EUROPEAN UNION

fowind
FACILITATING OFFSHORE WIND IN INDIA

FEASIBILITY STUDY FOR OFFSHORE WIND FARM DEVELOPMENT IN TAMIL NADU

MARCH 2018

EUROPEAN UNION

This report is co-funded by the European Union

THE EUROPEAN UNION IS A UNIQUE ECONOMIC AND POLITICAL PARTNERSHIP BETWEEN 28 EUROPEAN COUNTRIES

In 1957, the signature of the Treaties of Rome marked the will of the six founding countries to create a common economic space. Since then, first the Community and then the European Union has continued to enlarge and welcome new countries as members.

The Union has developed into a huge single market with the euro as its common currency.

What began as a purely economic union has evolved into an organisation spanning all areas, from development aid to environmental policy. Thanks to the abolition of border controls between EU countries, it is now possible for people to travel freely within most of the EU.

It has also become much easier to live and work in another EU country.

The five main institutions of the European Union are the European Parliament, the Council of Ministers, the European Commission, the Court of Justice and the Court of Auditors. The European Union is a major player in international cooperation and development aid. It is also the world's largest humanitarian aid donor. The primary aim of the EU's own development policy, agreed in November 2000, is the eradication of poverty.

http://europa.eu/

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

FOREWORD

On behalf of the FOWIND consortium, we are pleased to present this feasibility study for offshore wind development in the State of Tamil Nadu, which is one of the main outcomes of the project's final year. The study builds on previously published work, especially the Pre-feasibility Study published in 2015, the Supply Chain, Port Infrastructure and Logistics Study from 2016, and the Grid Integration Study published in 2017.

Beginning with selecting the optimum location for the project within the already identified Zone A, the report then focuses on defining baseline metocean and geotechnical parameters. This process leads to optimising the design and outline project costing using DNV GL's LCOE (levelised cost of energy) tool, 'Turbine.Architect'. Two different project sizes (approx. 150 and 500 MW) are analysed with 4, 6 and 10 MW turbines, coming to a range of conclusions as to project cost and cost of energy in a range of configurations.

Since the FOWIND project began at the end of 2013, there have been dramatic changes in the offshore wind business:

- Four years ago, offshore wind was largely a European affair, costly and difficult. However, due to strong public-private partnerships in the key countries surrounding the North, Irish and Baltic Seas, the industry is now booming with a strong supply chain, a new generation of turbines, and ever-decreasing costs. As a result of this, interest in offshore outside of Europe is on the rise, with plans for massive expansion of the industry in Asia and North America. China's offshore industry installed more than 1,000 MW in 2017, and the first commercial wind farm is now operational off the US East Coast, with very ambitious plans for rolling out gigawatts over the next 5-10 years.

- In 2015 the Indian government dramatically upscaled its ambition for renewable energy, setting very aggressive targets for 2022, including 60 GW of onshore wind. While offshore will not play a major role in meeting that target, it indicates a political direction for the future of the Indian energy sector in which offshore wind could play a significant role in the medium and longer term.

- The dramatic drop in price which was first hinted at in 2015, came to fruition in 2016 with prices in the €50-80/MWh range; and in 2017 we saw the first bid winners who had bid the wholesale price of electricity, i.e., with no fixed PPA. It should be noted that these latter prices are predicated on the development and deployment of a new, larger range of turbines and are not for delivery until the early 2020s. Offshore wind has become a competitive power source in the European market.

- We now have 8MW turbines in commercial operation, with rotor diameters of 164 meters. These will soon be surpassed by machines up to 9.5 MW, and a number of manufacturers will breach the 10MW barrier soon. According to a 2011 EU-funded study, with current materials machines of up to 20 MW can be built; and with advances in materials science and engineering experience, there is no telling what the upward limit might be.

All of this is to say that the current rapid rate of change is likely to continue, with improved technology, even larger and more cost-effective turbines, and increasingly efficient operation and maintenance practices.

For the moment, however, we are faced with the challenge of enabling the spread of the technology beyond European waters to India without taking 25 years to get to competitive prices! Every national circumstance is different, but there are lessons to be learned from each of them. Chief among them is the need for long-term and well-planned public-private partnerships that are necessary to create a competitive and sustainable offshore wind industry.

Our thanks to all our partners, and a special thanks to ReNew Power and the FOWPI project for their contributions to the report. We trust you will find the results instructive as the sector moves ahead.

ABOUT FOWIND

The consortium led by the Global Wind Energy Council (GWEC) is implementing the Facilitating Offshore Wind in India (FOWIND) project. Other consortium partners include the Centre for Study of Science, Technology and Policy (CSTEP), DNV GL, the Gujarat Power Corporation Limited (GPCL), and the World Institute of Sustainable Energy (WISE).

The National Institute of Wind Energy (NIWE), an autonomous R&D institution under the Ministry of New and Renewable Energy, Government of India, is a knowledge partner to the project since June 2015. Renew Power Ventures Private Limited, a leading Independent Power Producer in India joined as an industry partner to the project in June 2016.

The project seeks to establish structural collaboration and knowledge sharing between the EU and India on offshore wind technology, policy and regulation and serve as a platform for promoting offshore wind research and development activities. The project focuses on the states of Gujarat and Tamil Nadu for identification of potential zones for development through preliminary resource and feasibility assessments for future offshore wind developments, as well as through techno-commercial analysis and preliminary resource assessment.

This report has been developed as part of Work Package 5 on feasibility studies of offshore wind in Tamil Nadu. The aim of this report is to provide a concept design for a demonstration project of 150 to 504 MW in Tamil Nadu's most promising offshore wind development area, "zone A" identified in the Pre-feasibility Study [1]. This provides companies and government institutions with a starting point for future detailed offshore Front End Engineering Design (FEED) studies and assists with the identification of key project risks in Tamil Nadu. A parallel study has been conducted for the state of Gujarat.

EXECUTIVE SUMMARY

This Feasibility Study Report for the state of Tamil Nadu is a key milestone for the FOWIND project's final year of work and is the consecutive step following the Tamil Nadu Pre-feasibility Study delivered in 2015 [1]. This report is supported by FOWIND's Supply Chain, Port Infrastructure and Logistics Study [2] and the Grid Integration Study [3] delivered in 2016 and 2017 respectively.

The objective of this report is to provide a concept design for a demonstration project of 150 to 504 MW in Tamil Nadu's most promising offshore wind development area, "zone A" identified in the Pre-feasibility Study [1]. This provides companies and government institutions with a starting point for future detailed offshore Front End Engineering Design (FEED) studies and assists with the identification of key project risks in Tamil Nadu. A parallel study has been conducted for the state of Gujarat.

The study commences with a sub-zone selection exercise to identify the optimum zone A location for the demonstration project. This is followed by a preliminary environmental site data study, focused on defining baseline metocean and geotechnical conditions. This site data then facilitates concept design and outline project costing using DNV GL's Levelised Cost of Energy (LCOE) design tool "Turbine. Architect". Different configurations of project capacity (150-152 MW and 500-504 MW) and turbine MW class (4 MW, 6 MW & 10 MW) are investigated and supported by further technical, social and environmental studies.

Key findings formulated during the course of this feasibility study are summarised as follows:

- **WIND RESOURCE** – currently there is no installed LIDAR in Tamil Nadu, the mesoscale wind resource map modelled during the Pre-feasibility Study remains the only data source. NIWE have plans to commission a LIDAR in the Gulf of Mannar;
- **WAVE AND CURRENT** – a preliminary metocean study for zone A in Tamil Nadu provides wave, current and tidal data suitable for concept design. 50-year typhoon induced waves are estimated at 11.0m Hmax and tidal currents at 1.3 m/s;
- **GEOTECHNICAL CONDITIONS** – indicative lower/upper bound soil profiles defined for zone A indicate significant spatial variation in the southern Tamil Nadu offshore region; ranging from weak/loose sands/clays to strong cemented sand to depth. At the upper bound drivability would be a risk for piled foundations;
- **SELECTION OF POTENTIAL WIND SITE** – 10 sub zones within zone A have been defined and sub-zone A3 has been identified with the lowest cost of energy potential for a 150 to 504 MW demonstration project. The mean wind speed is estimated at 8.01 m/s (at 120 m AGL), average water depth is -18.1 m below LAT and distance to coast is 12.4 km;
- **TURBINE SELECTION** – predicted extreme typhoon wind conditions meant Class I or S wind turbines were taken forward for further investigation;
- **WINDFARM LAYOUT** – a minimum inter-turbine spacing of 8 x 7 rotor diameters (D), aligned with the prevailing wind direction, has been assumed;
- **ENERGY YIELD** – for the different project configurations and calculated wind speeds, Project Net Capacity Factors were estimated in the range of 30.0 % and 38.1 % (depending on the particular MW capacity of the farm and the turbine MW capacity);
- **ELECTRICAL CONCEPT** – the close proximity to shore is assumed to facilitate a direct HVAC connection of the offshore wind farm to the onshore substation. 66 kV collection system voltage level is assumed for all turbine MW capacities;
- **FOUNDATION CONCEPTS** – either monopile or jacket foundations will be likely options to take forward to the next stage of investigation. Gravity-based Structure (GBS) foundations could be financially favourable but will be very site-specific and dependent on the presence of highly competent soils. In terms of cost monopiles are more economical compared with jackets, however pile drivability is a risk;
- **INSTALLATION & LOGISTICS** – the preliminary studies have identified three major ports with significant potential. Vessel availability in the region is high but not optimised for offshore wind. The consortium recommend that site-specific transportation and installation planning is conducted during the early project development stages;
- **OPERATIONS & MAINTENANCE** – it is assumed that all the first offshore wind projects in India will use an O&M strategy based on work boat access;
- **COST OF ENERGY** – wind resource and the financial discount rate are the most significant factors affecting offshore wind Cost of Energy (COE). Increasing the capacity of the wind turbines from 4MW to 10MW results in a cost of energy reduction;
- **RISKS** – the highest risks highlighted for the feasibility study are associated with lack of and uncertainty within the available data for the following key areas: offshore wind resource, geotechnical conditions and grid connection;
- **ENVIRONMENTAL** – Tamil Nadu is home to sensitive marine ecosystems, including; coral reefs, mangroves and various marine mammals/organisms. It is recommended to allow a design envelope approach in EIA permit applications to give flexibility.

In summary, it is of paramount importance that the current high uncertainty with regards to wind resources, energy predictions, ground conditions and cost of energy are reduced and mitigated before an offshore wind farm is constructed in Tamil Nadu.

1. INTRODUCTION

The FOWIND consortium's, Tamil Nadu Feasibility Study Report, is a key milestone deliverable from the project's final year of work and is the consecutive step following the Tamil Nadu Pre-feasibility Study delivered in 2015 [4]. This report is supported by FOWIND's Supply Chain, Port Infrastructure and Logistics Study [2] and the Grid Integration Study [3] delivered in 2016 and 2017 respectively.

The objective of this report is to provide a concept design for a demonstration project of 150 to 504 MW in Tamil Nadu's most promising offshore wind development area, "zone A" identified in the Pre-feasibility Study [4]. This provides companies and government institutions with a starting point for future detailed offshore Front End Engineering Design (FEED) studies and assists with the identification of key project risks in Tamil Nadu. A parallel study has been conducted for the state of Gujarat.

The study builds on the FOWIND Pre-feasibility Study, which identified eight offshore wind development zones. Zones A to H range from 810 to 2,116 km^2 in area and each zone could feasibly accommodate multiple numbers of multi-MW offshore wind farms. Zone A with the lowest identified cost of energy has been sub-divided into 10 "sub-zones" to identify an optimal location for a future demonstration project. Any further known constraint parameters (e.g. technological barriers and spatial conflicts) were considered in this updated analysis. There is currently no installed LIDAR in Tamil Nadu, however NIWE have plans to commission a LIDAR in the Gulf of Mannar and have recently issued a tender (Jan 2018) for offshore geotechnical investigations. This investigation is aimed to support the design of the offshore LIDAR platform. Once 12 months of on-site Lidar data becomes from the NIWE LIDAR the MNRE may wish to conduct a full energy assessment in support of this Full Feasibility Study.

A preliminary metocean and geotechnical study has been conducted for the Tamil Nadu region, this was in direct response to key risks identified during the Pre-feasibility Study (e.g. lack of and uncertainty within the available data for offshore wind resource, metocean climate and geotechnical conditions). The metocean study provides wave and current parameters suitable for concept feasibility design and the geotechnical study provides a lower and upper bound soil profile envelope for preliminary design.

Demonstration site identification is followed by a concept wind farm design for each combination of project and wind turbine MW capacity. Two indicative project capacities of approximately 150 MW and 500 MW have been considered since these are broadly representative of typical European commercial offshore wind developments. Similarly, three wind turbine generator sizes of 4 MW, 6 MW and 10 MW have been considered in the modelling. These capacities are representative of established (4 MW), current (6 MW) and near future (10 MW) offshore wind turbine designs.

Based on these wind farm capacities and turbine sizes, a high level Annual Energy Production (AEP) assessment has been carried out for the potential demonstration project and indicative Capacity Utilisation Factors (CUF) have been estimated.

Concept demonstration project designs have been conducted for each combination of project capacity, wind turbine, foundation type (monopiles, jackets and gravity base) and the selected electrical connectivity configuration. Further technical considerations have been examined at high level for installation (ports, vessels and installation methodologies) and operations and maintenance (O&M).

Based on the estimated wind resource potential, concept designs, technical considerations and preliminary project costing, the Levelised Cost of Energy (LCOE) has been estimated for the potential demonstration project configurations using DNV GL's Turbine.Architect design tool (also used for foundation type comparison). The preliminary risk assessment from the Pre-feasibility Study has been updated to identify areas which require more detailed assessments.

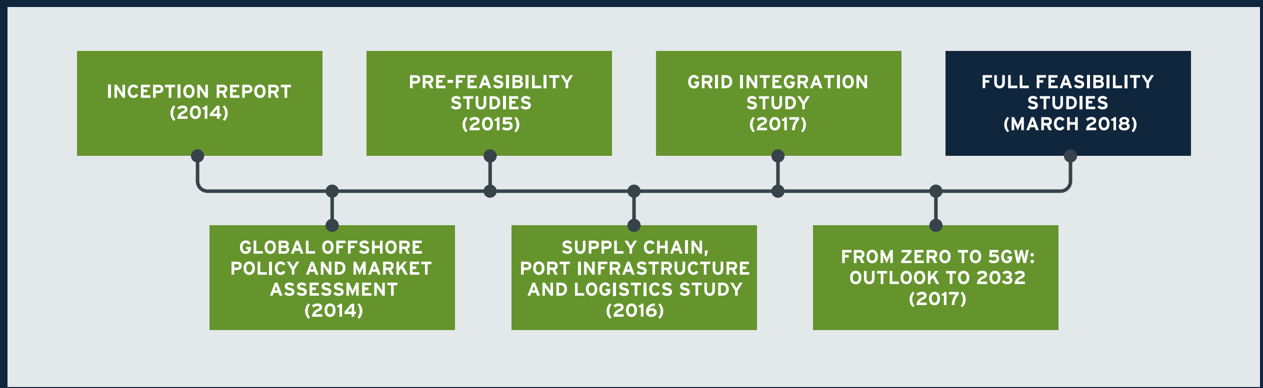
Beside technical considerations; high level social and environmental factors have been touched upon in this study.

Detailed descriptions for the applied methodology of the individual studies are provided with in each section of the report.

2. SUMMARY OF PREVIOUS FOWIND STUDIES

The FOWIND project has laid the groundwork for the development of the first offshore wind projects in India. A number of landmark reports have been published that bring together the partners' global experience in offshore wind and the understanding of the local context in the states of Tamil Nadu and Gujarat (see Figure 2-1).

FIGURE 2-1: KEY REPORTS RELEASED BY FOWIND



The Tamil Nadu Pre-feasibility report [4] identified several credible technical solutions for offshore wind development, in eight potential zones, through constraint modelling using existing public domain data. The report covered at a high level preliminary studies on project siting, wind farm design and installation strategies. Project costs were suggested using international experience and environmental considerations were covered. Finally, initial LIDAR device locations were suggested for critical onsite wind measurements.

The Supply Chain, Port Infrastructure and Logistics Study [2] provided an overview of the key supply chain elements required for offshore wind and carried out an initial review of the potential for Indian companies to enter the market. Building on this a port infrastructure and logistics assessment was done to identify key component specifications, vessel requirements, installation strategies and port infrastructure required for manufacturing to installation and through operation and maintenance of an offshore wind farm. The report culminated with an offshore wind port readiness assessment for Tamil Nadu and an insight into project decommissioning.

The Grid Integration Study [3] addressed the key question of how to prepare the state power systems to connect offshore wind projects in Tamil Nadu and Gujarat. It laid out the steps necessary to prepare the physical onshore grid for integration of offshore wind projects in the two states while also considering the requirements to facilitate new offshore grid development. The report also evaluated how the states in question will ensure stable system operation with increasing penetration of offshore wind and other renewable energy generation. Lastly, a suite of relevant grid codes was reviewed to ensure that they suitable for development of offshore wind projects in India.

The "From zero to five GW - Offshore Wind Outlook for Gujarat and Tamil Nadu 2018-2032" report [6] has developed a medium-term outlook for offshore wind development for the states of Tamil Nadu and Gujarat. The study further looks into the policy and regulatory framework aspects of what the two states need to go from zero to 5 GW of offshore wind installations over the upcoming plan periods out to 2032.

This Tamil Nadu Feasibility report builds on the key findings formulated during the course of the Pre-feasibility Study, which are summarised as follows:

- **Wind Resource** – no publicly available on-site wind measurements have been recorded within the Tamil Nadu offshore zone and the study had to rely on available satellite data and mesoscale modelling methods.
- **Zone Selection** – eight zones were identified with mean wind speeds in the range of 7.1 to 8.2 m/s (at 120 m AGL) and water depths in the range of 10 to 53 m below LAT;
- **Turbine Selection** – predicted extreme typhoon wind conditions meant Class I, II or S wind turbines were taken forward for further investigation;
- **Energy Yield** – for the eight zones and calculated wind speeds Project Net Capacity Factors were estimated in the range of 22.8 % and 40.4 % (depending on the particular zone, MW capacity of the farm and the turbine MW capacity);
- **Foundations** – monopile, jacket and tripod foundations would be likely choices to take forward for the next stage of investigation (it should be noted subsequent FOWIND studies [2] have indicated gravity base (GBS) foundations could also be feasible);
- **Electrical** – grid infrastructure already supports the highest capacity of onshore wind turbines of any Indian state, outages and overloading are experienced during peak load times which means expansion and improvement will be required to accommodate offshore production;
- **Installation** – the preliminary screening study has identified 3 ports with some potential. Vessel availability in the region is limited and not optimised for offshore wind. The consortium recommend that site-specific transportation and installation planning is conducted during the early project development stages;
- **Operations & Maintenance** – it is assumed that all the first offshore wind projects in India will use an O&M strategy based on work boat access;
- **Cost of Energy** – wind resource is the most significant factor affecting offshore wind Cost of Energy (CoE);
- **Risks** – the greatest risks highlighted for the Pre-feasibility Study were associated with the limited data available for the assessment. Where data were available, it was subject to high uncertainty. Specifically data relating to the following key areas: offshore wind resource, metocean climate, geotechnical conditions and grid connection;
- **Environmental** – Tamil Nadu is home to sensitive marine ecosystems, including; coral reefs, mangroves, various marine mammals/organisms.

It was considered of paramount importance that the high uncertainty with regards to zone level wind resources, energy predictions, ground conditions, metocean data and cost of energy are reduced and mitigated before the true level of offshore wind feasibility can be identified for Tamil Nadu. The Consortium has actively engaged with this objective through delivery of the subsequent FOWIND work packages including:

Reports

- Offshore Wind Policy and Market Assessment Report (delivered 2014);
- Pre-feasibility Offshore Wind Farm Development in Gujarat and Tamil Nadu (delivered 2015);
- Supply Chain, Port Infrastructure and Logistics Study [2] (delivered 2016);
- Grid Connection and Transmission Assessment [3] (delivered 2017);
- From zero to five GW - Offshore Wind Outlook for Gujarat and Tamil Nadu 2018-2032" report [6] (delivered 2017);
- Identification of further constraint data, with regards to ground conditions and metocean data (this Report);
- Full Site Specific Feasibility Study (this Report).

Workshops and Seminars

- Stakeholder Engagement Workshops in Delhi, Ahmedabad and Chennai (September 2014);
- External Field Visit and Study Tour to Germany (September 2014);
- International Workshop to promote R&D Initiatives (September 2015);
- Engineers' Training Workshop in Bengaluru (September 2016).

3. TURBINE.ARCHITECT

3.1 INTRODUCTION

This section provides the background and methodologies behind DNV GL's integrated cost of energy modelling tool, Turbine.Architect [7]. The tool provides a holistic approach, as a decision making tool for developers, investors, institutions, owners and operators. In the context of the FOWIND project Turbine.Architect is at the core of this Full Feasibility Study. It has been used for the following packages of work:

- Spatial analysis and selection of the demonstration wind farm location (Section 4);
- Concept design of representative 4 MW, 6 MW and 10 MW offshore wind turbine platforms;
- Estimation of electrical system CAPEX (Section 8.3.7)
- Preliminary foundation concepts and CAPEX estimates, monopiles, jackets and GBS (Section 8.4);
- Estimation of construction CAPEX (Section 9.1)
- Demo project Levelised Cost of Energy (LCOE) estimates for multiple configurations of MW capacity (150 to 504 MW) and wind turbines (4, 6 and 10 MW).

The specific approach and methodologies for the FOWIND project are defined in each relevant section, but the following sub-section highlights the general background for DNV GL's Turbine. Architect tool [7]. A detailed description of the theories behind Turbine.Architect are available in the Theory Manual [8].

3.2 TURBINE.ARCHITECT BACKGROUND

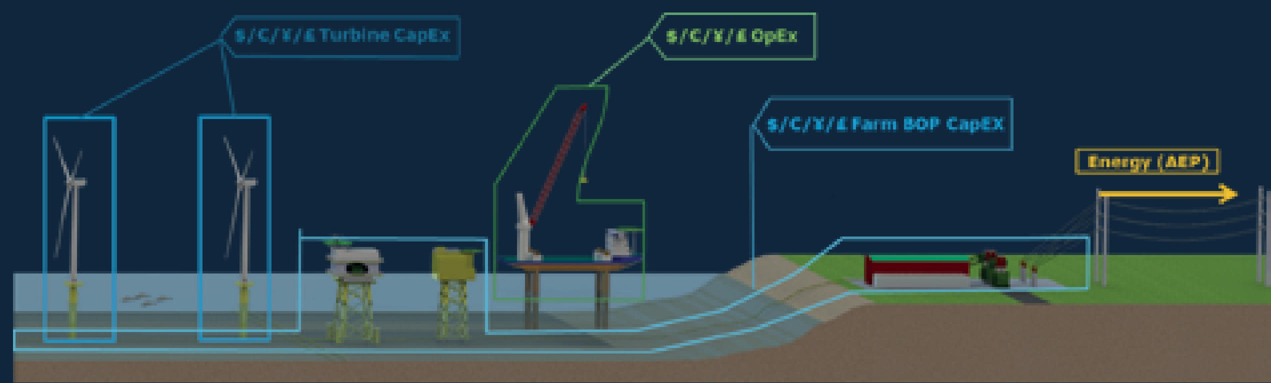
3.2.1 The challenge

Estimating the levelised cost of energy (LCOE) of an offshore wind farm as well as related economic metrics such as net present value (NPV) or internal rate of return (IRR) can be a challenge due to the range of technical and economic factors in play and their associated uncertainties.

Decision makers want to make informed and objective investment decisions based on a clear view of the complete techno-economic picture. Figure 3-1 highlights the dominant cost of energy constituents for an offshore wind farm.

