered for obtaining seismic coefficient are zone factor—0.16, reduction factor—2, importance factor—1.5, and soil type—medium soil. The damping ratio of 2.0% is considered as the material is steel [32]. This seismic coefficient is multiplied with seismic mass and acceleration due to gravity (g) to obtain

Mode no.	**Natural periods (s)**		
	Gravity foundation	**Monopile**	**Jacket**
1 & 2	3.065	3.244	2.03
3 & 4	0.382	0.419	0.42

Table 4. Natural periods of various substructures.

earthquake forces. The earthquake loads are then combined with operational environmental conditions with a wave height of 2 m and a period of 8 s along with 0.7 m/s surface currents.

4.2.4. Structural analysis of monopile

The monopile, monopole, and tower are modeled using beam elements. The mesh of pile is refined with a 1-m length, and at the end of each element, three nonlinear springs (two horizontal and one vertical spring) are modeled to simulate the behavior of the soil for a 1-m layer. Two horizontal springs represent the lateral stiffness and the vertical springs represent the axial stiffness. The nonlinear properties for horizontal springs are governed by p-y curve (lateral load vs. deflection of the pile), vertical springs for all layers except bottom-most layer by t-z curves (skin frictional resistance vs. deflection along pile), and vertical spring for bottom-most layer by Q-z curve (tip resistance vs. pile tip deflection). These curves are generated using API RP 2A–WSD, and the soil profiles considered are given in **Table 5**.

Monopile and jacket substructures with soil characteristics shown in **Table 5** were analyzed for extreme environment loads as described in Sections 4.2.2 and 4.2.3. The deflected profiles are shown in **Figure 9**. The observed deflections are well below the allowable limit (i.e., 1.25 times the tower height [33]).

4.2.5. Structural analysis of gravity-based foundation

The monopole and tower are modeled using the beam elements and analyzed for extreme conditions. The gravity-based foundation is modeled using a three-noded plate as shown in **Figure 10**, and rigid links are used to transfer the loads at the base of the monopole to the inner shaft of the gravity-based foundation. The gravity foundation mainly consists of five components: base plate, outer shaft, inner shaft, inclined shaft, and stiffeners (**Figure 10**). The base plate of the foundation is 20-m diameter, with two concentric shafts. The inner shaft has a radius of 3 m and 13-m height, which holds the monopole. The outer shaft has a radius of 10 m and its height being 6 m. An inclined slab connects the top of the inner and the outer shaft. There are six stiffeners to connect the inner and outer shafts and to increase the stiffness. The modeled structure is designed for bending moments in orthogonal directions, and the reinforcement is proved as per IS 456. The grades of concrete and steel for design are M40 and Fe415, respectively. The configuration of foundation is also checked for stability against sliding and overturning and bearing with a factor of safety of 22, 31 and 3, respectively.

S. no.	Depth (m)	Description	SPT value
1	3	Gray fine sand	12
2	10	Gray silty fine sand	34
3	12	Crushed pieces of rock	50 (for 6-cm penetration)
4	18	Fine silty sand	71
5	21	Silty fine sand	34

Table 5. Soil parameters considered for design.