FIGURE 3-1: THE DOMINANT COST OF ENERGY CONSTITUENTS

Note that the turbine foundation is part of the turbine CAPEX here.



3.2.2 The solution

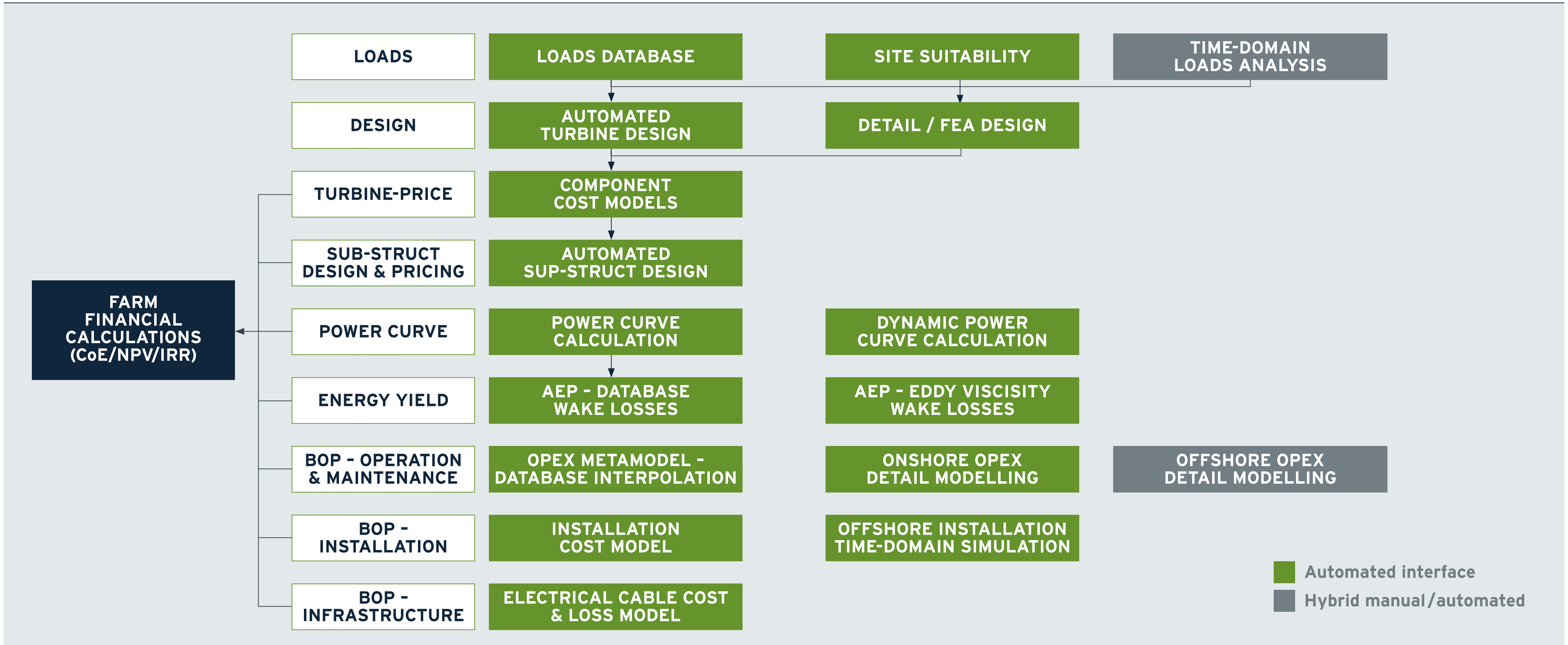
DNV GL has successfully applied detailed engineering-based LCOE models in the development of numerous megawatt scale wind turbines and offshore wind farms. From the experience gained in supporting customers design turbines and wind farms, such an engineering model approach becomes possible, drilling down to the fundamental physics of the system. This contrasts with simplistic high-level curve-fitting methods which are unable to predict sudden discontinuities in the system. Turbine.Architect builds a detailed virtual model of the turbine and key wind farm constituents (e.g. foundations and electrical systems). It calculates realistic load envelopes and strength margins, down to the level of tower/foundation plate thicknesses and sizing bolted ring flanges. With this, issues such as transportation geometry constraints and frequency of vibration interactions are dealt with appropriately. Turbine.Architect also accounts for production factors, such as the cost of labour, facilities and supplier profit; results are validated against industry data to ensure accuracy. Turbine. Architect considers the complete picture through a series of automated sub-modules and is supported by other DNV GL design tools, see Figure 3-2. Auxiliary software and tools include DNV GL Bladed, WindFarmer, Optimisation of Offshore Construction (O2C) and Optimisation of Operations and Maintenance (O2M).

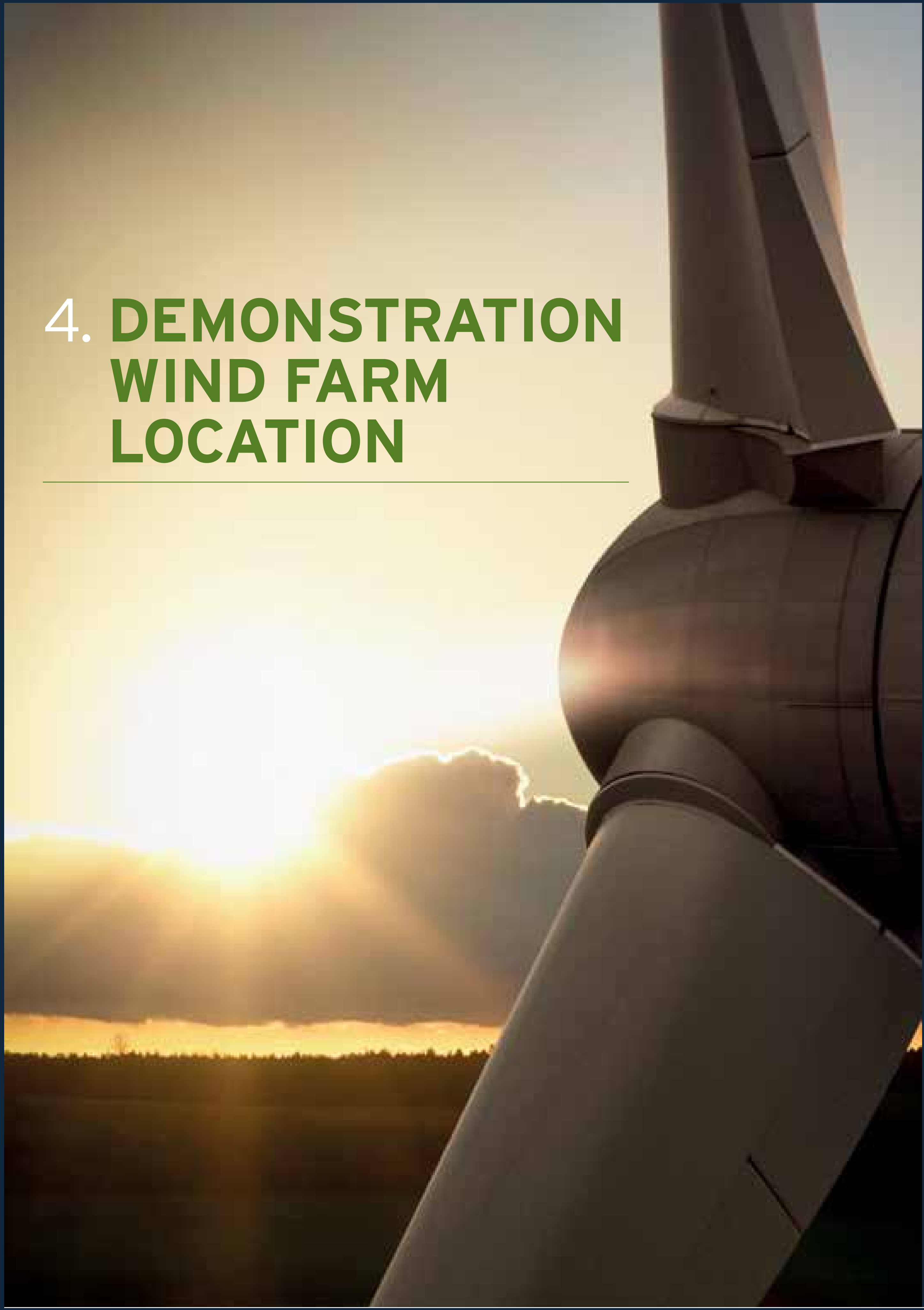
By bringing together cost modelling of not just the machines but the balance of plant, operations & maintenance and economic aspects, decisions can be made in the most objective way. With this functionality, questions such as the following can be more easily answered:

- Which sub-zone will yield the lowest LCOE?
- What if the price of steel changes by ten percent?
- Which combination of project capacity, turbine and foundation will achieve the lowest LCOE?
- What if five more turbines are squeezed onto the site?
- What if we optimise our layout based on LCOE rather than energy yield?

DNV GL's Turbine.Architect tool is helping India and the offshore wind industry navigate through a complex wind farm design space towards the lowest cost of energy.

FIGURE 3-2: TURBINE.ARCHITECT MODULES





4. DEMONSTRATION WIND FARM LOCATION

4.1 INTRODUCTION

The objective of this section is to identify optimal locations for demonstration projects of 150 to 504 MW in Tamil Nadu's most promising offshore wind development area, "zone A", as identified in the Pre-feasibility Study [4] - see summary, Section 4.2.

10 sub-zones have been defined in zone A and further known hard constraints have been identified, the sub-zone selection methodology is presented and discussed in Section 4.3.

These 10 sub-zones are subsequently modelled using DNV GL's system design and cost modelling tool Turbine.Architect and evaluated against their normalised levelised cost of energy (LCOE) to establish the optimum demonstration project locations within zone A. The Turbine.Architect methodology and results are presented in Section 4.4.

4.2 ZONE SELECTION SUMMARY

The eight zones identified, during the Pre-feasibility Study, as most suitable for the development of commercial scale offshore wind farms, were pragmatically ranked for their compliance with a set of defined technical and environmental parameters. The key hard constraints, considered immovable for offshore wind farm development were as follows; offshore wind resource, the Indian Exclusive Economic Zone (EEZ), feasible water depths, proximity with construction ports and distance to transmission grids. Further constraints were also considered within the analysis, such as; the proximity to pipelines, proximity to oil & gas platforms, proximity to shipping lanes, visual impact, seismic risk and cyclone risk. Where constraints were considered significant at a zone level, such as presence of oil and gas platforms in Zone A, either exclusion zones were established or statements made within the results table. Environmental factors such as a biosphere reserve within the Gulf of Mannar are likely to impede development in some zones within Tamil Nadu. Additionally, some areas of Tamil Nadu exhibit high tidal currents, which could make installation challenging (for example the Gulf of Mannar).

The eight zones identified have estimated mean wind speeds from the mesoscale wind map in the range of 7.1 to 8.2 m/s (at 120 m AGL) and water depths in the range of 10 to 53 m below LAT.

Figure 4-1 shows the identified eight zones based on the Pre-Feasibility assessment and the features of these eight zones are described in Table 4-1.

FIGURE 4-1: HEAT MAP SHOWING PRELIMINARY SITE SELECTION

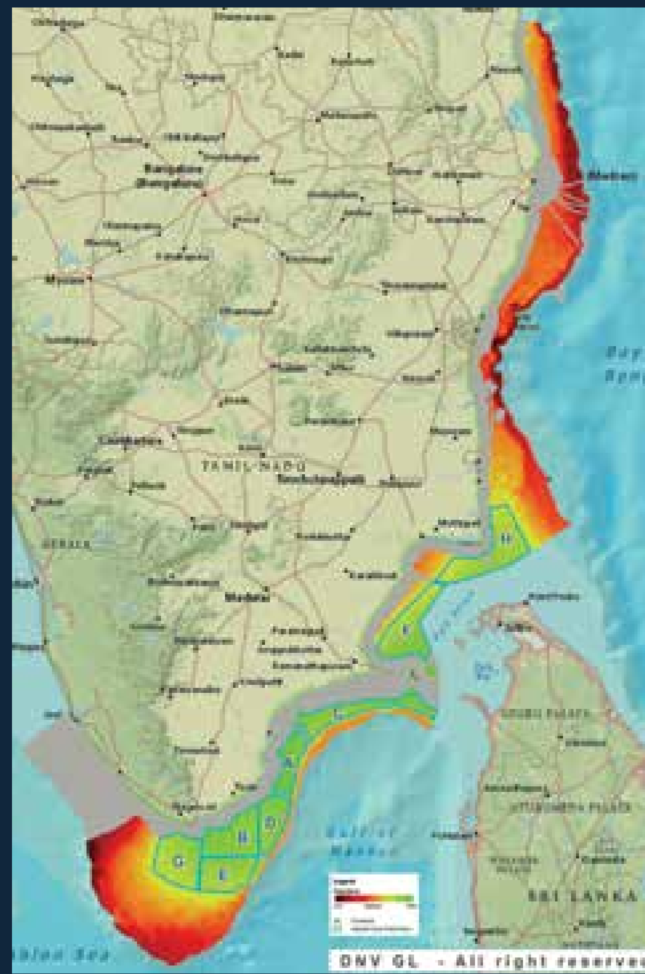


TABLE 4-1: POTENTIAL ZONES FOR DEVELOPMENT OF OFFSHORE WIND POWER PROJECT

Zone ID (highest to lowest score)	Indicative Mean WS at 120 m AGL (m/s)	Indicative Mean Percentage WS change between 100 m and 120 m AGL[1]	Indicative Mean Percentage WS change between 80 m and 100 m AGL[2]	depth (mLAT)	Minimum distance to existing substation (km)	Area (km²)	Notes *Based on the latest Gulf of Mannar constraint zones and cylone maps provided by CSTEP, zone C has a lower score than zone D
A	8.2	1.6%	3.9%	-22	21	588	▪ Safety: possible proximity of two oil/gas well and submarine cable; ▪ Closest ports: Manappad, Punnakayal, Tuticorin
B	8.1	1.1%	2.1%	-32	12	1,557	▪ Closest ports: Kanyakumari, Koodankulam, Manappad
*C	7.9	0.7%	1.5%	-37	24	810	▪ Safety: proximity to submarine cable; ▪ Shallow water: one sand bar is located east of the zone; ▪ Bathymetry at higher resolution is recommended (i.e. Tcarta); ▪ Closest ports: Valinokkam, Rameswaram, Tuticorin
*D	8.1	1.2%	2.2%	-30	36	1,015	▪ Shallow water: a few sand bars are located within the zone; ▪ Bathymetry at higher resolution is recommended (i.e. Tcarta); ▪ Closest port: Manappad
E	8.1	0.7%	1.4%	-53	32	1,316	▪ Closest ports: Kanyakumari, Koodankulam
F	7.2	0.7%	1.5%	-10	14	1,556	▪ Shallow water: a few sand bars are located within the zone; ▪ Bathymetry at higher resolution is recommended (i.e. Tcarta); ▪ Closest ports: Pamban, Rameswaram
G	7.8	0.8%	1.7%	-51	13	1,602	▪ Closest ports: Colachel, Muttom, Kanyakumari
H	7.1	0.7%	1.5%	-11	46	2,116	▪ Safety: shipping lane in vicinity; ▪ Closest port: Thirukkuvalai

1. Only wind speed at 120 m AGL have been used in the zone identification. Wind speeds at 100 m are stated for reference ONLY. Stated wind speeds are indicative and require validation.

2. Only wind speed at 120 m AGL have been used in the zone identification. Wind speeds at 80 m are stated for reference ONLY. Stated wind speeds are indicative and require validation.

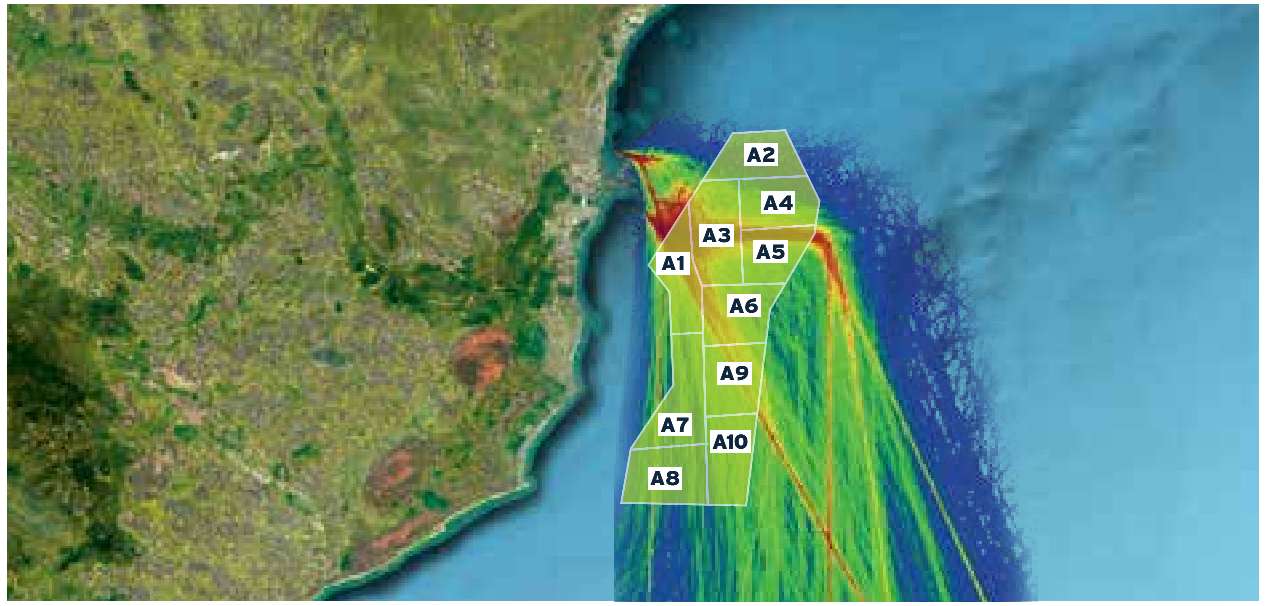
4.3 PRELIMINARY SUB-ZONE SELECTION

Sub-zones within Tamil Nadu "zone A" were selected on the assumption that they could each accommodate a wind farm with a capacity between 150 and 504 MW. Where the defined sub-zones do not have sufficient area to fully accommodate the larger configurations (e.g. 504 MW/4MW WTG and 504MW/6MW WTG) it is assumed that the layout will be designed such that the remaining "overflow" of turbines will be arranged in the neighbouring subzone of the lowest predicted cost of energy, this is in order to maintain optimised layout spacings.

Applying these assumptions, 10 sub-zones of similar area have been identified. Figure 4-2 visualises these sub-zones and Table 4-2 summarises the average data for each sub-zone.

FIGURE 4-2: TAMIL NADU ZONE A SUB-ZONE

FIGURE 4-3: TAMIL NADU SHIPPING DENSITY TRAFFIC



Further spatial constraints were investigated, specifically shipping traffic around zone A. Using publicly available information from automatic identification system (AIS) data from ships, a density map based on annual shipping traffic [9] in the vicinity was plotted (see Figure 4-3).

It has been noted that sub zones A1, A3 and A4 are potentially affected by some level of shipping traffic. It has been suggested that once the Government of India announces the final blocks for auction, the specific zone could be made into a single-user or similarly demarcated area. Currently the potential development zones have multi-user status, the Government of India can draft rules that can suit future offshore wind project development needs.

TABLE 4-2: TAMIL NADU ZONE A SUB-ZONE AVERAGE PARAMETERS

Sub-zone	WS 80m (m/s)	WS 100m (m/s)	WS 120m (m/s)	Water depth (m)	Distance to coast (km)	Distance to grid onshore (km)	Distance to port (km)	Area (km2)
A1	7.58	7.81	8.01	-14.42	11.53	11.57	12.90	79.4
A2	7.82	7.94	8.01	-19.22	16.83	6.99	18.69	79
A3	7.68	7.90	8.01	-18.07	12.35	6.99	14.22	105
A4	7.82	7.93	7.98	-25.53	19.48	6.99	21.54	80
A5	7.78	7.93	7.98	-29.24	20.39	6.99	22.37	70.5
A6	7.80	7.99	8.07	-27.50	20.83	12.72	22.65	86.9
A7	7.80	8.03	8.22	-16.51	14.87	26.90	21.15	98
A8	7.76	7.98	8.17	-18.44	17.90	32.17	23.16	91.3
A9	7.92	8.13	8.22	-22.90	22.35	26.51	26.60	82.1
A10	7.94	8.16	8.30	-18.77	23.96	30.14	31.18	80.4

4.4 TURBINE.ARCHITECT SPATIAL ANALYSIS

4.4.1 Introduction

An analysis has been undertaken to identify the most suitable sub-zone for wind farm development in the Tamil Nadu region. The analysis was completed using DNV GL's system design and cost modelling design tool Turbine.Architect.

4.4.2 Methodology

The goal of the spatial analysis is to form a quantitative ranking of cost of energy for each sub-zone in zone A to determine suitability for wind farm development.

Cost of energy will be calculated using DNV GL's Turbine.Architect tool. The tool is capable of forming detailed cost estimates for the majority of components of the wind farm and is sensitive to the parameters listed in Section 4.4.3, and many more. For further information on the Turbine. Architect cost modelling tool refer to Section 3.

4.4.3 Inputs

Inputs relevant to the cost modelling and systems design undertaken during the spatial analysis are presented in this section.

4.4.3.1 Regional Conditions

Conditions constant across all of the subzones modelled during the spatial analysis are presented in Table 4-3.

TABLE 4-3: SPATIAL ANALYSIS INPUTS FOR TAMIL NADU REGION

Tidal level HAT	0.8 m
50-year maximum wave height	11.0 m
50-year storm surge elevation	1.4 m
Annual mean significant wave height	1.24 m
Energy availability	92.8 %
Annual operational expenditure	4.30 mINR (million INR)[3]
Wind climate Weibull shape factor	2.0
Hub height	105 m
Wind shear calculation method	Roughness wind shear
Roughness height	0.001 m

The maximum wave height, storm surge and tidal parameters are used for producing offshore support structure estimates. The significant wave height, availability and annual OPEX parameters are used in the wind farm cost modelling calculations.

A constant soil profile has been assumed across the region. Soil parameters are used in the definition of support structure and are as presented in Table 4-4.

4.4.3.2 Site Conditions

Conditions which vary between sub-zone are presented for each sub-zone in Table 4-5.

TABLE 4-4: TAMIL NADU SOIL PROFILE FOR SPATIAL ANALYSIS

Depth from [m]	Depth to [m]	Soil type	Submerged unit weight [kN/m³]	Shear strength from [kPa]	Shear strength to [kPa]	Epsilon 50 [-]	Friction angle [deg]
0.0	3.8	Sand	7.0	-	-	-	20
3.8	10.8	Sand	8.5	-	-	-	25
10.8	21.2	Sand	8.5	-	-	-	20
21.2	100	Sand	8.5	-	-	-	25

TABLE 4-5: SPATIAL ANALYSIS INPUTS FOR SUB-ZONES WITHIN TAMIL NADU REGION

Sub-zone	Water depth to LAT [m]	Annual mean wind speed at 100 mLAT [m/s]	Distance to onshore grid connection [km]	Distance to construction port [km]
A1	14.42	7.81	11.53	12.90
A2	19.22	7.94	16.83	18.69
A3	18.07	7.9	12.35	14.22
A4	25.53	7.93	19.48	21.54
A5	29.24	7.93	20.39	22.37
A6	27.5	7.99	20.83	22.65
A7	16.51	8.03	14.87	21.15
A8	18.44	7.98	17.90	23.16
A9	22.9	8.13	22.35	26.60
A10	18.77	8.16	23.96	31.18

3. 1 mINR = 1 million INR = 1,000,000 INR. 1 Crore INR = 10 mINR = 10,000,000 INR. 1 Lakh INR = 0.1 mINR = 100,000 INR.

4.4.3.3 Turbine

A generic 6MW direct drive turbine with a 154m rotor diameter and a hub height of 105m LAT has been modelled. Further parameters are shown in Table 4-6.

TABLE 4-6: TURBINE PARAMETERS USED FOR SPATIAL ANALYSIS

Rating	6 MW
Rotor diameter	154 m
RNA mass	365 tonnes
Drive train configuration	Direct drive
Wind speed and turbulence class	1B
Cut-in wind speed	3 m/s
Cut-out wind speed	25 m/s

4.4.3.4 Support Structure

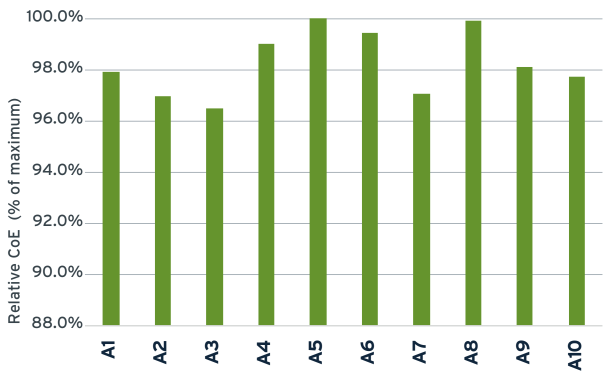
For the purposes of the spatial analysis a monopile support structure has been modelled as the foundation type. Preliminary analyses have shown that the spatial trends are the same regardless of support structure type and so the spatial analysis has been restricted to one type.

4.4.4 Results

4.4.4.1 Cost of Energy

Results in terms of cost of energy are shown in Figure 4-4.

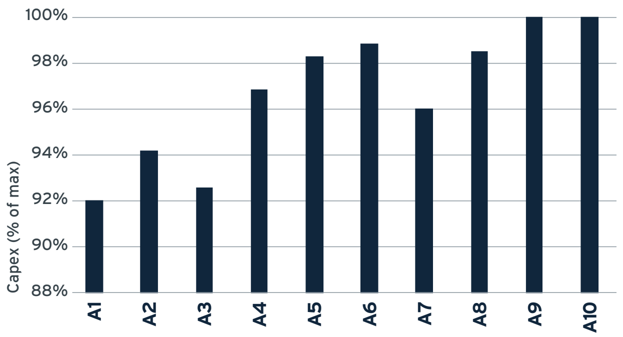
FIGURE 4-4: SPATIAL ANALYSIS RESULTS: COST OF ENERGY RELATIVE TO MAXIMUM OF SUB-ZONES



4.4.4.2 Capital Expenditure Costs

Variation in total CAPEX for the wind farms are shown in Figure 4-5.

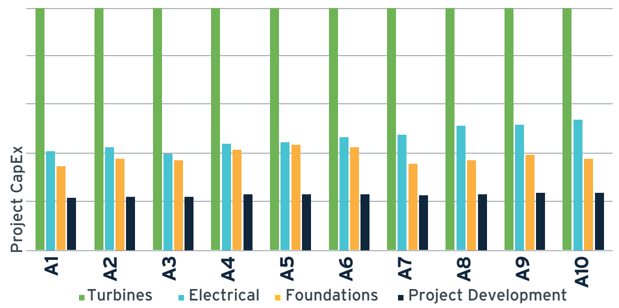
FIGURE 4-5: SPATIAL ANALYSIS RESULTS: CAPEX RELATIVE TO MAXIMUM OF SUB-ZONES



A breakdown of CAPEX for the major components is shown in Figure 4-6. The major components are:

- Electrical infrastructure;
- Turbines;
- Foundations;
- Project development (feasibility studies, consenting, package management etc.).

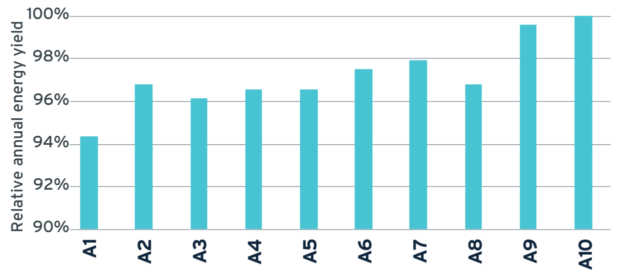
FIGURE 4-6: SPATIAL ANALYSIS RESULTS: CAPEX BREAKDOWN



4.4.4.3 Annual Energy Yield

Variation in annual energy yield across the Tamil Nadu sub-zones, expressed to the maximum of the sub-zones, is shown in, is shown in Figure 4-7.

FIGURE 4-7: SPATIAL ANALYSIS RESULTS – ANNUAL ENERGY YIELD RELATIVE TO MAXIMUM OF SUB-ZONES



4.4.4.4 Operational Expenditure Costs

At this stage of analysis operational expenditure has been assumed to be constant across the region and so the same value is used for each sub-zone. In reality, the costs will vary between the sub-zones due to the changes in distance from shore. However, this variation will be negligible in comparison to the total OPEX cost.

4.4.5 Conclusions

The sub-zone showing the lowest cost of energy is A3 (see Figure 4-4. This is a result of A3 being relatively close to shore and having a shallow water depth. A3 does not possess all the most favourable values in these properties out of all the sub-zones, but the combination of favourable values of each, results in it having the lowest cost of energy. Annual mean wind speed affects energy yield. Water depth and distance from shore affect foundation CAPEX and electrical infrastructure CAPEX respectively. Deeper water depth in general requires larger foundations whilst greater distances to shore requires longer cables.

In Table 4-7 each sub-zone has been placed in order of rank for the three parameters mentioned above – annual mean wind speed , water depth and distance to grid connection. It can be seen that A3 is in the top three sub-zones in terms of water depth and distance to grid. This is reflected in the CAPEX results, Figure 4-5, which show A3 as having the second lowest capital expenditure, with sub-zone A1 having the lowest. A3 ranks above A1 in terms of energy yield, however, as shown in Figure 4-7 the overall trend for the Tamil Nadu zone is that lower CAPEX drives lower cost of energy, however of the sub-zones with low CAPEX (A1, A2 & A3) it is the site with the higher annual energy yield – A3 – which has the lowest cost of energy overall.

TABLE 4-7: RANKING OF SUB-ZONES FOR GEOSPATIAL PROPERTIES

Rank	Annual mean wind speed		Water depth		Distance to onshore grid connection	
1	8.16	A10	14.42	A1	11.53	A1
2	8.13	A9	16.51	A7	12.35	A3
3	8.03	A7	18.07	A3	14.87	A7
4	7.99	A6	18.44	A8	16.83	A2
5	7.98	A8	18.77	A10	17.9	A8
6	7.94	A2	19.22	A2	19.48	A4
7	7.93	A4	22.9	A9	20.39	A5
8	7.93	A5	25.53	A4	20.83	A6
9	7.90	A3	27.5	A6	22.35	A9
10	7.81	A1	29.24	A5	23.96	A10

5. SITE DATA

5.1 INTRODUCTION

The Tamil Nadu Pre-feasibility Study [4] highlighted a high level of risk associated with the lack of and uncertainty with the available site data for offshore wind resource, metocean climate and geotechnical conditions. In response, the FOWIND consortium have conducted a more detailed desk based site investigation during this Full Feasibility Study, which provides critical inputs for the concept design and cost of energy modelling. The key components of this site data study can be summarised as follows:

- **Offshore wind resource** - Section 5.2, provides a summary of the mesoscale wind modelling that was conducted during the Pre-feasibility Study. A LIDAR is planned to be deployed by NIWE in Tamil Nadu.
- **Metocean study** - Section 5.3 provides preliminary metocean study for zone A in Tamil Nadu. Conducted by DNV GL's metocean department, it provides site-specific wave, current and tidal data suitable for concept design.
- **Geotechnical study** - Section 5.4 provides a preliminary desk based geotechnical study for Tamil Nadu's offshore zones and provides indicative lower/upper bound design soil profiles for zone A. The study was conducted by DNV GL's geotechnical department.

5.2 OFFSHORE WIND RESOURCE MODELLING

Introduction

The wind climate has a significant influence on the economic viability of offshore wind development for the Tamil Nadu region. A description of the long-term wind climate at a potential wind project is best determined using wind data recorded at the site. For Tamil Nadu, no long term wind data are currently available and the wind resource modelling studies require validation. Therefore, the analysis presented here is not validated and subject to high levels of uncertainty.

An offshore LIDAR is planned to be deployed by NIWE however this was not commissioned at the time of writing this report and the mesoscale model developed during the Pre-feasibility Study and presented in this section will be used.

This section covers the following:

- methodology used by DNV GL's mesoscale wind modelling to predict the wind regime over the area of interest;
- discussion regarding the model outputs;
- wind speed confirmation and uncertainties;
- description of NIWE's proposed offshore LIDAR;
- presentation of the Pre-feasibility mesoscale wind resource maps (100m and 120m).

5.2.2 Wind flow modelling

The spatial variation in wind speed at heights of 80 m, 100 m and 120 m (typical hub heights for offshore wind turbines) above sea level has been predicted by the consortium partners for the areas considered using the Mesoscale Compressible Community ("MC2") computational model as developed by Environment Canada. For this application, MC2 has been run at approximately 5 - 6 km resolution in EOLE mode in which a finite number of climate states are defined according to a global database of geostrophic weather statistics based on public domain reanalysis hindcast data. The National Centre for Environmental Prediction (NCEP) / National Centre for Atmospheric Research (NCAR) reanalysis dataset has been used for this purpose.

In this mode of operation, a number of simplifying assumptions are made relating to atmospheric stratification to allow for a faster convergence for the sake of computational efficiency. In addition, certain thermally driven atmospheric phenomena such as katabatic and anabatic flows are neglected in the modelling, again to allow computational efficiency gains.

These simplifications are not considered to significantly alter the wind energy potential predicted by the model. Each climate state is simulated individually until convergence has been reached.

Following the simulations for each of the standard climate states, the results are weighted by frequency of occurrence [10]. The results from the mesoscale modelling have then been used to initiate the MS-Micro linear wind flow model. This model has then been used to predict the wind regime, with a grid spacing of approximately 500 m, across the region of interest.

The geophysical model, which is comprised of surface roughness and elevation data, is a crucial input to the wind flow modelling process, and has been based on a number of databases. Typically, Anemoscope utilises the GenGEO database [11] for this purpose. However, due to a number of inconsistencies noted in the GenGEO database, alternative sources were sought.

The mesoscale surface roughness has been based on land cover information obtained from the ISCGM database [12], which provides worldwide data at a resolution of 30 arc-seconds (approximately 1 km) and is understood to be more accurate and up to date than the GenGEO database. To accommodate the increased resolution of the modelling domain, the surface roughness used for the microscale modelling procedure was digitised by the FOWIND consortium based upon an assessment of land cover shown by aerial and satellite imagery provided by Google Earth. The land cover is relevant largely for wind directions where the wind first passes over land then to sea, but also has an impact on the land/sea interface at the coastline. How quickly and to what extent the ocean wind flows are affected as this passes over the coastline to land is a function of the surface roughness and topographic elevation. This can have impact further upstream, and is therefore still a significant effect to try to capture. The FOWIND consortium partners have also included a digitisation of the coastline in this process, to more accurately define this important feature in the model.

The elevation data used for the model comes from either the SRTM30 or SRTM3 [13] databases. These two databases provide worldwide elevation data at a horizontal resolution of 30 and 3 arc-seconds respectively (approximately 1 km and 100 m). The lower resolution SRTM30 data set has been used as an input to the mesoscale model, while higher resolution SRTM3 data has been employed during the microscale modelling.

These sources of terrain data, along with the NCEP/NCAR Reanalysis dataset [14], provide the models with the information needed to simulate the wind flow over the designated area.

5.2.3 Model outputs

The results obtained from the MC2 mesoscale model include detailed information on the wind regime at each point on the grid established over the modelled area, at a resolution of approximately 5 – 6 km.

The results obtained from the MS-Micro microscale model include mean wind speed at each point in the 500 m resolution grid established over the modelled area.

Mesoscale and microscale wind flow modelling was carried out to determine the wind speed variation over the study area.

The wind speed results have been compared to an alternative set of mesoscale modelling results. The results of this work for Tamil Nadu, as part of the Pre-feasibility Study [4] are shown within Section 5.2.7 as wind speed maps for 100 m and 120 m above sea level (the 80 m map can be found within the Pre-feasibility Study).

5.2.4 Wind speed confirmation

If reliable long-term reference wind speed measurements are available within the modelled area, they can be used to validate or calibrate the wind speed maps obtained from Anemoscope and reduce the uncertainty associated with the results.

The FOWIND consortium has not been provided with any offshore measured wind speed data, nor is it aware of any sources of long-term offshore reference data in the region. Therefore, additional confidence in the predicted variation of wind speeds across the site was obtained through comparison with alternative mesoscale modelling results sourced from DNV GL's Virtual Meteorological Data (VMD) service at specific locations across the study area.

The VMD service is a mesoscale-model-based downscaling system that provides high resolution long-term reference time series for any location in the world. At the core of VMD is the Weather Research and Forecasting (WRF) model, developed and maintained by a consortium of more than 150 international agencies, laboratories and universities. VMD is driven by a number of high resolution inputs, such as Modern-Era Retrospective analysis for Research and Applications (MERRA) reanalysis data [15], global 25 km resolution 3 hourly and daily analyses of soil temperature and moisture, sea surface temperature, sea ice and snow depth. A sophisticated land surface model predicts surface fluxes of heat and moisture in the atmosphere, reflected shortwave radiation, and longwave radiation emitted to the atmosphere.

MERRA is a NASA reanalysis product which couples numerical modelling with large quantities of empirical data such as surface measurements and earth observation satellite data to generate a long term continuous datasets. MERRA data is available on an hourly basis over a grid spanning most of the globe at a resolution of 1/2 ° in latitude and 2/3 ° in longitude and at a height of 50 m above ground level.

Mean wind speeds across the study area were predicted from VMD simulations at heights of 80 m, 100 m and 120 m above sea level. The mesoscale wind speed results from Anemoscope were then compared to the mesoscale results obtained from the VMD service at the study heights. Adjustments were made to the Anemoscope microscope results in order to bring them into agreement with the VMD results in areas where it was deemed that the VMD results were more accurately reflecting the wind regime.

The absence of offshore wind speed measurements and the nature of the modelling results should be considered when interpreting the wind speed map produced. There is significant uncertainty associated with the process used here to confirm the modelling results, and therefore also with these preliminary wind speed results.

To help reduce some of the uncertainties associated with the current studies, the MNRE may wish to update the results presented here upon review and validation of site data, once obtained from the proposed LIDAR in Tamil Nadu, and when it has a sufficient duration of measurement data (typically 12 months minimum).

5.2.5 Consideration of uncertainty

It is not considered appropriate to formally quantify the uncertainty associated with the results presented here; however, some of the sources of uncertainty are discussed below. Due to the uncertainty associated with the modelling process, the FOWIND consortium recommends that the results presented are used for pre-feasibility purposes only.

There is uncertainty inherent in the results of the mesoscale simulation due to:

- Assumptions and simplifications inherent in the modelling process;
- The limited fidelity of the land cover database; and
- Re-gridding of the geophysical model at a grid spacing of approximately 5 – 6 km.

The microscale modelling uses an increased grid resolution with spacing of approximately 500 m. This enables the terrain and hence the wind flow to be modelled at a higher resolution.

In order to best interpret the microscale modelling results the following points must be noted:

- The mesoscale modelling output is used as input data and consequently the uncertainty in the mesoscale modelling is inherent in the microscale wind speed predictions;
- The wind speed confirmation has been based upon alternative mesoscale modelling results, without any reliable measurements in the region to support the findings; and
- The modelled wind speeds have not been validated against measurements.

5.2.6 Offshore LIDAR Tamil Nadu

NIWE has recently released a tender for offshore geotechnical investigations around a proposed LIDAR location in the Gulf of Mannar, Tamil Nadu. The successful contractor will work in water depths of 17 m to 20 m to carry out soil and subsoil investigations which will aid the design of the offshore platform foundation for the LIDAR. The LIDAR will be used to collect wind measurements for proposed offshore wind projects.

5.2.7 Mesoscale wind resource maps

FIGURE 5-1 MODELLED WIND SPEED OVER TAMIL NADU

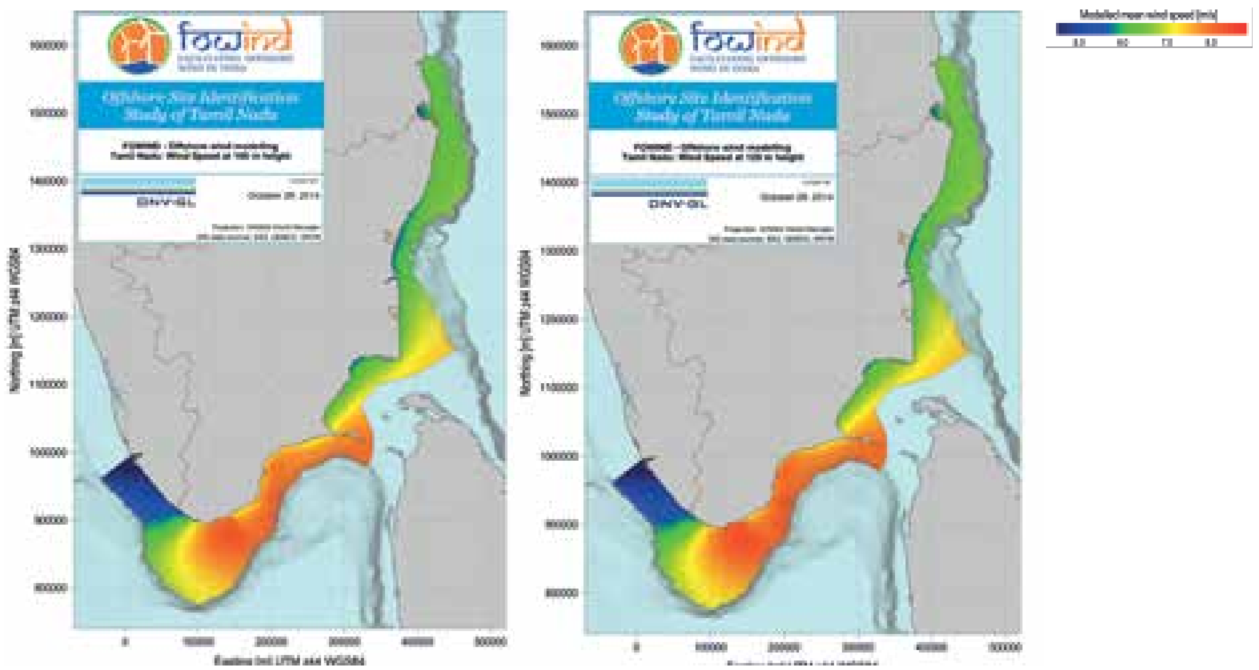
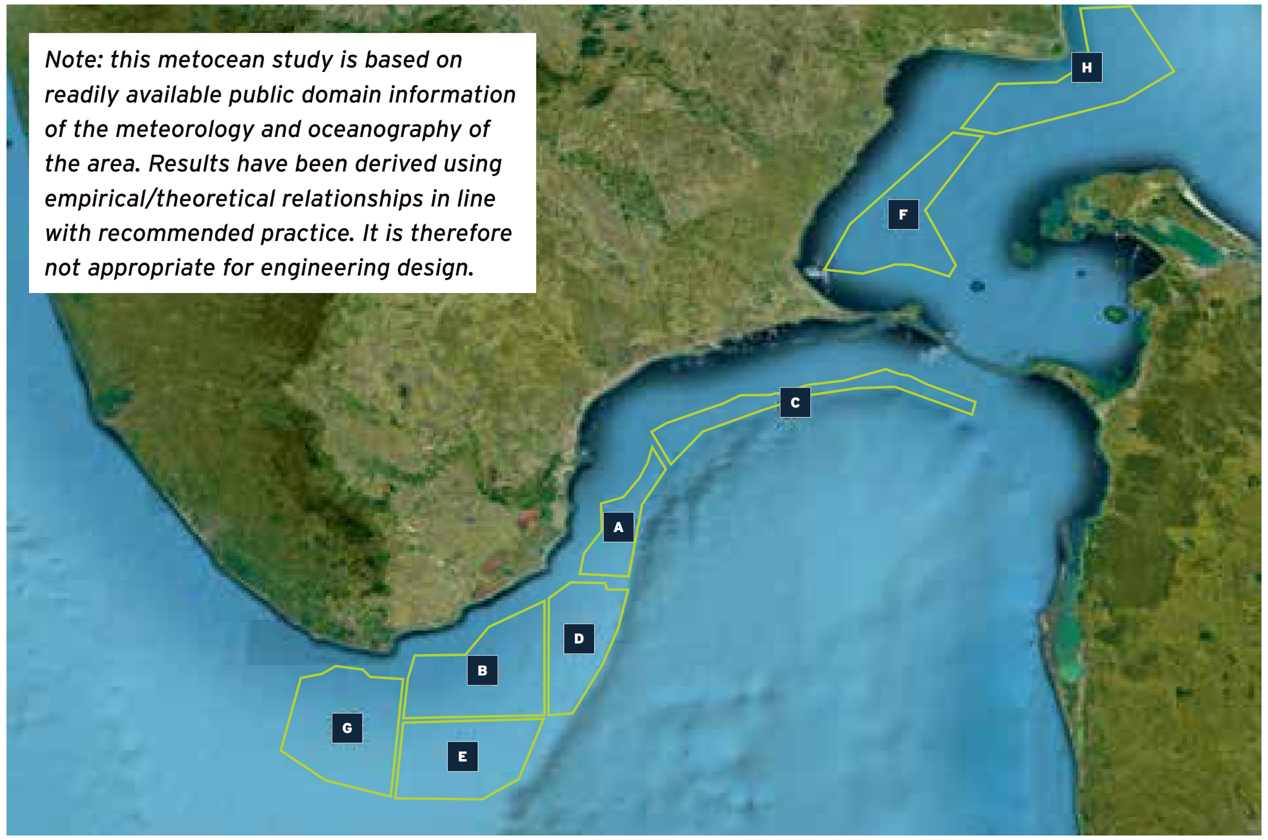


FIGURE 5-2: LOCATION OF INTEREST: TAMIL NADU (Google Earth)



5.3 METOCEAN STUDY

5.3.1 Introduction

This metocean study presents wind, wave, water levels and current environmental data for a location in Tamil Nadu's zone A.

Results are presented in the form of all-year omni-directional extremes of wind speed, wave height, water levels and currents for the return periods of 5, 10 and 50 years, for non-cyclone and cyclone conditions where applicable, as well as H_s–T_p scatter tables and tidal levels tables at each location.

The location considered for this study is:

- **Tamil Nadu:** 08.05°N, 78.30°E, with a water depth of 23m LAT approx.

5.3.2 Data sources

5.3.2.1 Wave and wind data

NOAA Wave Watch III model data

The NOAA (National Oceanic and Atmospheric Administration) has released a 31 years long hindcast based on the Wave Watch III third generation model with a global resolution of 30 minutes in the area of interest [16], [17], [18].

For each output point, the model provides 3-hourly time series including: significant wave height, peak period, wave direction, wind speed and wind direction, for a period of 31 years (from 01 January 1979 to 31 December 2009).

The grid point used has the following coordinates:

- **Tamil Nadu:** NOAA WW3: 08.5°N, 78.5°E.