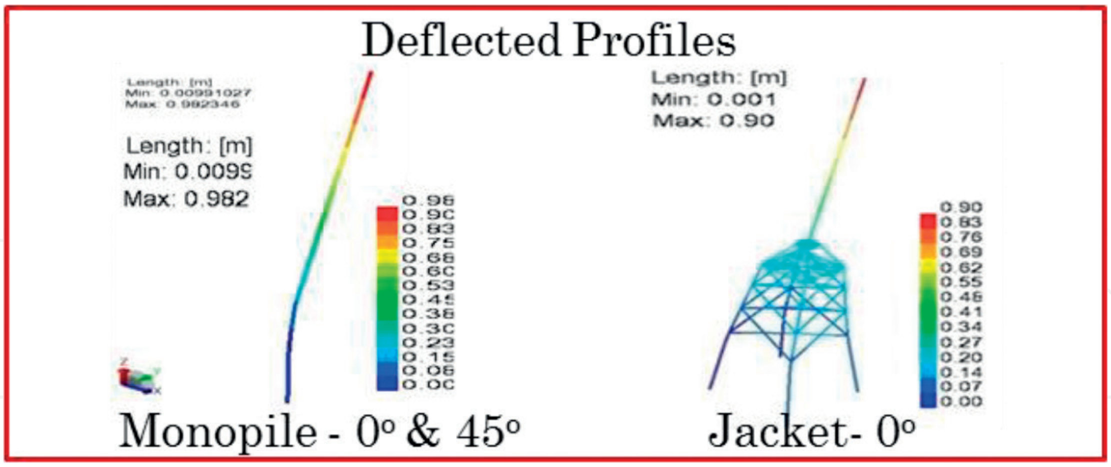

Figure 9. Deflected profiles for monopile and jacket structures.

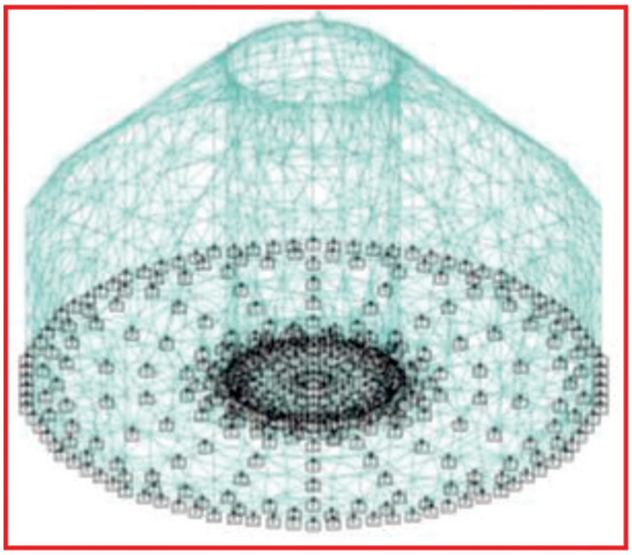

Figure 10. FEM models gravity-based foundation.

5. Installation methodology

5.1. Monopile

The length of monopile is 30 m with diameters of 6 m and requires huge hydraulic hammers for driving the pile. These hammers are usually equipped on a floating barge or jack-up platforms. Jack-up platforms are generally used under severe sea-state conditions and floating barges for relatively calm sea conditions. The jack-up platforms are associated with high rentals and less deck space than floating barges. In case of floating barges, the large deck space on the barge can reduce the time and costs needed for the transportation of monopiles and transition pieces by using the barge as a floating storage. Considering the low-wave climate along potential sites of Tamil Nadu, floating barge would be an ideal solution. However, these

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vessels (floating barges/specialized jack-up platforms) are not available in India and have to be hired from Europe or to be developed in India. Hence, the cost of mobilization and demobilization will be high during the installation phase of offshore wind project.

The installation methodology for a monopile using specialized vessel is shown in **Figure 11**. The ship is loaded with four to five monopiles in the port and sailed to the wind farm. The monopile will be lowered through a guide with the help of a deck crane and driven using a hydraulic hammer. Once the monopile is driven to the required depth, the transition piece is installed over it. The gap between the monopile and the transition piece is grouted for appropriate transfer of loads and to adjust the alignment of platform. The main advantage of the monopile is easy and quick installation. On the other hand, its disadvantages include high cost due to unavailability in India and additional charges for mobilization and demobilization.

5.2. Gravity-based foundation

The installation methodology for gravity-based foundation is shown in **Figure 12**. The gravity-based foundation is constructed on a steel platform nearby the fishing harbor. The monopole is then installed through the inner ring of the foundation. In the second stage, the landside edge of the platform is raised by hydraulic jacks. The gravity-based foundation is slid into the water. Due to buoyancy effects, the structure will float. The gravity-based foundation is then towed to the required position using a tug. Before lowering the foundation, the seabed has to be leveled using a gravel bed. The foundation is then positioned using tugs and then lowered by ballasting water into it. The hollow chambers inside the foundation are filled with plain cement concrete to increase the stability of the foundation.