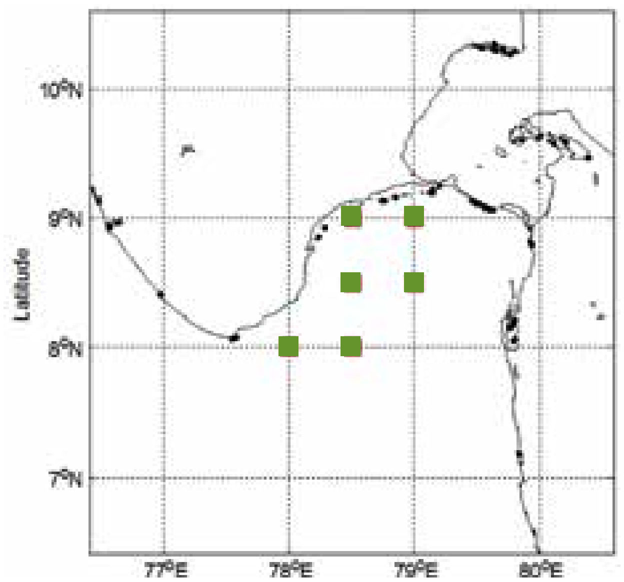
In order to compare the NOAA model data against merged satellite data, additional model points from the model have been obtained at several coordinates.

Satellite data

Satellite measurements from GlobWave Project has been used in order to verify the model wave and wind data before using it for further analysis, as necessary [19], [20].

Subsidised by the Centre National d'Études Spatiales (CNES), the GlobWave Project is an initiative funded by the European Space Agency (ESA) through the Date User Element (DUE) program. This is a programmatic element of the 3rd period of the Earth Observation Envelope Programme (EOEP-3), an optional programme of ESA. The main goals are: (1) to develop and maintain a GlobWave web portal providing a single point of reference for satellite wave data and its associated calibration and validation information and (2) to provide a uniform, harmonised, quality controlled, multi-sensor set of satellite wave data and ancillary information in a common format, with a consistent characterisation of errors and bias. GlobWave Database consists of eight satellite post-processed missions: ERS-1, ERS-2, ENVISAT, TOPEX/Poseidon, Jason-1, Jason-2, GEOSAT and GEOSAT Follow-On (GFO), covering a 29-year period (from 1985 to 2014). The raw-data satellite measurements were calibrated and quality-controlled before being made available.

FIGURE 5-3: NOAA WW3 MODEL AND MERGED SATELLITE CO-LOCATED DATA LOCATIONS, TAMIL NADU



Satellite data collocated with the available NOAA data in the area, as shown in Figure 5-5, was used in this study.

Cross-Calibrated Multi-Platform (CCMP) ocean surface wind components

In collaboration with private and government institutions, a team led by Dr. Robert Atlas (PI; proposal originally solicited by REASoN, and currently funded by MEaSUREs through NASA) has created a cross-calibrated, multi-platform (CCMP) [21] multi-instrument ocean surface wind velocity dataset, for the period extending from 01 July 1987 to 31 December 2011, with wide ranging research applications in meteorology and oceanography.

This dataset combines data derived from SSM/I, AMSRE, TRMM TMI, QuikSCAT and other missions using a variational analysis method (VAM) to produce a consistent climatological record of ocean surface vector winds at 25 km resolution.

Data at the following point has been obtained:

- **Tamil Nadu:** CCMP: 8.625 °N, 78.375 °E.

5.3.2.2 Current and water level data

HYCOM residual current and level

The residual (non-tidal) current and level data has been obtained from the HYCOM model [22]. The HYCOM model is a state of the art ocean circulation model. It uses meteorological forcing and a water column representation of the ocean structure. The global HYCOM dataset provides non-tidal levels at 1/12 degree spatial resolution. Current velocity and water level data are available at daily and three hourly intervals over the period 1992 to 2012.

The closest grid point to the interest location that have been obtained has the following coordinates:

- **Tamil Nadu:** HYCOM: 8.4800°N, 78.3199°E.

Global tide model (KMS)

The astronomical tide has been extracted from the Global Tide Model included in the MIKE 21 package [23]. The KMS provides worldwide data representing the major diurnal (K1, O1, P1 and Q1) and semi-diurnal tidal constituents (M2, S2, N2 and K2) based on TOPEX / POSEIDON altimeter data. This has a spatial resolution of 0.25° and is suitable for water depths deeper than 20m.

NOVELTIS TIPS model tidal currents and levels

Tidal levels and currents have been obtained from the NOVELTIS Tide Prediction Service [24], from the regional model North East Atlantic (TIPS-NEA, 2013).

For many years, NOVELTIS has developed tidal atlases on behalf of the French Space Agency. Among other applications, these atlases are used to correct the satellite altimetry measurements and to provide boundary conditions to ocean models. NOVELTIS uses the TUGO hydrodynamic model developed at LEGOS. The most recent bathymetry and coastline databases have been used, as well as high resolution unstructured grids.

Data have been obtained at the following coordinates:

- **Tamil Nadu:** NOVELTIS TIPS: 8.5000 °N, 78.3000 °E.

OSU Tidal Inversion Software

The Oregon State University Tidal Inversion Software [25] provides tidal signal for different domains; in this study, the Indian Ocean domain is used. Its spatial resolution is 1/12° and it assimilated 531 cycles of TOPEX/Poseidon, 114 cycles of TOPEX/Tandem and 108 cycles of ERS/Envisat satellites. The model is also validated by several tide gauges.

Tidal current information has been obtained from the OSU at:

- **Tamil Nadu:** OSU: 8.4800°N, 78.3200°E.

5.3.2.3 IBTrACS wind cyclone data

Tropical cyclone track data, including wind speeds and locations every 6 hours are in the public domain and made available by various agencies. In this report, the best track data have been obtained from the International Best Tracks for Climate Stewardship (IBTrACS) database [26] [27].

The IBTrACS project contains the most complete global set of historical tropical cyclones available. It combines information from numerous tropical cyclone datasets, simplifying interagency comparisons by providing storm data from multiple sources in one place. As part of the project the quality of storm inventories, positions, pressures, and wind speeds are checked and information about the quality of the data is passed on to the user.

The World Meteorological Organization (WMO) Tropical Cyclone Programme has endorsed IBTrACS as an official archiving and distribution resource for tropical cyclone best track data. In addition, the WMO endorses one set of best track data for each cyclone; the data originating from various agencies depending on the region. This final WMO endorsed dataset of best track information has been used in this project to remove cyclonic data prior to analysis in order to obtain non-cyclonic extremes. The latest update of that database is IBTrACS v03r06, which contains cyclone data from 1848 up to 2013 (included) and was released in September 2014.

5.3.2.4 Published data

DNV GL maintains a library of reports, publications and information (some of them unpublished) which is scanned to assist with the definition of extreme values, design criteria and operational conditions.

Publications and software of particular relevance include:

- ISO Standard for offshore activities, ISO 19901-1 [28]
- Interim Guidance on Hurricane Conditions in the Gulf of Mexico''. American Petroleum Institute [29]
- Admiralty Sailing Directions (Pilots) published by the Hydrographer of the Navy (UK) [30]
- Reports held by DNV GL relating to nearby areas. For confidentiality reasons, these cannot be quoted directly, but they contain useful supporting data which helped to place the statistics in context
- Web based resources.

5.3.3 Analysis

5.3.3 .1 Non-cyclone extremes

Removal of cyclonic data

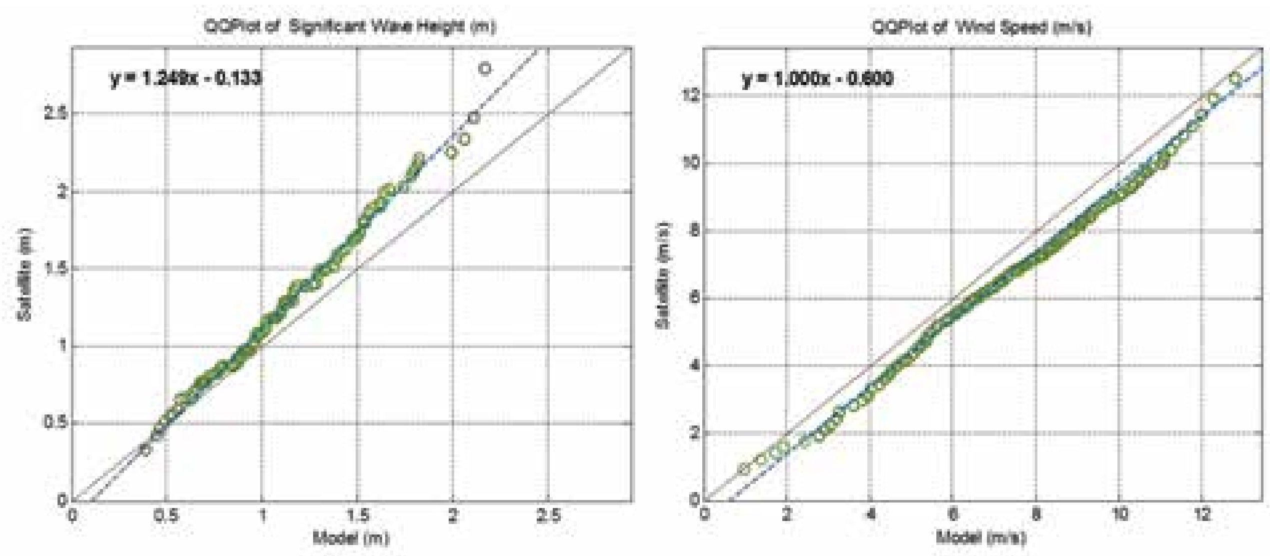
Global hindcast models generally provide a poor representation of cyclones and therefore, cyclonic data within the hindcast data have been removed prior to using it. Tracks of the cyclones that occurred in the overlapping period have been downloaded from IBTrACS (see Section 5.3.2.3). Subsequently, cyclones within a radius of 5° have been identified and corresponding records in the model output removed. The radius has been adjusted to remove the entire peak due to a tropical cyclone by visual inspection of the data.

Hindcast Data Verification

The hindcast model data has been verified against satellite measurements before using it for further analysis as recommended in ISO 19901-1 [28].

Co-located wave and wind data from the NOAA WWIII and merged satellite data in the area, as explained in Section 5.3.2, has been used to carry out the verification which consisted in producing Q-Q plots.

FIGURE 5-4: NOAA WW3 MODEL AND SATELLITE CO-LOCATED WAVES (LEFT) AND WIND (RIGHT). TAMIL NADU



At Tamil Nadu, the closest grid point available was located at water depths higher than the location of interest. Consequently, in order to consider the reduction of the wave height with the water depth, the extreme values of wave height were reduced to the local depth of 30m applying the Tucker & Pitt method [31]. No correction was applied to wind data in order to keep more conservative values.

Derivation of extreme values

Extreme value analysis of wind speed, significant wave height and positive storm surge and residual/non-tidal current were derived by applying validated software developed by DNV GL:

1. Extrapolation of cumulative frequency distributions, by fitting various statistical distributions to a range of percentages of the data of interest.
2. Peaks over threshold, in which an exponential or a Weibull distribution is fitted to a number of peaks over a range of percentages of the highest peaks in the dataset.

Selection of appropriate extreme values was made on the basis of fit quality determined by visual inspection of the extrapolation plots, and oceanographic judgement.

Wind speeds at different averaging intervals

Wind speeds at averaging intervals other than hourly mean are based on relationships provided in the ISO [28] and DNV [32] standards.

Associated wave parameters

Wave period and height parameters associated with the extreme estimates have been derived using industry standard relationships, for example:

- The bivariate frequency distribution H_s–T_p was calculated from the NOAA time series at the location of interest. The weighted mean T_p that correspond to each H_s was calculated. Subsequently, an appropriate curve of best fit was selected to derive a suitable equation that describes the H_s–T_p relationship.
- The zero-crossing period T_z was derived using appropriate spectral formulations
- The maximum wave height H_{max} was derived using the Glukhovskiy-Klopman (1996), distribution
- The crest elevation was estimated by applying the Fenton approximation [33].

Tidal levels and currents

Tidal levels were derived carrying out a harmonic analysis on the tide elevation time series obtained from the Global tidal model (KMS) at the location of interest.

The extreme positive surge levels were obtained by conducting extreme value analyses using HYCOM dataset. Extreme total water level was calculated by combining the surge elevation, the tidal elevation and the crest elevation.

Current extreme was calculated as the sum of a tidal component, a wind-driven component and a residual component associated to each return period.

Currents at intervals through the water column were based on the surface total currents, scaled using a theoretical vertical profile such as that given in ISO [28] and DNV [32].

5.3.3.2 Cyclone extremes

Need of parametric models

Since neither hindcast model data nor satellite data can adequately capture the extremes of wind and wave caused by the passing of a tropical cyclone, it is necessary to employ parametric wind models to obtain an estimate of the cyclonic wind field at each time step in the storm track. The wave extremes can then be approximated based on the wind extremes.

The majority of parametric models require as input the maximum wind speed, V_{max}, the radius-to-maximum-winds, R_{mws}, the cyclone forward speed and direction, as well as the cyclone track. In addition, some models require the minimum pressure, P_c , and the ambient pressure, P_n. With the exception of the ambient pressure and the radius-to-maximum-winds, which are not often reported for historic cyclones, the remaining parameters can be easily obtained from databases in the public domain, such as the IBTrACS database used in this study. In these databases, the cyclone forward speed and direction are not usually reported but can be approximated with relative ease using the best track information.

Using the IBTrACS database, all cyclones passing within a certain radius (for example 500 km) of the location of interest are identified. For each of those cyclones the parametric wind model is used to identify the maximum wind speed caused at the location due to the passing of the cyclone. An extreme value analysis is then undertaken on the distribution of maximum wind speeds caused by all cyclones within the radius, to identify extreme wind speeds with a given return period. It should be noted that to identify cyclonic extremes for a route, a number of different locations along the route are considered and the analysis applied to those locations with the highest cyclone risk.

More information on the adopted approach can be found in [34], [35] [36].

Extreme Value Analysis

The arrival of cyclones in the vicinity of the location is assumed to be a Poisson process. The Poisson process, with parameter λ, can be shown to be the appropriate stochastic model for events that occur randomly in time at a uniform rate of λ per unit time interval. The suitability of this model may be demonstrated by calculating the mean and standard deviation of the number of storms per year. If these two statistics are approximately equal, then the arrival of storms can be assumed to be a Poisson process.

To proceed with identifying extreme conditions, an appropriate extreme value distribution must be used to fit the maximum wind speeds at the location. In this case a Gumbel distribution is assumed and the distribution parameters calculated using the method of moments, as this is found to provide a good representation of the data. In addition, a Peaks over Threshold (POT) technique was used with varying thresholds. The extreme values can be calculated in terms of the numbers of storms per year converting to return period in years by using the average occurrence of storms per year.

Ratio of significant wave height to wind speed For a given 1-minute cyclonic wind speed, the corresponding significant wave height can be approximated by: H_s–U/k where k is a factor with a mean value of 4.0.

API Interim guidelines present results for the four different regions in the Gulf of Mexico which show that the factor k varies from 3.7 to 4.2 for water depth equal or greater than 1000 m. This factor is then increased with decreasing water depths. For 300 m water depth, it varies from 3.8 to 4.4, and for 30m water depth, from 5.0 to 6.0.

The H_s extreme presented has been derived by fitting a curve of best fit to the information provided in the API guidelines taking into account the total water depth at the location of interest.

Associated wave parameters

Wave period and height parameters associated with the extreme significant wave height estimates were derived as follows:

- The API Interim guidelines recommend that "hurricane-driven seas can be reasonably represented by the JONSWAP spectrum with a γ of 2.0 – 2.5". Using a mean of 2.25, the following peak period associated with the significant wave height can be derived as $T_p = 4.3\sqrt{(H_s)}$
- The zero-crossing period T_z was derived using appropriate spectral formulations
- The maximum wave height (H_{max}) was derived using a standard ratio as per API recommendation.
- The crest elevation was estimated by applying the Fenton approximation [33].

Current

Current extreme was calculated as the sum of a tidal component, a residual component from the non-cyclone analysis, and a wind-driven component equal to 3% of the 1-hour mean wind speed at 10m above sea level.

A $1/7^{th}$ power law is used for the tidal current profile through water column, and a wind-driven current profile as recommended in DNV-RP-C205.

5.3.4 Results

The annual mean Hs at the Tamil Nadu location (calculated for the period between 01 January 1979 to 31 December 2009) is 1.24 m.

TABLE 5-1: 5, 10, 50-YEAR OMNI-DIRECTIONAL NON-CYCLONE EXTREMES - TAMIL NADU

SEASON	NON-CYCLONE		
Return Period	**5**	**10**	**50**
WIND SPEED			
Hourly mean wind speed at 10m [m/s]	13	19	30
10-minute mean wind speed at 10m [m/s]	14	20	33
1-minute mean wind speed at 10m [m/s]	16	22	37
3-second gust wind speed at 10m [m/s]	17	24	42
SEA STATE (3-HOUR)			
Maximum individual wave height [m]	6.1	7.6	11.0
Associated period [s]	7.4	8.3	9.9
Associated wave length [m]	85	103	139
Significant wave height [m]	3.5	4.4	6.3
Zero crossing period [s]	6.0	6.8	8.1
Peak energy period [s]	8.0	9.0	10.8
WATER LEVELS			
Wave crest elevation [m]	3.5	4.5	7.0
Tidal rise [m]	0.8	0.8	0.8
Storm surge [m]	0.1	0.3	1.4
Safety margin [m]			1.5
Minimum airgap [m]			10.7
CURRENT			
Total surface current [m/s]	1.0	1.2	1.6
Current at 25% of water depth [m/s]	0.9	1.1	1.5
Current at mid-depth [m/s]	0.8	1.0	1.3
Current at 75% of water depth [m/s]	0.7	0.9	1.2
Current at 1m above seabed [m/s]	0.6	0.7	0.9

TABLE 5-2: 5, 10, 50-YEAR OMNI-DIRECTIONAL CYCLONE EXTREMES - TAMIL NADU

SEASON	CYCLONE		
Return Period	**5**	**10**	**50**
WIND SPEED			
Hourly mean wind speed at 10m [m/s]	16	16	18
10-minute mean wind speed at 10m [m/s]	17	17	19
1-minute mean wind speed at 10m [m/s]	18	19	21
3-second gust wind speed at 10m [m/s]	20	21	23
SEA STATE (3-HOUR)			
Maximum individual wave height [m]	5.5	5.9	6.6
Associated period [s]	14.7	15.1	15.7
Associated wave length [m]	214	220	233
Significant wave height [m]	3.1	3.4	3.8
Zero crossing period [s]	11.4	11.6	12.2
Peak energy period [s]	16.0	16.4	17.1
WATER LEVELS			
Wave crest elevation [m]	3.4	3.7	4.2
Tidal rise [m]	0.8	0.8	0.8
Storm surge [m]	0.3	0.3	0.3
Safety margin [m]			1.5
Minimum airgap [m]			6.8
CURRENT			
Total surface current [m/s]	0.9	0.9	1.1
Current at 25% of water depth [m/s]	0.8	0.9	1.0
Current at mid-depth [m/s]	0.8	0.8	0.9
Current at 75% of water depth [m/s]	0.7	0.7	0.8
Current at 1m above seabed [m/s]	0.5	0.6	0.7

Note: Extreme cyclone values lower than the 10-year return periods are not recommended due to the statistical uncertainty in the estimation.

TABLE 5-3: TIDAL LEVELS - TAMIL NADU

TAMIL NADU TIDAL LEVELS (M)		
	rel MSL	**rel LAT**
HAT	0.48	0.90
MHWS	0.34	0.77
MHHW	0.30	0.73
MHW	0.23	0.66
MHWN	0.14	0.57
MSL	0.00	0.43
MLWN	-0.14	0.28
MLW	-0.23	0.19
MLLW	-0.27	0.15
MLWS	-0.31	0.12
LAT	-0.43	0.00

TABLE 5-4: ALL-YEAR OMNI-DIRECTIONAL HS VERSUS TP – TAMIL NADU

TAMIL NADU: SEASON IS ALL-YEAR NON-CYCLONE CONDITIONS
Direction From: All directions

Significant Wave Height, Hs [m]	PEAK ENERGY PERIOD, TP [S]																									
	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24	24-25	Total
5.5 - 6.0																										
5.0 - 5.5																										
4.5 - 5.0																										
4.0 - 4.5									1																	1
3.5 - 4.0									2																	2
3.0 - 3.5									1	1	2						1	4	5	5	3					22
2.5 - 3.0								3	30	6	3			4	43	53	50	33	14	9	11	1				260
2.0 - 2.5						20	42	55	68	51	50	186	257	428	600	609	549	371	208	79	46	20				3639
1.5 - 2.0					136	592	249	144	176	238	1511	2958	2274	2668	2847	2511	1822	1194	562	304	172	56	13	8	2	20437
1.0 - 1.5				306	4344	294	60	117	218	1359	4055	4406	3839	4452	4214	3276	2237	1188	551	291	176	68	16	6	1	35474
0.5 - 1.0			6	1396	839	3	15	44	571	2596	3497	3999	3645	3690	3107	2115	1274	674	234	143	100	26	8	5		27987
0.0 - 0.5			3	2				3	53	83	97	107	79	51	59	48	16	6	1		1	1				610
TOTAL			9	1704	5319	909	366	366	1120	4334	9215	11656	10094	11293	10870	8612	5949	3470	1575	831	509	172	37	19	3	88432

Note: Data from NOAA hindcast without calibration

5.4 GEOTECHNICAL STUDY

5.4.1 Introduction

During the Pre-feasibility Study [4] a desk based geological review was conducted and it provides a summary of possible geological and seismic hazards in Tamil Nadu, and highlights the risks that these hazards might present to typical offshore wind foundations. The summary of these geohazards should be considered indicative and not exhaustive. Section 5.4.2 provides high-level geological descriptions for the Tamil Nadu offshore region.

In order to facilitate outline foundation design for this feasibility study, DNV GL's offshore geotechnical department has developed an experience based Geotechnical zone description for the Tamil Nadu offshore region and provided indicative lower/upper bound soil profiles (see Sections 5.4.3 and 5.4.4). This is based on publicly available data and knowledge/experience from working offshore in this region for a number of decades.

The soil profiles presented in Section 5.4.4 shall only be considered broadly representative of the offshore ground conditions in zone A. They are indicative and experience based as no geotechnical surveys are publicly available, and should only be used for the purposes of feasibility studies such as this. It should be noted that due to the level of data available there is a limit to the amount of detail and the conclusions that can be drawn from such an exercise.

5.4.2 Geological background

Tamil Nadu is situated in the south east of India with the selected development zones located broadly between the Indian and Sri Lankan coastlines. The coastal and offshore areas in the Tamil Nadu region consist of moderately hard sedimentary rocks ranging in age from Late Jurassic (~ 120 million years ago) to Recent and the Present day. These sedimentary rocks have formed into a series of alternating basins (depressions) and ridges (rises). The basins and ridges are controlled by deep crustal faults with vertical uplifts, producing a series of "horst (ridge) – graben (basin)" structures. These ridge-basin (or horst-graben) structures are oriented in four main directions making them relatively unpredictable (NNE-SSW, NE-SW, N-S, and E-W [37] [38] [39].

Though the geology of the Palk Bay and Gulf of Mannar areas are generally comprised of sedimentary features and exhibit similar large faulting features; the stratigraphic succession indicates that the geological settings of Palk Bay and the Gulf of Mannar are quite different. They are separated by the Rameswaram-Ram Sethu/ Adams Bridge feature, and while Palk Bay exhibits a complete succession of 5 sedimentary rocks ranging in age from Late Jurassic (~ 120 million years ago) to the unconsolidated loose sediments of Present day; the Gulf of Mannar is shown to have a underlying geology comprising hard Mannar volcanic rocks interspersed with minor sedimentary rocks and overlain by thick tertiary and recent marine sedimentary rocks and the present day unconsolidated sediments [40].

Gulf of Mannar (Areas "A" to "E" and "G")

The sedimentary geology of the areas identified as "A" to "E " and "G" in the Pre-feasibility Study [4] are predominantly part of the "Gulf of Mannar Sub-basin". The Gulf of Mannar Sub-basin constitutes of the south eastern offshore part of the Cauvery Basin, the southern most of the Mesozoic rift basins along the east coast of India. The Gulf of Mannar Sub-basin comprises of two cretaceous depositional centres separated by the southward plunging NE-SW aligned Mandapam-Delft ridge. The western part forms the shallow water area of the Gulf of Mannar in which Zones "A , D and B" are located. The typical geology is similar to that of the general Cauvery Basin, however mafic rock intrusions are reported. These are unlikely to penetrate into the tertiary sedimentary formations relevant for offshore wind farms (100-300m thickness of either the Tittacheri Sandstone Formation (Late Miocene), Madanam Limestone (Lower Miocene) or the Tirutturaipundi formation (Oligocene)).

Along the west coast of the Kanyakumari District, a sequence of sandstone and clay with thin lignite seams are recorded. These are correlated to Warkhali beds of the Mio-Pliocene age of South Kerala and are similar to the Cuddalore Formation. As well as typical sand, silt and soft clay marine deposits, red coloured sand known locally as teri may also be present towards the western regions of the Gulf of Mannar areas. The 'teri' lies some distance away from the shore and forms large barren wastelands with high mounds and ridges composed of red dunes with intervening depressions. The formation is made up primarily of red stained quartz with an admixture of fine red clayey dust and fine grains of iron ore. The thickness of the teri sand increases from the coast to the interior of the Gulf of Mannar from about 1.5 m to maximum 7.0 m [41].

5.4.3 Tamil Nadu southern zone geotechnical description

The stratigraphy within southern zones is believed to generally comprise of a sand and cemented sands with occasional stiff clay seams to depths of around 45m, with relative density of the sands ranging from loose to very dense.

5.4.4 Tamil Nadu southern zones concept design soil profile

Table 5-5 and Table 5-6 provide estimated lower and upper bound soil profiles for Tamil Nadu's southern zones. As stated these profiles are indicative and experience based ONLY and shall be considered to broadly apply across the zone A sub-zones.

A lower and upper bound has been provided to estimate a "Rochdale Envelope" of soil conditions for the zone and as such provide a range of possible conditions for foundation concept design.

The two soil profiles vary quite significantly in terms of competence. The upper bound soil profile represents conditions where cemented ground is present to depth. In terms of soil parameters this is represented by a sand layer with a very high angle of friction. A soil profile of this type lends very strong lateral and vertical support to foundations and is ideal for the deployment of offshore wind, however it may present problems for pile driving. The lower bound soil profile is significantly weaker and features loose sand layers. These loose sand layers may present problems for lateral and vertical resistance. Of considerable uncertainty is the spatial distribution of each soil type. The variation in ground conditions across the zone will be of importance to the applicability of different foundation types, and their relative costs.

To obtain more accurate estimates of soil parameters and stratification in the region, and for any future projects, a detailed site-specific offshore geophysical and geotechnical survey campaign should be conducted and combined with a comprehensive ground model to capture spatial variability and geohazards across the site (see recommendations in Section 5.5).

5.5 FUTURE SURVEY RECOMMENDATIONS

In order to conduct FEED, detailed design and deliver a bankable offshore wind project a range of comprehensive site-specific surveys are required upfront; these include wind measurement, oceanographic surveys, geological surveys (geophysical & geotechnical) and any relevant hazard identification surveys such as unexploded ordinance (UXO) in some areas. The Supply Chain, Port Infrastructure and Logistics Study [2] Section 2.1.1 and the Pre-feasibility Study [4] Section 6.1.5.5 provides preliminary guidance for offshore surveys.

TABLE 5-5: TAMIL NADU SOUTHERN ZONE INDICATIVE LOWER BOUND "SAND" SOIL PROFILE

Depth from [m]	Depth to [m]	Soil type	Submerged unit weight [kN/m3]	Shear strength from [kPa]	Shear strength to [kPa]	Epsilon 50 [-]	Friction angle [deg]
0.0	3.8	Sand	7.0	-	-	-	20
3.8	10.8	Sand	8.5	-	-	-	25
10.8	21.2	Sand	8.5	-	-	-	20
21.2	To depth	Sand	8.5	-	-	-	25

TABLE 5-6: TAMIL NADU SOUTHERN ZONE INDICATIVE UPPER BOUND "CEMENTED" SOIL PROFILE

Depth from [m]	Depth to [m]	Soil type	Submerged unit weight [kN/m3]	Shear strength from [kPa]	Shear strength to [kPa]	Epsilon 50 [-]	Friction angle [deg]
0.0	To depth	Sand	9.0	-	-	-	45

6. TURBINE SELECTION STUDY

6.1 INTRODUCTION

The FOWIND consortium has completed a review of potential wind turbine offerings for the Tamil Nadu Region, given a commercial turbine procurement date target between 2020 and 2025. The objective of this exercise is to review the suitability of these wind turbine offerings considering the key drivers for wind turbine selection, specifically:

- Site suitability (ability to withstand the site climatic conditions over the design operating life);
- WTG track record (a loose measure of wind turbine reliability);
- Suitability of wind turbine to the site foundation selection (see Section 8.4 for foundation concept designs considering 4 MW, 6 MW and 10 MW representative turbines);
- Site specific power production (which contributes significantly towards the cost of energy).

It should be noted that this section is not a full 'Levelised Cost of Energy' assessment and, as such, only considers the factors mentioned above. Assuming a wind turbine is technically suitable for the site, the optimal wind turbine selection will result in the lowest cost of energy for the project.

Section 8.2 presents results from a high level energy production assessment for the identified sub-zone in Tamil Nadu.

6.2 SUMMARY OF COMMERCIALLY AVAILABLE WIND TURBINES

Table 6-1 presents the characteristics of wind turbines that should be commercially available assuming a procurement date target between 2020 and 2025. Only wind turbines greater than 4.0 MW in rated capacity have been identified.

TABLE 6-1: POTENTIAL OFFSHORE TURBINES FOR THE TAMIL NADU SELECTED ZONES

Turbine Model	Rated Power[1] (MW)	IEC Class	Rotor diameter (m)	Commercial Timeline[2]
2-b Energy 2B6	6	IEC 1	140.6	2015
Adwen AD 8-180	8	IEC 1B	180	2018
Adwen AD 5-116	5	-	116	2012
Adwen AD 5-132	5	IEC S	132	2014
Adwen AD 5-135	5	IEC 1B	135	2013
Aerodyn Engineering aM 5.0/139	5	IEC 2B	139	2015
Aerodyn SCD 6MW	6	IEC 2B	140	2014
AMSC SeaTitan 10MW	10	IEC 1B	190	Concept
H127-5MW (CSIC Haizhuang)	5	-	127	2015
H151-5MW (CSIC Haizhuang)	5	IEC 3B	151	2015
HQ5500/140 (Hyundai Heavy Industries)	5.5	IEC 1B	140	2015
Envision EN-4.0-136	4	IEC S	136	2016
Gamesa Azimut project	15	-	N/A	Concept
GE 4.1-113	4.1	IEC 1B	113	2013
GE Haliade 6MW	6	IEC 1B	150.8	2016
Goldwind GW154/6.7MW	6.7	-	154	2018
Goldwind GW164/6.45MW	6.45	-	164	2018
Goldwind GW171/6.45MW	6.45	-	171	2018
Guodian power UP6000-136	6	IEC 1B	136	2012
Hitachi HTW5.0-126	5	IEC S	126	2016
Hitachi HTW5.2-136	5.2	IEC 3A	136	2016
Hitachi HTW5.2-127	5.2	IEC 1A	127	2016
MHI Vestas V117-4.2MW	4.2	IEC 1B	117	2010
MHI Vestas V164-9.5MW	9.5	IEC S	164	2020
MHI Vestas V164-8.0MW	8	IEC S	164	2014

TABLE 6-1: POTENTIAL OFFSHORE TURBINES FOR THE TAMIL NADU SELECTED ZONES CONT.

Turbine Model	Rated Power[1] (MW)	IEC Class	Rotor diameter (m)	Commercial Timeline[2]
Mingyang SCD 6MW	6	IEC 2B	140	2014
Mingyang SCD 6.5MW	6.5	IEC 1	140	2013
Nautica Advance floating turbine	7	-	N/A	Concept
Wind Lens	5	-	100	Concept
Samsung heavy industries S7.0-171	7	IEC 1A	171	2015
Seatwirl 10MW	10	-	N/A	Concept
Seawind 6	6.2	IEC 1	126	2015
Senvion 6.2M152	6.2	IEC S	152	2014
Senvion 6.2M126	6.2	IEC 1B	126	2014
Senvion 6.3M152	6.2	IEC S	152	2017
Siemens SWT4.0-120	4	IEC 1A	120	2010
Siemens SWT4.0-130	4	IEC 1B	130	2015
Siemens SWT-6.0-154	6	IEC 1	154	2014
Siemens SWT-7.0-154	6	IEC 1B	154	2016
Siemens Gamesa SWT-8.0-167	8	IEC 1B	167	2016
Siemens Gamesa D1x	10	-	N/A	Concept
Sinovel SL6000/155	6	IEC S	155	2017
Sinovel SL5000	5	IEC 1A	126	2012
Sway turbine ST10	10	IEC 1B	164	Prototype in development
Taiyuan heavy industry TZ5000-153	5	-	153	2017
SUPRAPOWER project	10	-	N/A	Concept
Aerogenerator X	10	IEC 1	270	Concept
XEMC - Darwind XD115-5MW	5	IEC 1C	115	2006
XEMC - Darwind XD128-5MW	5	IEC 2B	128	2014

Notes.
1. *This value is based on the nameplate rated power rather than the peak power of the power curve.*
2. *Estimated full commercial availability on the basis of public domain information.*
3. *This is the rotor productivity at rated power of the turbine.*
4. *TBC refers to a turbine characteristic that is "To Be Confirmed" and not yet publically reported by the wind turbine manufacture*

6.3 REVIEW OF CLIMATIC CONDITIONS IN THE TAMIL NADU REGION

Currently available offshore wind turbines are designed and certified against International Electro-technical Commission (IEC) requirements (or a variant of), which principally represent European environmental conditions. The current IEC 61400 edition 3 Standard states [42]; "The particular external conditions defined for classes I, II and III are neither intended to cover offshore conditions nor wind conditions experienced in tropical storms such as hurricanes, cyclones and typhoons. Such conditions may require wind turbine class S design." However it should be noted that IEC 61400 edition 4 is set to be released during 2018 and will offer further consideration for typhoons.

With respect to the current situation, utilising an existing wind turbine design for India requires careful consideration of the environment in which it operates and will ultimately require discussions with wind turbine suppliers. However, at this feasibility stage it is important to focus on the critical environmental considerations which may preclude wind turbine suitability, namely normal and extreme operating conditions.

The IEC 61400-1 edition 3 standard [42], provides a classification of turbines accordingly to site wind conditions. Turbines are classed by three main parameters: the average wind speed, extreme 50-year gust, and turbulence. Table 6-2 shows the wind turbine classes described in this standard.

Mean wind climate

The estimated mean annual wind speed, at 100 m MSL, for the identified wind farm development zones, ranges between 7.1 m/s and 8.2 m/s. For sub-zone A3 the mean annual wind speed has been estimated at 7.9 m/s and 8.0 m/s at 100 and 120 mMSL respectively. According to IEC 61400 this equates to a requirement for wind turbines which will be certified on a site-specific basis to IEC Class II and above. However, further considerations on the IEC Class requirements for the turbines are discussed below.

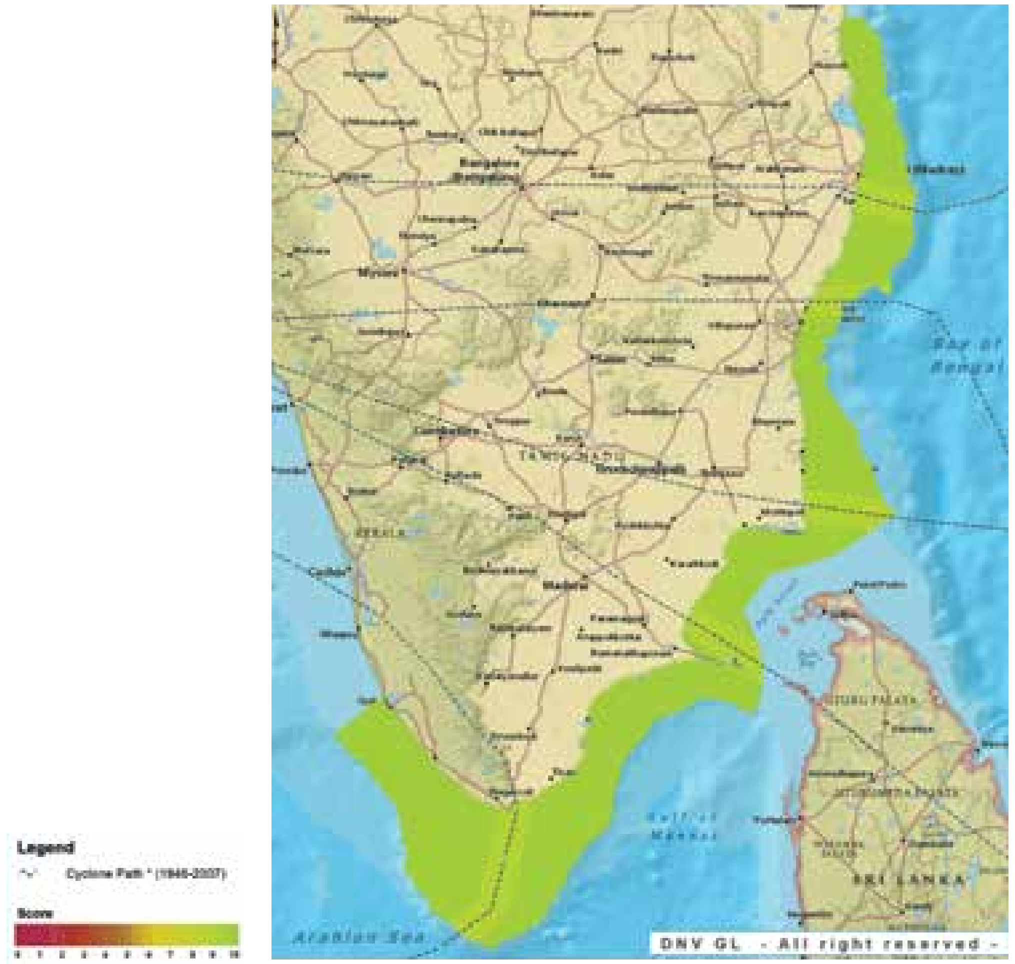
Extreme wind climate

A very important aspect of the climate of Tamil Nadu is the risk of cyclonic conditions. Tamil Nadu falls under the region of tropical cyclones. Most of the cyclones affecting the Tamil Nadu State are generated in the Arabian Sea and Gulf of Mannar. The region experiences two cyclonic storm seasons: May to June (advancing southwest monsoon) and September to November (retreating monsoon). Figure 6-1 presents a map showing the path of cyclones in the Tamil Nadu Region over the period 1946 to 2007.

TABLE 6-2: WIND TURBINE CLASSES

WTG classes	I	II	III	IV	S
Reference wind speed, U_{ref}	50	42.5	37.5	30	Values specified by the manufacturer
Annual avg. wind speed $U_{avg} = 0.2 \times U_{ref}$	10	8.5	7.5	6.0	
50 year return gust speed, $Ue50 = 1.4 \times U_{ref}$	70	59.5	52.5	42	
Turbulence classes	A	B			
I_{15} characteristic turbulence intensity at 15m/s	18%	16%			

FIGURE 6-1: PATH OF CYCLONE IN THE TAMIL NADU REGION FOR THE PERIOD 1946 TO 2007



To assess the extreme wind conditions at the site, specifically focused on 50-year return period, best practice would dictate that 10-years of hub-height wind measurements be supplied at the proposed project site, from which a statistical analysis of the extreme wind speed with fixed return periods can be conducted. However, no long-term hub-height offshore wind measurements are available in the Tamil Nadu region.

In lieu of long term on-site measurements FOWIND have estimated the 50-year return gust wind speed using two approaches and compared the results:

1. **Metocean study** (Section 5.3): the 50-year return 10-minute annual mean wind speed is provided both with and without consideration of cyclones at 10 m above MSL. The value including cyclone conditions can then be extrapolated to hub-height using methods defined in IEC 61400-3 [42]. The 50-year return gust can then be projected from the 10-minute mean using the relationship in Table 6-2. This method is subject to the inherent uncertainty of a preliminary metocean study that has not been validated with a period of on-site measurements.
2. **Indian Standard relating to Codes of Practice for Design Loads for Buildings and Structure** (IS 875-3 [31]): this document has been designed primarily for onshore structures and its application offshore is subject to significant uncertainty.

Applying method 1, using results for extreme wind speeds including cyclones from the metocean study presented in Table 5-2 (Section 5.3.4), the estimated 50-year return 10-minute annual mean wind speed at 10 m above MSL is 33 m/s (Uref). Applying the power law for normal wind speed presented in IEC 61400-3 [42] the 10 mMSL value can be extrapolated to hub-height as follows:

$$U_{(ref(hub))} = U_{(ref(10m))} \left(\frac{z\_hub}{z\_10m}\right)^{\alpha}$$

where:

α = power law exponent, estimated as 0.14 for normal conditions offshore [42].

z = elevation above MSL (either 10m reference or hub-height)

Hence the extrapolated 50-year return 10-minute annual mean wind speed are estimated as 45.6 m/s and 46.7 m/s for hub-heights of 100 mMSL and 120mMSL respectively. These magnitudes exceed the IEC Class II requirement of 42.5 m/s (Table 6-2) and indicates a IEC Class I turbine should be sufficient. Similar requirements for IEC Class I can be seen when estimating the 3 second 50-year return gust (U_{e50} = 1.4 x U_{ref}), where U_{e50} is calculated as 63.8 m/s and 65.4 m/s for hub-heights of 100 mMSL and 120mMSL respectively.

In parallel to using results from the metocean study FOWIND have also applied the second method as follows using the Indian Standard relating to Codes of Practice for Design Loads for Buildings and Structure.

Figure 6-2 presents the cyclone hazard zoning along with the basic wind speed in Tamil Nadu according to IS 875-3. From this map, it is observed that Tiruvallur, Kanchipuram, Viluppuram and Cuddalore districts, are exposed to high intensity cyclonic and storm impact. The colours on the map correspond to a base wind speed which is a peak gust wind speed, averaged over a period of about 3 seconds, corresponding to 10 m height above the mean ground level in open terrain.

The Standard Method is used, employing the following definitions:

- The basic wind speed, Vb, is obtained from a supplied map of maximum gust (3-second average) wind speeds, independent of direction, at a height of 10 m above level terrain, with a probability of 0.02 being exceeded in any one year.
- For the identified zones A, B, C, D, E and G, the basic wind speed of the coast of Tamil Nadu is somewhere in the region of 33 m/s to 39 m/s. For zones F & H, the basic wind speed is in the region of 44 m/s to 47 m/s;
- The site wind speed, Vs, is estimated by applying factors to account to variation in height and exposure of the site. Extrapolating to 100 m MSL and off the coast relies on estimated factors of 1.272 and 1.284 respectively, resulting in an estimated site gust wind speed of 49.6 m/s for zones A, B, C, D, E and G and 60.3 m/s for zones F & H.

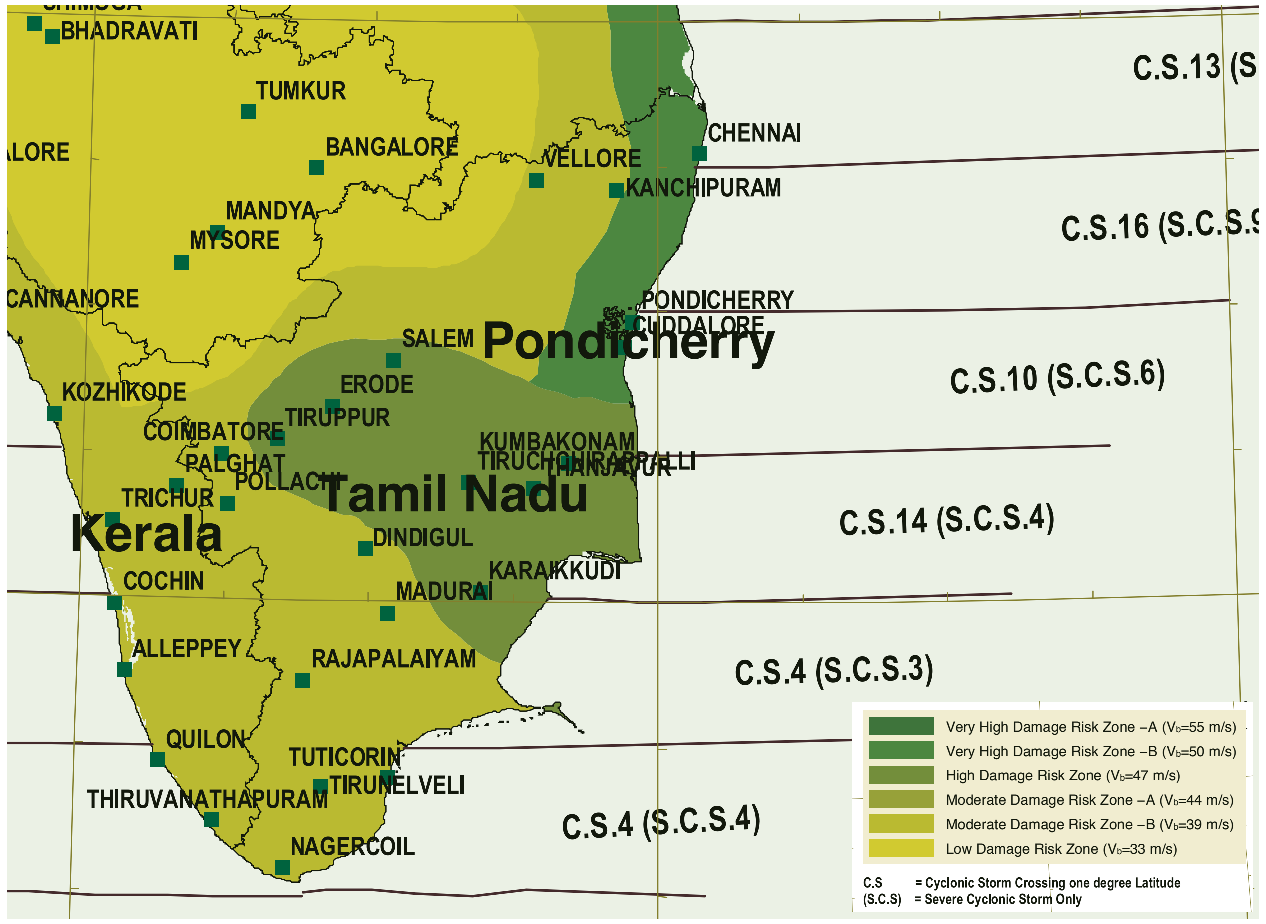
Examination of Table 6-2 indicates that these conditions require IEC Class I classification for all zones.

In summary for zone A (including sub-zone A3) both method 1 and method 2 indicate IEC Class I turbines could be sufficient. More detailed extreme wind speed studies are recommended to verify this preliminary analysis.

It should also be noted that the design of wind turbines for cyclone conditions requires consideration of fast-changing, twisted wind shear profiles combined with sudden changes in wind direction and flow inclination, common in extreme situations. These conditions create additional loading on the turbines; therefore, some areas that are subjected to typhoons which produce maximum wind speeds less than those relating to IEC Class I may still be unsuitable, even when considering a Class I turbine. The added risk due to this can be reduced by the turbine manufacturer taking on the operation and maintenance risk for periods where the extreme wind speeds are above the design conditions or some limited curtailment could also be implemented during these periods.

FIGURE 6-2: CYCLONE HAZARD ZONE & THE BASIC WIND SPEED IN TAMIL NADU

Source: (Building Materials & Technology Promotopn Council (BMTPC); India.)