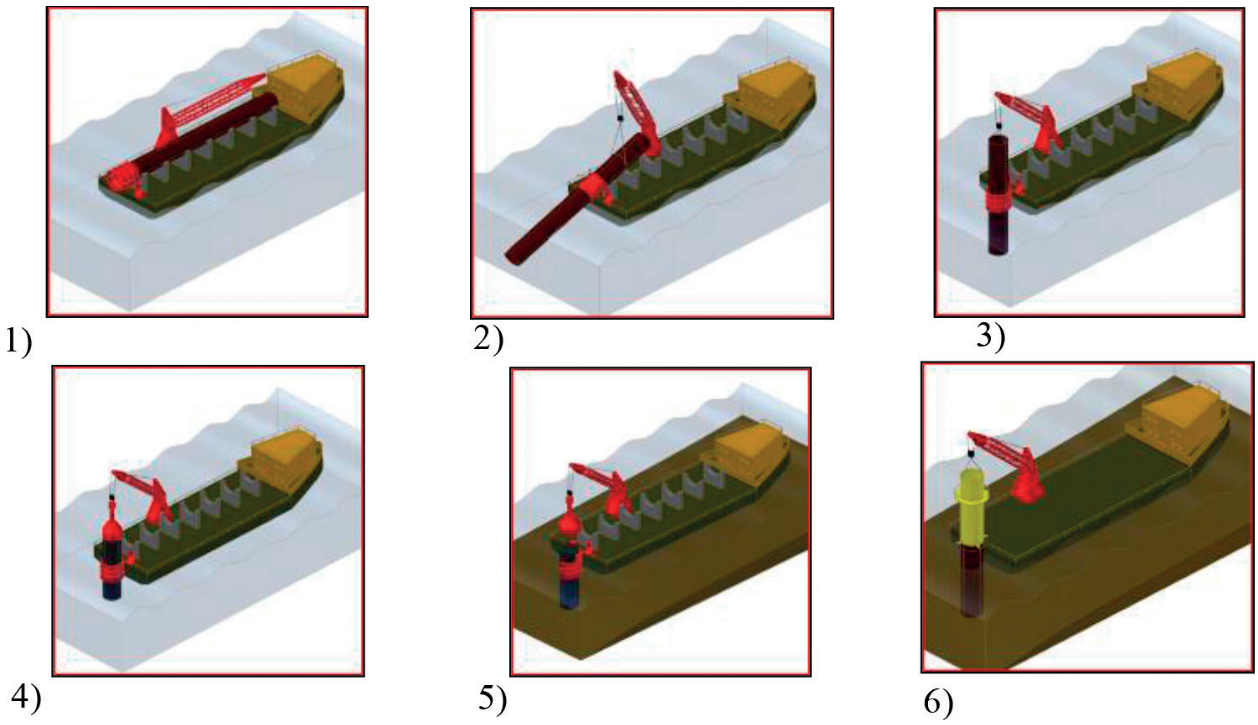

Figure 11. Installation methodology of monopile.