Further review of the site conditions may prove that turbines taken forward for any future project may require "Class S" certification. The alternative approach (one which has been used in the USA) is for the manufacturer to provide a warranty for the wind turbine up to the design class (in this case Class I), and to supplement the manufacturer's warranty with insurance to extend the cover up to typhoon conditions. This approach will need as a minimum a single met mast with wind speed measurement at hub height, to determine the wind speed experienced by the wind farm.

Classification of a wind turbine as Class A or B is dependent on the turbulence level within the wind farm. This will be mainly driven by wind turbine array layout and can be quantified and mitigated at a later stage however it is probable Class B will be sufficient offshore in Tamil Nadu.

Based on the above assessment, Class I or S wind turbines have been taken forward for further assessment. Where a wind turbine's classification is currently unknown, it has been removed.

6.4 SITE SPECIFIC POWER PRODUCTION

The two primary design parameters for wind turbines can be considered to be the size of the rotor and the capacity of the turbine electrical design. Both of these parameters can be regarded to be a constraint on production. At low wind speeds the maximum amount of energy that can be generated is limited by the size of the area from which the turbine can capture the free flowing energy in the wind (the rotor). At higher wind speeds, it is the wind turbine electrical design which constrains the amount of power that can be produced (the generator).

It can be considered that the interrelationship between the above mechanical and electrical characteristics and their costs will determine the optimal turbine design for a given site. The estimated mean annual wind speed at 100 m MSL for the identified wind farm development sites ranges between 7.1 m/s and 8.2 m/s. This is considered to be a low mean wind speed for offshore sites, by Northern European standards, therefore generated energy is thus limited by the swept area of the rotor.

Figure 6-3 and Figure 6-4 depict the performance of a sub-selection of wind turbine in terms of wind turbine Gross Capacity Factor (which does not include any energy losses, wake, electrical, etc.) and Rated Rotor Productivity, considering both lowest and highest mean wind speed estimates for the zones identified within the Tamil Nadu Region. Rated Rotor Productivity is used to assess the performance of the wind turbine rotor as a function of its rated power. A larger value indicates a machine which has a small rotor to generator size and a lower value indicates the opposite. Ignoring the influence of a wind turbine control system, it is general for machines with a lower Rated Rotor Productivity metric to have a higher wind turbine Capacity Factor at low wind speeds.

It can be seen that turbines can be grouped into the following performance categories;

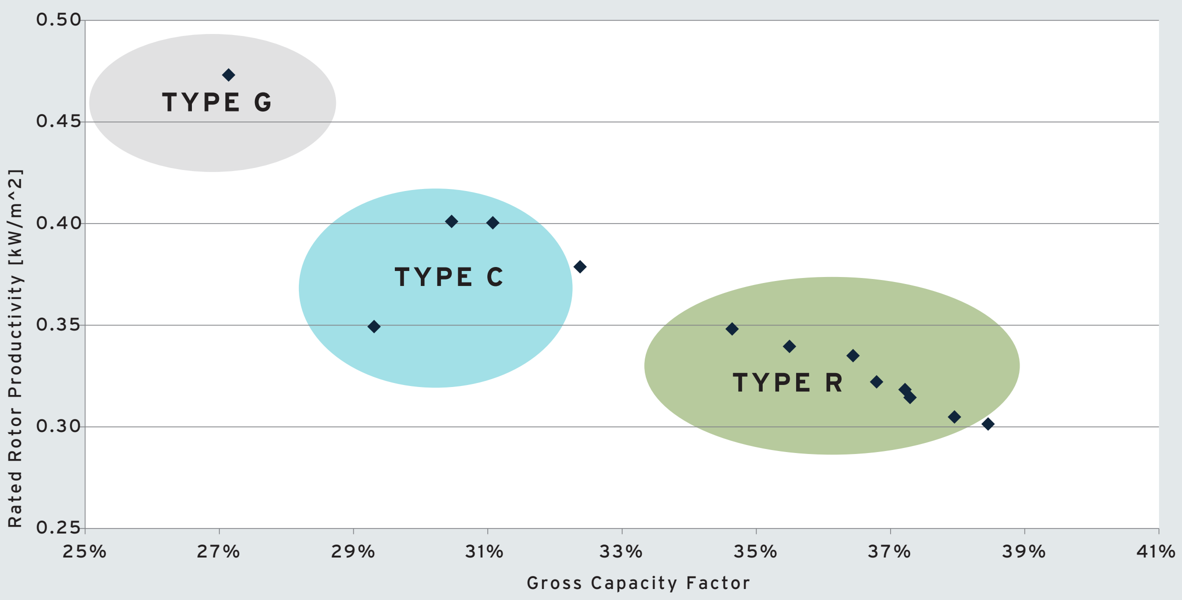
- A **large Rotor** to small generator ratio (Defined here as 'Type **R**');
- A small rotor to **large Generator** ratio (Defined here as 'Type **G**'); and;
- A **Central** case between the two above extremes (Defined here as 'Type **C**').

In Northern Europe, an offshore gross capacity factor of 55% would be expected in order to achieve Project Net Capacity Factors in the order of 40% to 45%, once all losses have been taken into consideration. It is noted that, due to the lower wind speed conditions in the Tamil Nadu, gross capacity factors of between 30% and 38% are estimated.

In order to likely achieve the best possible project return, a project in the Tamil Nadu Region will have to consider a Type R wind turbine with a large rotor to a small generator ratio. Based on the above, the FOWIND consortium has only considered wind turbines that have a Rated Rotor Productivity lower than or equal to 0.35 kW/m2 and which fall under the Type R category, as presented in Table 6-3.

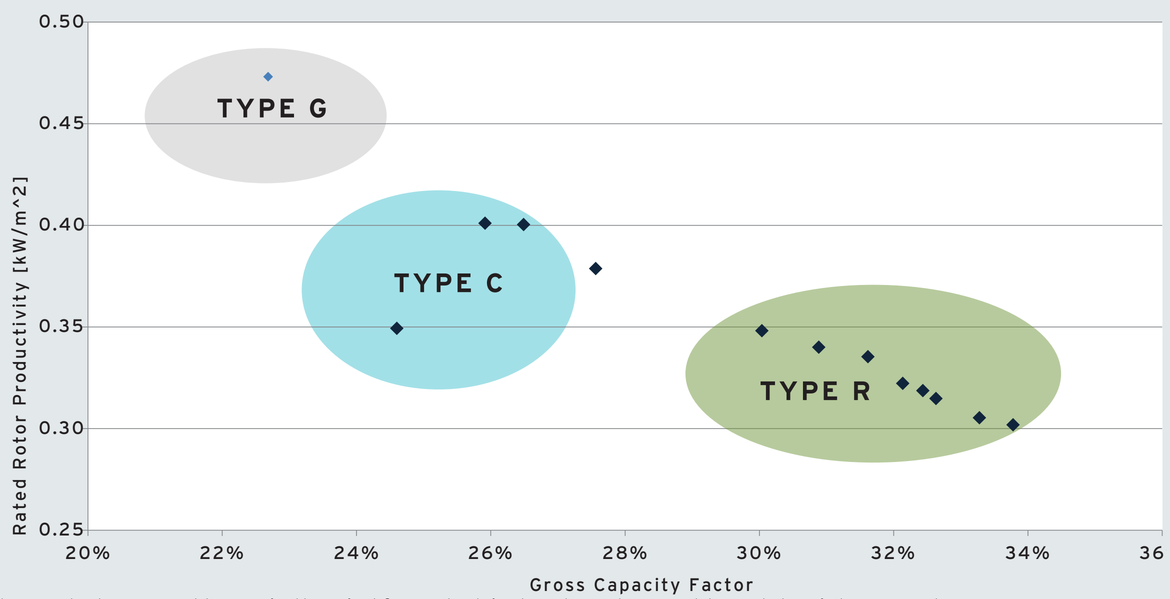
Table 6-3 presents the shortlisted wind turbines for the identified Tamil Nadu zones, following the climatic conditions down-selection. Those highlighted are recommended to be taken forward for further consideration. Table 6-3 also presents three generic wind turbines which have been taken forward for further analysis in this report. These generic wind turbines have been developed to be representative of the likely commercial offerings available to potential projects in the region.

FIGURE 6-3: WIND TURBINE GROSS CAPACITY FACTOR AGAINST RATED ROTOR PRODUCTIVITY (7.9 M/S MEAN ANNUAL WIND SPEED AT 100 M MSL)



Notes: Wake losses and losses in the wind farm electrical systems have not been taken into account.

FIGURE 6-4: WIND TURBINE GROSS CAPACITY FACTOR AGAINST RATED ROTOR PRODUCTIVITY. (7.8 M/S MEAN ANNUAL WIND SPEED AT 80 M MSL)



Notes: Wake losses and losses in the wind farm electrical systems have not been taken into account.

TABLE 6-3: TYPE R SHORTLISTED WIND TURBINES FOR THE TAMIL NADU ZONES

Turbine	Rated Power1 (MW)	IEC Class	Rotor diameter (m)	Commercial Timeline[2]	Rated Rotor Productivity[3] (kW/m^2)
2-b Energy 2B6	6	IEC 1	140.6	2015	0.39
Adwen AD 8-180	8	IEC 1B	180	2018	0.31
Adwen AD 5-116	5	-	116	2012	0.47
Adwen AD 5-132	5	IEC S	132	2014	0.37
Adwen AD 5-135	5	IEC 1B	135	2013	0.35
Aerodyn Engineering aM 5.0/139	5	IEC 2B	139	2015	0.33
Aerodyn SCD 6MW	6	IEC 2B	140	2014	0.39
AMSC SeaTitan 10MW	10	IEC 1B	190	Concept	0.35
H127-5MW (CSIC Haizhuang)	5	-	127	2015	0.39
H151-5MW (CSIC Haizhuang)	5	IEC 3B	151	2015	0.28
HQ5500/140 (Hyundai Heavy Industries)	5.5	IEC 1B	140	2015	0.36
Envision EN-4.0-136	4	IEC S	136	2016	0.28
Gamesa Azimut project	15	-	-	Concept	-
	4.1	IEC 1B	113	2013	0.41
GE Haliade 6MW	6	IEC 1B	150.8	2016	0.34
Goldwind GW154/6.7MW	6.7	-	154	2018	0.36
Goldwind GW164/6.45MW	6.45	-	164	2018	0.31
Goldwind GW171/6.45MW	6.45	-	171	2018	0.28
Guodian power UP6000-136	6	IEC 1B	136	2012	0.41
Hitachi HTW5.0-126	5	IEC S	126	2016	0.40
Hitachi HTW5.2-127	5.2	IEC 1A	127	2016	0.41
MHI Vestas V117-4.2MW	4.2	IEC 1B	117	2010	0.39
MHI Vestas V164-9.5MW	9.5	IEC S	164	TBC	0.45
MHI Vestas V164-8.0MW	8	IEC S	164	2014	0.38
Mingyang SCD 6MW	6	IEC 2B	140	2014	0.39
Mingyang SCD 6.5MW	6.5	IEC 1	140	2013	0.42

TABLE 6-3: TYPE R SHORTLISTED WIND TURBINES FOR THE TAMIL NADU ZONES CONT.

Turbine	Rated Power1 (MW)	IEC Class	Rotor diameter (m)	Commercial Timeline[2]	Rated Rotor Productivity[3] (kW/m^2)
Nautica Advance floating turbine	7	-	-	Concept	-
Wind Lens	5	-	100	Concept	0.64
Samsung heavy industries S7.0-171	7	IEC 1A	171	2015	0.30
Seatwirl 10MW	10	-	N/A	Concept	-
Seawind 6	6.2	IEC 1	126	2015	0.50
Senvion 6.2M152	6.2	IEC S	152	2014	0.34
Senvion 6.2M126	6.2	IEC 1B	126	2014	0.50
Siemens SWT4.0-120	4	IEC 1A	120	2010	0.35
Siemens SWT4.0-130	4	IEC 1B	130	2015	0.30
Siemens SWT-6.0-154	6	IEC 1	154	2014	0.32
Siemens Gamesa SWT-7.0-154	7	IEC 1B	154	2016	0.38
Siemens Gamesa SWT-8.0-154	8	IEC 1B	154	2016	0.43
Siemens Gamesa D1x	10	-	N/A	Concept	-
Sinovel SL6000/155	6	IEC S	155	2017	0.32
Sinovel SL5000	5	IEC 1A	126	2012	0.40
Sway turbine ST10	10	IEC 1B	164	Protoype in development	0.47
Taiyuan heavy industry TZ5000-153	5	-	153	2017	0.27
SUPRAPOWER project	10	-	N/A	Concept	-
Aerogenerator X	10	IEC 1	270	Concept	0.17
XEMC - Darwind XD115-5MW	5	IEC 1C	115	2006	0.48
XEMC - Darwind XD128-5MW	5	IEC 2B	128	2014	0.39
Generic 4MW	4.0	-	120.0	-	0.35
Generic 6MW	6.0	-	154.0	-	0.32
Generic 10MW	10.0	-	190.0	-	0.35

Notes.
1 This value is based on the nameplate rated power rather than the peak power of the power curve.
2 Estimated commercial availability on the basis of public domain information.
3 This is the rotor productivity at rated power of the turbine.

6.5 WIND TURBINE TRACK RECORD

The offshore track record of a wind turbine generator (WTG) indicates the level of maturity of a turbine with higher levels of experience preferred to turbines without a significant track record. An ideal metric corresponding to this element of selection process is 'turbine offshore operating months' and for a specific WTG, this metric directly measures the cumulative number of months of all turbines that have been installed and operating in an offshore environment and is portrayed in Figure 6-5.

FIGURE 6-5: OFFSHORE TURBINE TRACK RECORDS AND PROTOTYPE COMMISSIONING DATES

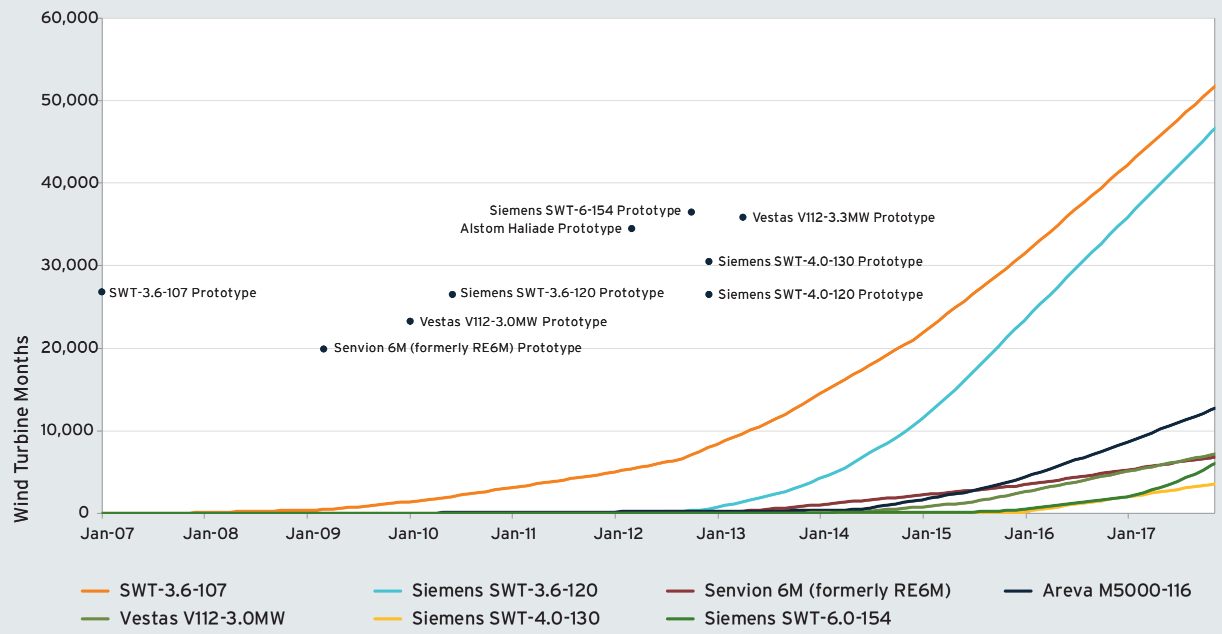


TABLE 6-4: WIND TURBINE INDICATIVE SUPPLY COSTS PER MW

Supply	Onshore Best Estimate	Offshore Lower Bound (EUR / MW)	Offshore Upper Bound (EUR / MW)
European	950,000	1,000,000	1,400,000
India	685,000	800,000	1,120,000
Difference	-28%	-20%	-20%

Only WTG orders where contracts have been signed to date are included in Figure 6-5 and WTG models with no orders are not depicted. It should be noted that prototypes are not included in the analysis; however, they are inserted into Figure 6-5 as milestones.

Since 2013 the number of offshore turbine suppliers in the market has contracted significantly through joint ventures, mergers and acquisitions with the big players. On the 27th September 2013 Vestas Wind Systems and Mitsubishi Heavy Industries formed the MHI Vestas joint-venture, this was followed on the 2nd November 2015 when GE completed the acquisition of Alstom.

Most recently on the 3rd April 2017 Siemens and Gamesa completed their merger, and subsequently on the 26th July 2017 the newly formed Siemens Gamesa announced they would integrate Adwen (originally an JV between Gamesa and Areva) within the group's broader offshore operations, these events have consolidated the groups position as the leading offshore wind turbine supplier. With the consolidation of the big players, this narrows the number of WTG OEMs with significant offshore operational track record. For projects constructed between 2012 and 2018 the offshore turbine supply market is dominated by the Siemens Gamesa group and MHI Vestas, with a combined share between 80-90% [45]. Furthermore, with the successful offshore cost reductions recently seen in Europe and with subsidy-free offshore wind bids (excluding grid connection costs) already received in Germany and the Netherlands, the next round of bids in Europe are predicted to feature much larger "1x MW" turbine platforms with MW capacities exceeding 10 MW and with rotor diameters more than 200 m.

These larger turbines are critical to meet the LCOE targets and as such developers will need to accept "1x MW" platforms with limited operational hours, but likely from suppliers with extensive experience of the design and operation of established smaller platforms. These larger turbines present challenges with design, manufacture, construction and will require significantly larger loads to be resisted during operation. However, WTG OEMs have already developed large offshore wind turbines that are "smarter" using technologies such as advanced control strategies, tower dampers and advanced condition monitoring systems.

6.6 OFFSHORE TURBINE PRICING

Wind turbine pricing is inherently site specific and dependent on a wide variety of costs including materials, manufacturing, transport and profit margin. For the purposes of this study, FOWIND has performed a basic bottom up cost modelling exercise using known information and assumptions about the supply of turbines in both India and Europe. The final price estimates will vary substantially and it is essential to directly engage with turbine suppliers to acquire accurate turbine prices and the costs given here are indicative only.

With regards to onshore wind, local turbine manufacturers in India can supply turbines at a lower cost than their European counterparts. If local turbine suppliers in India diversify further into developing offshore platforms it might be assumed similar cost savings could be achieved. As such based-on experience and research FOWIND has provided indicative turbine supply costs per MW for both European WTG OEM supply and for future localised WTG OEM supply in India.

For the purposes of this feasibility study (see Section 10) overseas supply has been assumed. This is also in line with findings presented in the Supply Chain, Port Infrastructure and Logistics Study [2] where it was anticipated that the first projects in India might utilise overseas turbines.

Predicting future cost trends is extremely difficult and will depend on a number of drivers of price. On the whole though FOWIND believes that prices are significantly more likely to fall per MW, particularly if the global supply picture improves and a number of new entrants begin offering turbines into the market.

7. WINDFARM LAYOUT

7.1 INTRODUCTION

In order to achieve the best possible project return, a project in the Tamil Nadu Region will have to consider a Type R wind turbine with a large rotor to a small generator ratio. Based on the reasons discussed in section 6.4, the FOWIND consortium has only considered wind turbines that have a Rated Rotor Productivity lower than or equal to 0.35 kW/m2 and which fall under the Type R category.

Three generic offshore wind turbines models of 4MW, 6MW, 10MW have been taken forward for further analysis in this report. These models have been developed using DNV GL's Turbine. Architect software, industry trends and input from DNV GL's turbine engineering experience.

7.2 SUB ZONE A3 PRELIMINARY WIND FARM LAYOUT

An offshore wind farm layout using the 6MW and a 154m rotor diameter generic offshore wind turbine with a 504MW project capacity has been developed to represent a base case, as shown in Figure 7-2. A minimum inter-turbine constant spacing of 8 x 7 rotor diameters (D) has been assumed for the proposed layout. This layout would be broadly similar for other project configurations and wind turbine capacities.

It should be noted that the proposed layout is preliminary in nature and should be revised further based on the onsite measured wind resource and detailed grid studies specific to sub zone A3. An elliptical exclusion zone around the turbines was generated using DNV GL's WindFarmer software. The ellipse is defined by three parameters:

- Length of the long axis, in rotor diameters;
- Direction of long axis;
- Minimum separation distance (short axis), in rotor diameters.

During the wind farm layout design (see Figure 7-2), the long axis of the ellipse has been aligned with the assumed prevailing wind direction (see Figure 7-1) in order to minimise both losses due to wake effects and loads on downwind turbines.

FIGURE 7-1: TAMIL NADU ZONE A WIND ROSE Source: [46]

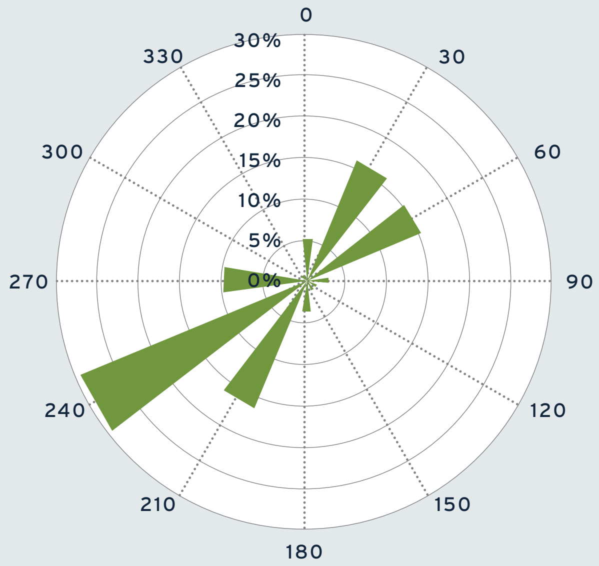


FIGURE 7-2: TAMIL NADU SUB ZONE A3 504MW 6MW OFFSHORE WINDFARM LAYOUT

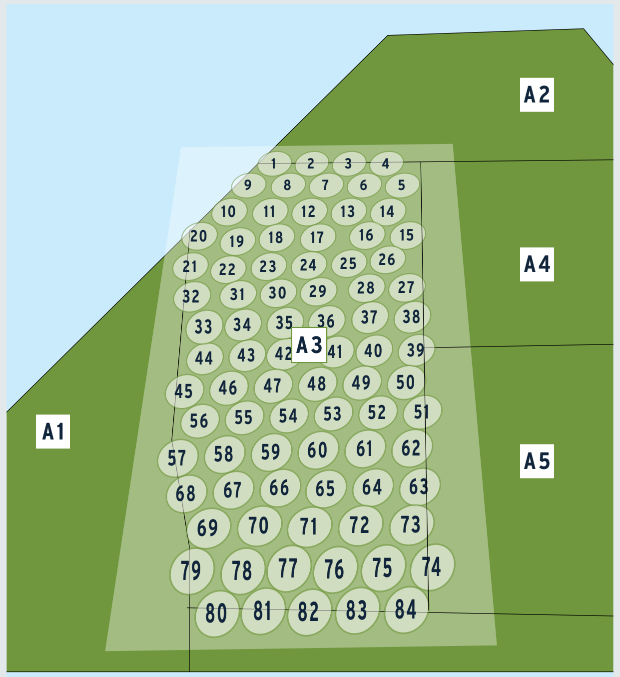
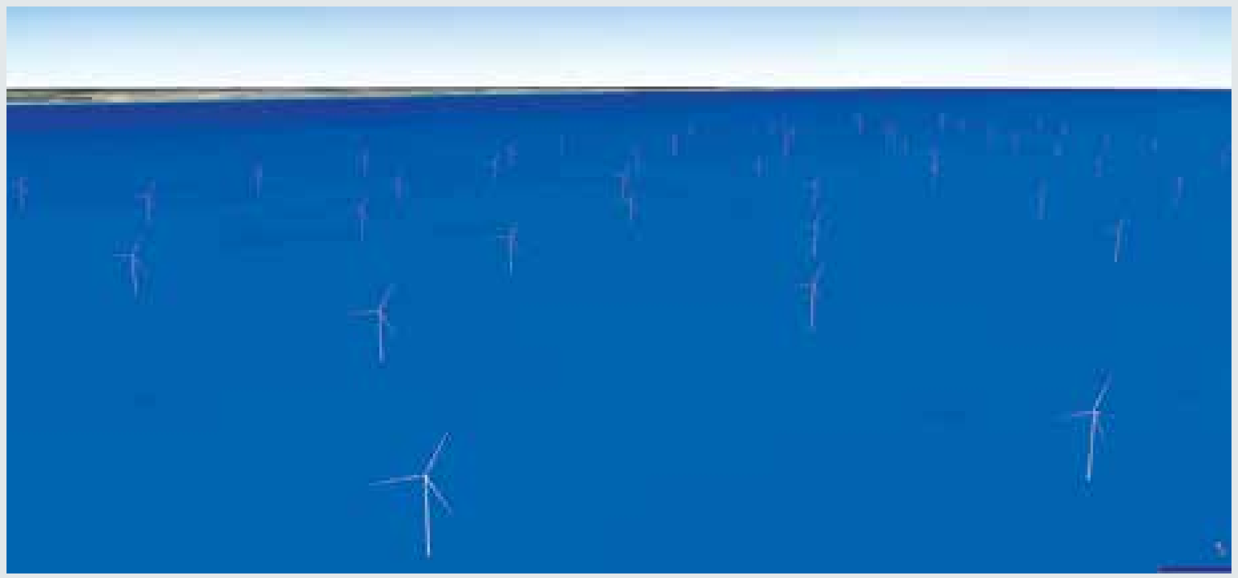


FIGURE 7-3: TAMIL NADU SUB ZONE A3 504MW 6MW OFFSHORE WINDFARM 3D LAYOUT



8. CONCEPT WIND FARM DESIGN

8.1 INTRODUCTION

This section presents concept design studies that have been conducted by the FOWIND consortium to provide key inputs into the overall project costing and LCOE calculations presented in Section 10. The objective is to develop feasible and creditable design solutions that enable initial site-specific annual energy yield and CAPEX cost estimates to be made. In addition to this concept design studies enable the feasibility and optimisation of different project configurations to be tested and key project risks to be identified.

Section 8.2 provides an energy production assessment for the potential demonstration project for different project configurations – including; combinations of 150 & 504 MW approximate wind farm capacities and 4/6/10 MW wind turbine name plate capacities.

Section 8.3 documents an outline electrical design and CAPEX estimates for an onshore substation and array/export cables. It is assumed that the Tamil Nadu offshore wind farm development will not include an offshore substation.

Section 8.4 documents an outline foundation design study and CAPEX estimates for different combinations of wind turbine name plate capacities and foundation types (monopiles, jackets and gravity base). Both the upper and lower bound soil conditions are considered.

8.2 ENERGY PRODUCTION

The FOWIND consortium has conducted a high level energy production assessment for sub-zone A3 in Tamil Nadu. The assessment was undertaken assuming a minimum inter-turbine constant spacing of 8 x 7 rotor diameters (D) for the proposed layout, for both 150 MW and 500 MW approximate wind farm capacities, using the generic 4 MW, 6 MW and 10 MW wind turbines described in Section 7.

The wind climate has been estimated for sub-zone A3 using preliminary modelling from DNV GL's WindFarmer wake model to estimate wake losses. Following this, a number of energy loss factors have been assessed either through estimation or assumption, in order to provide net annual energy production estimates, as described below. Cases where important potential sources of energy loss have been deliberately omitted from consideration have been clearly identified in the following sub-sections. The derived loss factors have been considered as independent energy production efficiencies throughout.

8.2.1 Array efficiency (Internal wake estimates)

In light of operational evidence, there is considerable uncertainty associated with the prediction of wake losses within large offshore wind projects. In addition, there is a wide variety of approaches available to the industry to provide such predictions.

DNV GL's WindFarmer Large Wind Farm Model has been adopted for the determination of wake losses in the Tamil Nadu region, which is built upon an Eddy Viscosity Model. To estimate wake losses in this study, a minimum inter-turbine constant spacing of 8 x 7 rotor diameters (D) has been assumed.

8.2.2 Wind farm availability

This factor represents the expected energy-based average turbine availability over the operational lifetime of the project including the Balance of Plant availability. The Balance of Plant of the wind farm covers the availability of: inter-turbine cables, offshore substations, export cables and the onshore substation infrastructure up to the point of connection to the grid. The availability is defined as the net production after turbine and balance of plant downtime has been taken into account, with respect to the net production assuming all turbines and balance of plant equipment are operating all of the time and is typically quoted as a percentage.

It is noted that the availability estimates are generic in nature. Review of the specific turbine model, O&M arrangements, O&M budgets and warranties are not included within this Pre-feasibility Study. The estimations presented here are subject to amendment as more information becomes available on the O&M provision for a wind farm in the Tamil Nadu Region. For the purposes of this assessment, the DNV GL in-house model "O2M" has been used to estimate the wind turbine availability at the demonstration offshore wind farm location within zone A as detailed in Section 9.2.

8.2.3 Electrical efficiency

There will be electrical losses experienced between the high voltage terminals of each of the wind turbines and the metering point. This factor defines the electrical losses encountered when the project is operational, which will manifest themselves as a reduction in the energy measured by an export meter. This is presented as an overall electrical efficiency and is based on the long-term average expected production pattern of the project. DNV GL has estimated this efficiency.

It should be noted that the electrical losses applied should be considered to the point where the revenue meter will be installed. It is unclear where that location would be, given the early stage in the project development. The choice of metering point will be highly dependent on where responsibilities lie for the provision of the export electrical system. For example, in the German Offshore Market, responsibility is placed on the transmission system operator to provide on offshore connection point to wind farms developed in German Federal waters.

The FOWIND consortium recommends that a formal calculation of the electrical loss should be undertaken when the electrical system has been defined in greater detail.

8.2.4 Wind Farm Performance

The performance of wind farm can be affected by many different factors which include:

- **Blade degradation:** The accretion of dirt or salt, which may be washed off by rain from time to time, as well as physical degradation of the blade surface over prolonged operation.
- **Wind sector management:** Wind sector management is a form of wind farm control in which selected wind turbines are curtailed or shut down under specified wind conditions in order to reduce operational loads experienced by the WTGs and their support structures when high wind speeds coincide with high levels of turbulence. A commonly applied form of wind sector management is "alternate shut down" whereby every alternate machines within a row is shut down when the wind sector management wind speed and direction criteria are met. For example, WTGs 2, 4, 6, 8, etc. may be shut down. No wind sector management scheme is proposed nor, from the layout design, does the FOWIND consortium consider one likely to be necessary. Therefore, no deductions have been made for this potential source of energy loss.
- **Project power consumption:** This factor defines the electrical efficiency due to the electrical consumption of the project during periods of non operation due to transformer no load losses and consumption by electrical equipment within the turbines and substation. For most projects this factor may be neglected and considered as an operational cost rather than an electrical efficiency factor. However, for some metering arrangements it may be appropriate to include this as an electrical efficiency factor.

- **Grid availability:** This factor defines the expected grid availability for the project. It is stressed that this factor relates to the grid being outside the operational parameters defined within the grid connection agreement as well as actual grid downtime. This factor also accounts for delays in the project coming back to full operation following a grid outage. A typical assumption for generic projects in Europe is 99.5 %, however, grid availability in India could have different behaviours and therefore this value should be regarded with caution.

- **High wind hysteresis losses:** Wind turbines will shut down when the wind speed exceeds a certain limit. High wind speed shut down events can cause significant fatigue loading. Therefore, to prevent repeated start up and shut down of the turbine when winds are close to the shutdown threshold, hysteresis is commonly introduced into the turbine control algorithm. Where a detailed description of the wind turbine cut-in and cut-out parameters are available, this is used to estimate the loss of production due to high wind hysteresis by repeating the analysis using a power curve with a reduced cut-out wind speed. Due to the low wind conditions expected at all sites, the FOWIND consortium has assumed these losses to be negligible.

- **Power curve compliance:** Wind turbines will have some sub-optimal efficiencies when considering the power curves provided by the manufacturer. These inefficiencies are due to different factors such as pitch/yaw misalignment, controller performance, etc. For this reason, DNV GL typically assumes a power curve compliance efficiency of 99.5 %.

After consideration of all the factors mentioned above, DNV GL has assumed an overall Wind Farm Performance availability of 98.0% for all different scenarios.

TABLE 8-1: SUMMARY OF ENERGY PRODUCTION ESTIMATES FOR THE TAMIL NADU ZONES BETWEEN 150 MW AND 504 MW WIND FARM

Project scenario	Zone A	Zone A	Zone A	Zone A	Zone A	Zone A	
Turbine model	4.0 MW	6.0 MW	10.0 MW	4.0 MW	6.0 MW	10.0 MW	
Project capacity[5]	152	150	150	504	504	500	MW
Hub height	83	100	118	83	100	118	(m) MSL
Mean Annual Wind Speed	7.76	7.8	7.84	7.76	7.8	7.84	(m/s)
Gross energy output	587.7	656.6	660.9	1948.6	2206.3	2246.9	GWh/annum
Array efficiency[1]	88.4%	91.3%	92.3%	78.4%	82.3%	81.8%	DNV GL estimate
Wind farm availability[2]	91.9%	91.6%	91.6%	92.2%	92.9%	94.1%	DNV GL estimate
Electrical efficiency[3]	97.1%	97.1%	97.1%	97.1%	97.1%	97.1%	DNV GL estimate
Wind farm performance[4]	98.0%	98.0%	98.0%	98.0%	98.0%	98.0%	DNV GL assumption
Net Energy Output	471	508	498	1502	1661	1627	GWh/annum
Project Net Capacity Factor	35.3%	38.1%	37.9%	30.0%	37.6%	37.1%	

Notes:
1 *Internal wake losses*
2 *Includes assumed Balance of Plant (BoP) availability*
3 *Includes array and export cable losses*
4 *Includes sub-optimal efficiencies (power curve compliance, blade degradation, power consumption, grid availability, etc.*

8.2.5 Energy production summary

The projected energy production for each of the proposed project configurations are is summarised in Table 8-1. These results represent an estimate of the annual production expected over the lifetime of the project assumed to be 20 years.

The table includes potential sources of energy loss that have been estimated or assumed.

The methods used to calculate losses, the losses for which assumptions have been necessary and those losses which have not been considered have been discussed in this section. It is recommended that the various loss factors are reviewed and considered carefully.

8.2.6 Energy production estimate uncertainties

The following uncertainties have been identified as important to the analysis of the wind farm layouts undertaken:

- The wind climate predicted by DNV GL in this study is subject to significant uncertainties given the input data and methods employed. In particular, errors in the long-term wind rose will affect layout optimisation, given the uni-directional nature of the wind rose;

- Further to the estimated losses, DNV GL has made several generic or typical assumptions to be able to perform the present analysis; therefore, these values must be taken as indicative and subject to changes according to the final plant configuration;

- The prediction of wake losses for large offshore wind farms is an area of significant uncertainty and although a correction has been applied to the analysis to take account of recent operational evidence, it should be noted that wake models used in this analysis may be updated in the future, in light of new analytical developments or empirical data.

For the purpose of this study, it has been assumed that there are no planned wind farms in the immediate vicinity of any of the identified sites. Given the immaturity of the market it is not considered appropriate to account for reduction in yield due to the presence of other wind farms.

8.3 ELECTRICAL CONCEPT DESIGN

8.3.1 Introduction

This section provides the outcomes of a preliminary investigation into the electrical layouts of the onshore substation and offshore cabling. It also provides indicative costing and sizing for the electrical equipment.

It is assumed that the Tamil Nadu offshore wind farm development will not include an offshore substation. The onshore substation will be the central location for the collection of energy from the Wind Turbine Generators (WTGs) located offshore.

For the purpose of the electrical concept design the following configuration has been considered, 84 WTGs each of 6 MW capacity. The overall installation capacity is therefore calculated as 504 MW. For the remaining project configurations Turbine.Architect has been used to validate and scale the results from this concept design study. 66 kV array cables have been assumed for all turbines 4 MW, 6 MW and 10 MW.

The offshore wind farm location within zone A is assumed at 15 km away from the shore during this electrical study. The wind farm being near to the shore and with 66 kV collection system voltage level, FOWIND estimates the possibility of direct HVAC connection of the offshore wind farm to the onshore substation. This arrangement reduces the overall CAPEX and future operation and maintenance cost. However, towards the detail engineering if the offshore wind farm is finally located more than 20 km from the shore, then the requirement of having an offshore substation should be assessed.

As 220 kV is an operational network voltage in Tamil Nadu, 220 kV is utilised as the operating voltage for the connection to the network at the onshore substation.

Figure 8-1 illustrates the assumed location of the 504 MW Tamil Nadu offshore wind farm development (during this electrical study) and approximate locations (with red crosses) of existing onshore grid substations.

8.3.2 Onshore Substation

DNV GL has prepared a preliminary schematic electrical diagram showing the electrical system for the onshore substation. This is shown in Figure 8-2.

This conceptual design represents a typical solution for an onshore substation based on the use of standard components. Both active power and reactive power requirements should be considered during detailed design so that grid code requirements can be met at the point of connection. Compensation equipment will be required at the different operating voltages to address the capacitive effects of the cabling as well as to satisfy the requirements of the grid code.

The normal running arrangement is with all onshore transformers in service. The following main equipment has been assessed and determined as being suitable for the onshore substation configuration:

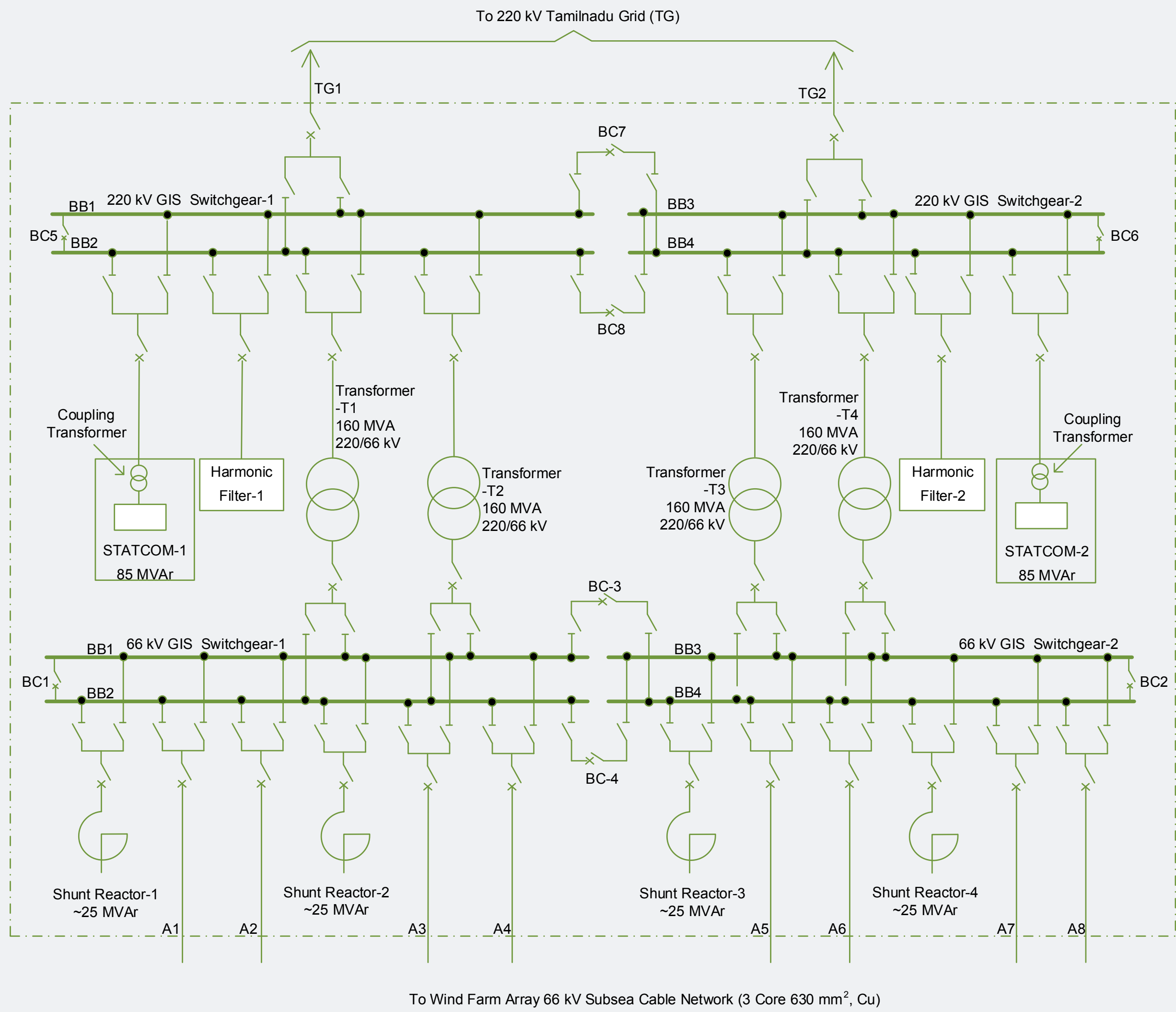
- 4 x 160 MVA Offshore Transformers
- 2 x 90 MVAr Dynamic Reactive Compensation (approximate value)
- 4 x 30 MVAr Shunt Reactors (approximate value)
- 2 x Harmonic Filters
- 8 x feeder circuits operated at 66 kV
- The maximum apparent power and current flow in the transformer connected circuit breakers are calculated as:
- 160 MVA and 0.420 kA on 220 kV winding
- 160 MVA and 1.4 kA on 66 kV winding

Considering the above apparent power values, the transformer connected circuit breakers should be selected with appropriate capacity. The following are recommendations as a preliminary design:

- Circuit breaker with a capacity of 2500 Amps on 66 kV winding
- Circuit breaker with a capacity of 3150 Amps on 220 kV winding

FIGURE 8-1: TAMIL NADU OFFSHORE DEVELOPMENT AND THE ONSHORE NODES (Google Earth)

FIGURE 8-2: OFFSHORE SUBSTATION PRELIMINARY SCHEMATIC



The main components of onshore substation are discussed in the following sub-sections.

8.3.2.1 Main Transformers

DNV GL has assumed the installation of four transformers at the onshore substation. Each one has a rating of 160 MVA which is equivalent to approximately 30% of the total windfarm capacity. The total wind farm apparent power rating being 531 MVA when a power factor of 0.95 is assumed.

The failure of a single transformer will not jeopardise the operation of the whole development. Transformers of this rating are reasonably straightforward in terms of transportation and it is also feasible to store a spare. Consideration of the marine environment should be undertaken due to the placement of the transformers outdoors and within proximity of the coastline. Oil as the primary insulating medium is suggested. Forced-air units are not recommended as the fans mounted on the radiators may be subject to heavy corrosion due to the marine environment and would need to be replaced or maintained in relatively short cycles (e.g. after a few years or less of operation). If one or more fans fail, the transformer rating decreases and would lead to constraint of the associated connected wind farm feeder circuit.

8.3.2.2 GIS Switchgear

DNV GL has considered a GIS double-split-busbar arrangement for the onshore substation. This design arrangement is achieved using disconnecting switches to connect any two busbars via a common circuit breaker. The cost of this system is less prohibitive when compared with other double busbar architectures achieving the same level of redundancy. Advantages of having a double-split-busbar system with disconnectors for the onshore substation include:

- Providing flexibility of operation during inspection and maintenance with little or no, load interruption.
- Load shedding of feeder circuits with different levels of importance during emergency conditions.
- Extension of switchgear can be achieved without prolonged shutdown.

8.3.2.3 Reactive Compensation

Long lengths of array cables can generate reactive power (due to the charging current and impedance in AC systems) which requires compensation to ensure the maximum capacity of the cable is available. To address this issue, DNV GL has considered four shunt reactors each of 30 MVAr (indicative rating) connected to the 66 kV busbars. The requirement for reactive power compensation, the quantity needed and the rating of 66 kV shunt reactors will need to be determined during the more detailed design phases. Furthermore, the need to address the issue of reactive power flows could potentially be addressed through other means, i.e. the wind turbine reactive power capabilities or the utilisation of some dynamic reactive power compensation equipment.

8.3.2.4 Power Quality

The connection of the wind farm to the network may bring about an increase in harmonic emissions or exacerbate network resonance issues. As such, harmonic filtering equipment may be required at the onshore substation to ensure that harmonic emissions remain within acceptable limits and thus maintain the power quality at the point of common coupling.

The requirement should be assessed during the detailed design stages.

8.3.2.5 Dynamic Compensation

Grid code connection conditions are assumed to be applicable at the connection point with the network. It is possible that the wind turbine operational capabilities are sufficient to address grid code compliance issues without additional equipment.

A STATCOM associated with each half of the wind farm is recommended with an indicative dynamic reactive power range of 90 MVAr (Capacitive/ Inductive) to cover an assumed power factor range from 0.95 lagging to 0.95 leading as well as for fault ride-through requirements.

A final network connection study should be carried out to evaluate the specific rating of each STATCOM.

8.3.2.6 Auxiliary Systems

An Auxiliary supply for the onshore substation will be required. Although auxiliary transformer(s) and other auxiliaries are not shown in the schematic diagram, the requirement for their inclusion within the electrical system design should be considered as the electrical design progresses.

8.3.3 Wind farm Array

Figure 8-3 provides an indication as to a possible feeder circuit arrangements, connected directly to the onshore substation.

Each feeder circuit in this concept design can carry a maximum of 66 MW of active power from the wind turbines. As the maximum normal operating current in the wind farm feeder circuit breakers will not exceed 608 Amperes, the 66 kV circuit breakers with a rated capacity of 1250 Amperes are considered appropriate.

The subsea array cables shall be suitable for the following requirements (as appropriate):

- To carry the expected levels of power and therefore the current throughout the following areas:
  - Sea bed burial,
  - J-tube entry,
  - Beach crossing,
  - Connection to the switchgear at the WTG Substation
  - Jointing at the Onshore Transition Pit
- To provide fibre optic communications between the WTG's and Onshore Substations, and
- To withstand the subsea installation process without damage.

FIGURE 8-3: PRELIMINARY ARRAY SCHEMATIC

The subsea array cables are expected to be of a 3-core, copper conductor design. The cables shall contain embedded optical fibres between the cores, which shall be suitable for both data communication and for temperature monitoring of the cable through a temperature monitoring system. The cable burial depths can vary although for array cable networks 1m is usual. The depth being dependent upon the marine vessel activity in the area and the seabed conditions, particularly where sand waves are present.

Interlink cables are optional and can provide redundancy in the case of failure of an array cable. Suitable turbine switchgear and cables should be selected in considering the optimized solution. It is to be noted that the indicative cable sizes in Figure 8-3 have not considered the inclusion of interlink cables as full power carrying conductors. If full power capability were required, this would need to be considered as part of the detailed design and the cable sizes adjusted to accommodate a greater power flow form the increased number of WTG's that would be connected. The 66 kV circuit breakers would still be able to accommodate the required current capacity of the full 21 WTG's being connected.

DNV GL recommends the array cable design optimisation be carried out as part of the detailed design work.