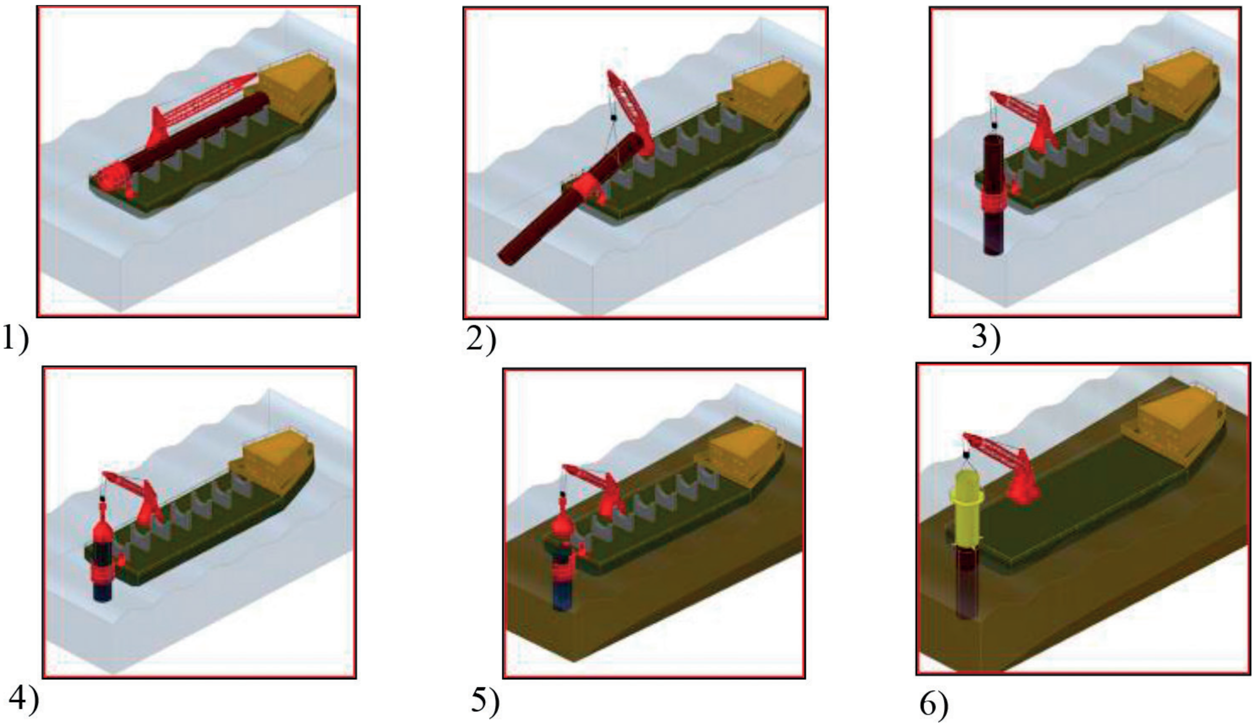

Figure 12. Installation methodology of gravity foundation.

The static stability of the foundation is carried out, and the draft is estimated to be 4 m from the bottom. As the foundation needs to be towed for a long distance, it is essential to identify the natural frequencies and response amplitude operations (RAO). Natural frequencies and RAOs are computed for three translation modes and three rotation modes. It is observed that the natural frequency is far away from the encounter frequency of waves (5–10 s).

6. Summary and conclusions

Offshore wind being pollution-free would be an ideal solution to meet the increasing demand as Indian coast is blessed with significant winds. The Ministry of New and Renewable Energy (MNRE) has published the offshore wind policy for offshore wind development in India [23]. Offshore wind would be commercially viable, if potential sites are identified and economical substructure concepts along with installation methodology are developed considering local conditions. Hence, studies were taken up to identify potential sites, perform commercial viability studies, and design the optimum substructure configuration along with installation methodology.

Wind assessment studies based on secondary wind data like offshore satellite winds and onshore mast data by various organizations helped in identifying potential sites along the coast of Gujarat and Tamil Nadu. Commercial viability studies based on these data were carried out and indicated the need for suitable incentives by the Government of India to attract huge investments for offshore wind industry. NIWE has attempted to capture the offshore wind parameters by installing an onshore mast in a narrow strip extending into the sea. LiDAR-based offshore wind data collection platforms are successfully commissioned in Gulf of Khambhat for MNRE-NIWE and Gulf of Kutch for M/S Suzlon with technical support from NIOT for recording the continuous wind data and validation.

Considering the bathymetry and geotechnical conditions along potential sites, three substructure concepts, monopile, gravity-based foundation, and jacket, were analyzed. A preliminary design based on aerodynamic loads on turbine, hydrodynamic loads on the structures, pile-soil interaction, and floatation analysis for gravity-based structures is carried out to arrive at suitable substructure concepts for Gujarat and Tamil Nadu. Installation methodologies were developed for identified substructure concepts for Indian scenario and the infrastructure needs assessed. These studies will also assist in arriving at the cost for implementation of the offshore wind farm projects.

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