8.3.4 Onshore electrical layout

Figure 8-4 illustrates the physical layout of the onshore substation. All dimensions are shown in millimetres and are indicative.

Space for harmonic filters and incoming/outgoing cables are indicative and can be refined in consideration of the physical directions of the transmission interface point and offshore export circuit routing. The overall dimension of the layout here is 124 x 100 metres.

There are four onshore grid transformers considered in this design, however this requirement should be assessed during the detailed design phase.

Environmental noise emissions should also be assessed as local environmental conditions need to be considered.

The installation is to be compatible with and designed for reliable operation in a coastal/marine environment.

The arrangement of the switchgear bays should be of a clear and logical arrangement and allow adequate accessibility to all external panels and instrumentation. Table 8-2 and Table 8-3 indicate the number of bays for the 220 kV and 66 kV GIS switchgear.

TABLE 8-2: 220 KV BAYS

Equipment	Bays
Main transformer feeders	4
Coupler bays	4
Harmonic filter bays (reserve, if required)	2
Dynamic Reactive Compensation bays (reserve, if required)	2
220 kV grid circuits	2
Spare	1
Total Bays	**15**

FIGURE 8-4: ONSHORE SUBSTATION LAYOUT

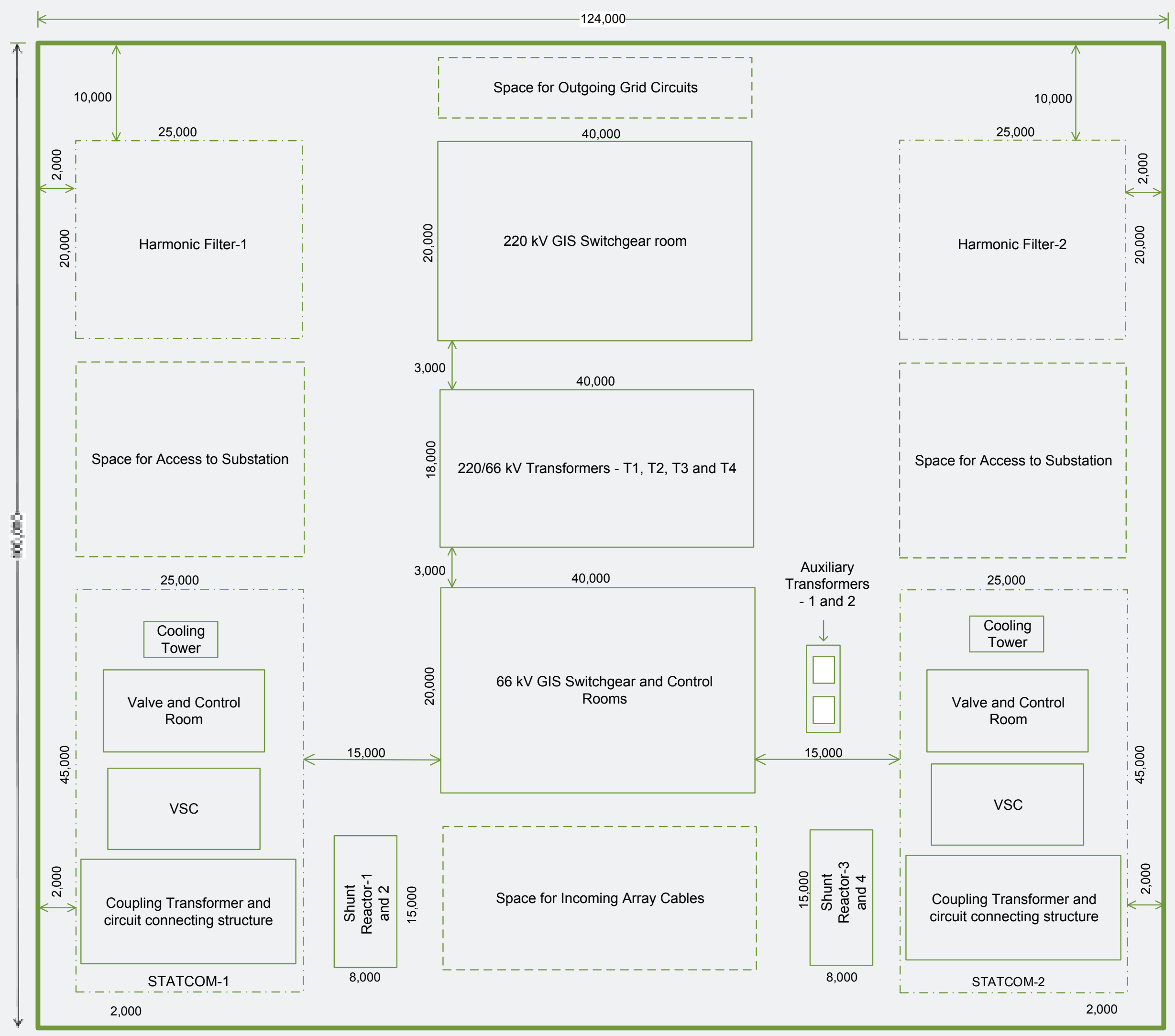


TABLE 8-3: 66 KV BAYS

Equipment	Bays
Array feeders	8
Coupler bays	4
Reactive compensation bays (reserve, if required)	4
Main transformer feeders	4
Auxiliary transformer feeders	2
Spare	2
Total Bays	**24**

8.3.5 CAPEX Cost - Onshore Equipment and Submarine Cables

Table 8-4 and Table 8-5 below illustrate the likely costs for the main onshore equipment including submarine array cables. The cost for the auxiliaries and civil works are not included but should be considered during the detailed design phase. Consideration should be given to the Indian Rupee (INR) exchange rate. The exchange rate of the INR against other currencies can fluctuate (sometime significantly) which is likely to affect the overall cost.

The cost of the harmonic filter will depend on its rating. However indicative costing is provided based on offshore wind farm project experience. This should be updated towards the development of final design.

8.3.6 Conclusion

DNV GL has completed a preliminary costing exercise for the onshore substation that might be constructed for the Tamil Nadu offshore wind farm of 504 MW capacity using 6 MW wind turbines.

DNV GL has considered the case without an offshore substation. The wind farm is located 15 km from the shore and the cabling is brought ashore with an operating voltage of 66 kV. The onshore substation costing exercise has considered all main electrical elements required to transfer power from the offshore wind farm to the local grid in Tamil Nadu.

A summary of the overall equipment cost including submarine cabling is provided in Table 8-6.

The total cost of all the elements stated above is estimated as INR 903 Crore.

This cost includes only the supply cost. It excludes any cost associated with design, management and installation. It also excludes the cost of equipment within the wind turbines. Installation costs are estimated using Turbine.Architect, see Section 9.1.

TABLE 8-4: ONSHORE EQUIPMENT COST

Particulars	Quantity/Bays	Cost (Crore INR)
Main Transformers (160 MVA)	4	68
Double BB 220 GIS Switchgear	15	83
Double BB 66 kV GIS	24	111
220 kV Shunt Reactor (~25 MVAr)	4	22
220 kV STATCOM (~85 MVAr)	2	153
Harmonic Filter	2	51
Auxiliary Transformer	2	1
Total cost -> (Crore INR)		490

TABLE 8-5: ARRAY SUBMARINE CABLE COST

Particulars	Length (km)	Cost (Crore INR)
66 kV- 150 sq.mm (3 Core Cu- Array Cable)	72	78
66 kV- 400 sq.mm (3 Core Cu- Array Cable)	54	84
66 kV- 630 sq.mm (3 Core Cu- Collector Cable)	80	251
Total cost -> (Crore INR)		413

TABLE 8-6: OVERALL EQUIPMENT COST

Particulars	Cost (Crore INR)
Onshore Equipment Cost	490
Array Submarine Cable Cost	413
Total Equipment cost (Crore INR)	903

8.3.7 Electrical CAPEX for Turbine.Architect

The above recommendations for electrical layout have been used as the basis for electrical cost modelling in Turbine.Architect during the Outline Project Costing study. To produce estimates of electrical CAPEX for other wind farm electrical configurations, the cost modelling software has first been calibrated to produce predictions equivalent to those shown in the sections above, and then used to calculate CAPEX predictions for other configurations.

A simple per-MW scale is used to estimate substation cost. Inter-array cable costs are determined through calculations involving number of turbines per array string, maximum power per string, and number of turbines in the wind farm. Export cable costs are scaled as a function of the distance to grid connection.

8.4 PRELIMINARY FOUNDATION COMPARISON

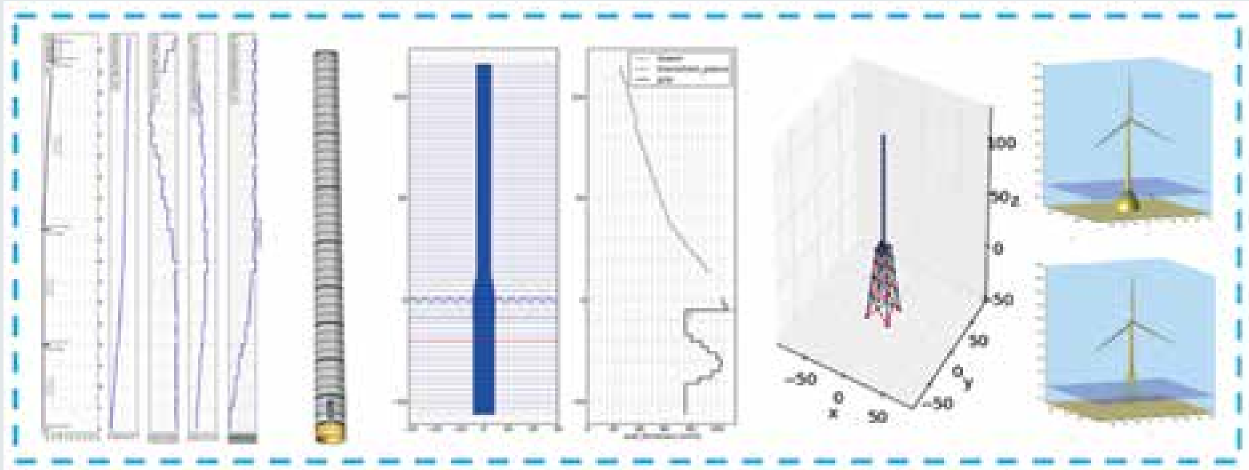
8.4.1 Introduction

Turbine.Architect's foundation module (Figure 8-5) has been used to undertake a foundation comparison. In this comparison monopile, jacket and gravity base (GBS) foundation types have been assessed to determine preliminary estimates of dimensions, masses and costs. Three turbine types have been considered and each combination of foundation and turbine has been assessed using upper and lower bound soil conditions. Monopile, jacket and GBS types have been selected for Tamil Nadu, based on findings from the Pre-feasibility Study [4], Supply Chain, Port Infrastructure and Logistics Study [2] and findings from the site data study (see Section 5). Tripod foundations have not been taken forward as typically costs are prohibitive when comparted with jackets for deeper water.

TABLE 8-7: TURBINE.ARCHITECT ELECTRICAL COSTS

Config Name	Wind Farm Capacity (MW)	WTG Rating (MW)	Interarray Cable Voltage (kV)	Cables Cost Including Installation	Onshore Equipment Cost (Crore INR)	Total Cost (Crore INR)
T1	152	4	66	700	150	850
T2	150	6	66	560	150	710
T3	150	10	66	290	150	440
T4	504	4	66	800	490	1290
T5	504	6	66	650	490	1140
T6	500	10	66	380	490	870

FIGURE 8-5: TURBINE.ARCHITECT'S TOWER AND FOUNDATION MODULE



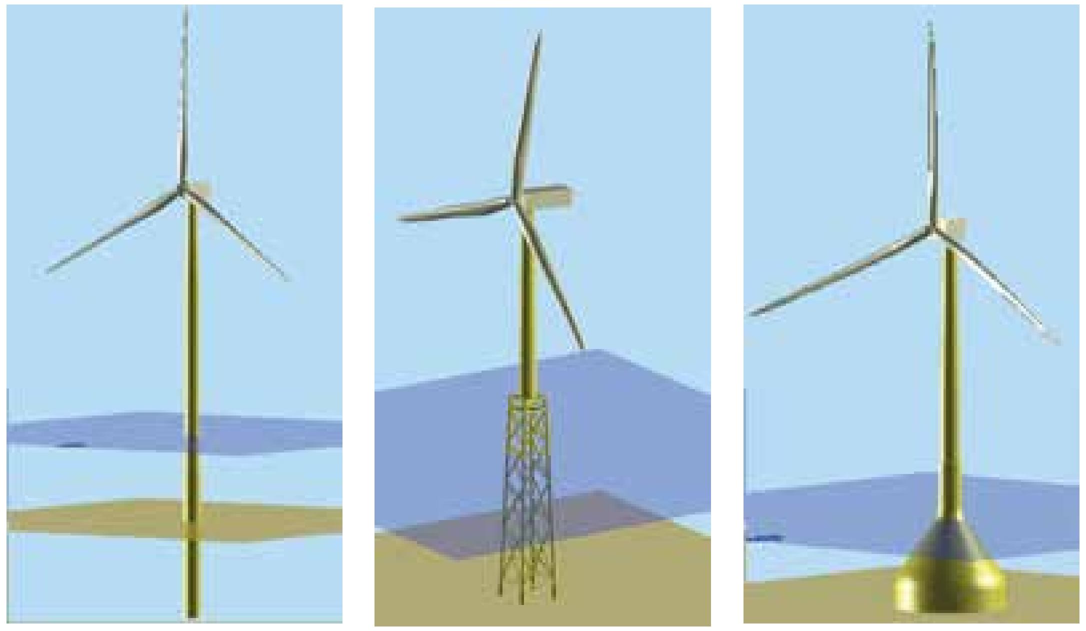
8.4.2 Methodology

The Turbine.Architect foundation module follows preliminary design methodologies to produce bespoke foundation designs considering ground and metocean conditions, turbine properties, and fabrication costs.

For this study jacket, monopile and GBS designs (see visualisation Figure 8-6) have been produced for the optimum sub-zone identified during the spatial analysis study (Section 4.4). The effect of variations in soil conditions have been assessed by considering both lower and upper bound soil profiles.

The broad process for foundation assessment entails assessing candidate foundation designs against design criteria over a range of structure dimensions and selecting the optimum viable foundation as the solution. Optimum in this sense refers to the foundation with the lowest fabrication cost. The design criteria and dimensions considered vary for foundation type and are detailed in Section 8.4.2.1 and 8.4.2.2.

FIGURE 8-6: VISUALISATION OF A GENERIC MONOPILE (LEFT), JACKET (CENTRE) AND GBS (RIGHT), DNV GL BLADED



8.4.2.1 Monopiles

Predictions for monopile designs are produced by assessing a range of monopile diameters to determine:

a) Which monopile diameters lead to viable designs; and
b) Out of those viable designs which is optimum in terms of fabrication cost.

Whether a design is viable or not is determined by checking a series of design criteria. These are:

- Whether it is possible to set the monopile embedment to a level such that the sensitivity of deflection at mudline to changes in the monopile's embedment is minimal under extreme loading (i.e. on the flat part of the embedment vs mudline deflection curve);
- Whether the natural frequency of the support structure and turbine is within the defined natural frequency window of the turbine;
- Whether the instantaneous rotation of the monopile at mudline under extreme loading is below a specified level;
- That can thickness requirements under fatigue loading do not exceed maximum or minimum limits.

The specific values used for these design checks are shown in Table 8-8.

Designs that do not satisfy these criteria are discarded whilst those that do are assessed against each other in terms of fabrication cost. The design with the lowest cost is selected as the optimum and put forward for further consideration.

The monopile designs considered are of a form consisting of an embedded hollow tubular monopile connected to a hollow tubular transition piece which is surmounted by the tower and turbine. The transition piece overlaps the exterior of the monopile and a bond is formed by grout poured into the annulus between them. The transition piece and tower are connected by a bolted flange.

8.4.2.2 Jackets

Predictions for jacket designs are produced by assessing a range of jacket footprint sizes and numbers of bays of bracing – or stories – to determine:

a) Which combinations of jacket footprint sizes and stories lead to viable designs; and
b) Out of those viable designs which is optimum in terms of fabrication cost.

Whether a design is viable or not is determined by checking a series of design criteria. These are:

- Whether it is possible to set the embedment of the jacket's piles to a level such that the maximum vertical load is resisted by the ground;
- Whether the natural frequency of the support structure and turbine is within the natural frequency window of the turbine;
- That can thickness requirements under fatigue loading do not exceed maximum or minimum limits.

Designs that do not satisfy these criteria are discarded whilst those that do are assessed against each other in terms of fabrication cost. The design with the lowest cost is selected as the optimum and put forward for further consideration.

The values used for these design checks are shown in Table 8-9. An overview of the jacket design process is shown in Figure 8-7. Internal loads in the jacket members are determined using the finite beam element method. Frequency is assessed using an eigenfrequency calculation. Approximations are made as to the level of fatigue and extreme loading contributed to member loads and pile vertical loads, respectively.

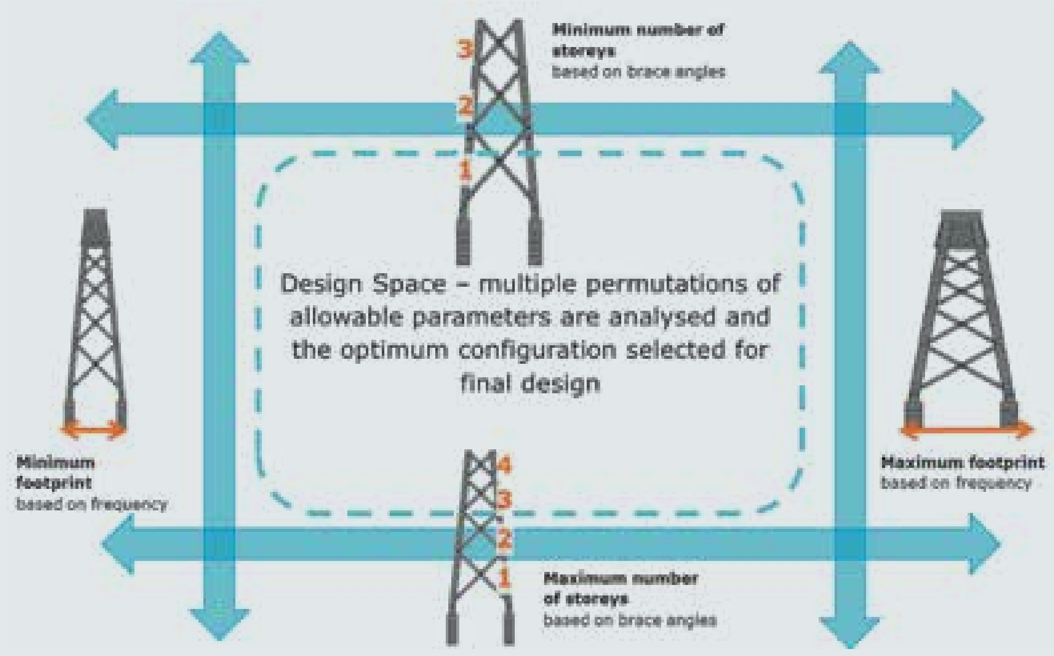
TABLE 8-8: MONOPILE DESIGN CRITERIA

Turbine Rating	4MW	6MW	10MW
Natural frequency window	0.310 to 0.460 Hz	0.242 to 0.316 Hz	0.196 to 0.256 Hz
Maximum can plate thickness	160mm		
Maximum can plate thickness relative to diameter	Diameter / 20		
Minimum can plate thickness relative to diameter	Diameter / 120		
Maximum allowable instantaneous mudline deflection	0.5 degrees		

TABLE 8-9: JACKET DESIGN CRITERIA

Turbine Rating	4MW	6MW	10MW
Natural frequency window	0.310 to 0.460 Hz	0.242 to 0.316 Hz	0.196 to 0.256 Hz
Maximum can plate thickness	160mm		
Maximum can plate thickness relative to diameter	Diameter / 20		
Minimum can plate thickness relative to diameter	Diameter / 120		
Permissible footprint range	14 to 28m		

FIGURE 8-7: JACKET MODEL OVERVIEW



8.4.2.3 Gravity Base Structures

Predictions for gravity base structure (GBS) designs are produced by assessing GBS designs over a range of base diameters to determine:
c) Which diameters lead to viable designs; and
d) Out of those viable designs which is optimum in terms of fabrication cost.

Whether a design is viable or not is determined by checking a series of design criteria. These are:

- Whether the GBS has sufficient resistance against sliding failure under extreme loading;
- Whether the GBS has sufficient resistance against bearing failure under extreme loading;
- Whether the GBS has sufficient resistance against uplift and overturning under extreme loading;
- That it is possible to derive a concrete thickness sufficient to withstand extreme overturning moment.

Designs that do not satisfy these criteria are discarded whilst those that do are assessed against each other in terms of fabrication cost. The design with the lowest cost is selected as the optimum and put forward for further consideration.

The GBS output from the diameter search has sufficient dimensions defined to enable an estimate of mass to be formed. The structural mass is then combined with unit cost rates to produce a cost estimate.

The GBS designs considered are of a form consisting of a solid concrete slab forming the structure's base. This base is surmounted by a hollow frustum shape which transitions into a cylindrical shaft. The shaft rises above water level and is connected by the tower and turbine. Pre-stressing tendons are assumed to be present within the frustum and shaft. The form of the design assumes installation performed by a lift vessel.

Derivation of wave loads and the extrapolation of wind and wave loads down to mudline are undertaken within the program and recalculated for each structure variation assessed. Consideration of soil strength is included in the calculation of the bearing and sliding capacity.

8.4.3 Inputs

8.4.3.1 Site Conditions

Conditions at the Tamil Nadu A3 sub-zone are presented in Table 8-10. See metocean study Section 5.3 for further details.

8.4.3.2 Turbines

Three generic turbines have been modelled and their key parameters are shown in Table 8-11.

8.4.3.3 Financial

The unit costs rates for the fabricated supply of different foundation components have been estimated based on DNV GL's understanding of European fabrication rates for offshore wind structures. Local unit cost rates for India have been estimated by factoring the European rates by utilising DNV GL's experience of fabrication within the local oil and gas industry in India. It should be noted that these rates are indicative only and such rates are subject to significant fluctuations, which depend on factors such as material source, the specific fabricator and current market conditions.

Material costs used during the assessment of support structure cost are the India local rates presented in Table 8-12. As stated in the Supply Chain, Port Infrastructure and Logistics Study [2] it is anticipated that fabrication of support structures is likely to be localised in India.

Jacket and monopile cost rates are based on an understanding of prices typically offered by fabrication companies as part of the tender bidding process. The costs therefore include overheads such as labour, plant, facilities and profit.

The GBS costs are for material only and do not include these factors and therefore a mark-up factor needs to be applied. DNV GL have used a mark-up factor of 1.80 for this study. This value is based on project experience and discussions with GBS manufacturers.

8.4.3.4 Ground Conditions

Soil parameters are used in the definition of support structures and are as presented for lower and upper bound conditions in Table 8-13 and Table 8-14 respectively. See geotechnical study Section 5.4 for further details.

TABLE 8-10: SITE CONDITIONS FOR FOUNDATION COMPARISON

Water depth to LAT	18.07 m
Tidal level HAT	0.8 m
50 year maximum wave height	11.0 m
50 year storm surge elevation	1.4 m

TABLE 8-11: TURBINE PARAMETERS FOR FOUNDATION COMPARISON

Rating	4 MW	6 MW	10 MW
Rotor diameter	120 m	154 m	190 m
Hub height	83 mLAT	100 mLAT	118 mLAT
RNA mass	205 tonnes	365 tonnes	605 tonnes
Drive train configuration	Geared	Direct drive	Geared
Wind speed and turbulence class	1B		
Cut-in wind speed	3 m/s		
Cut-out wind speed	25 m/s		

TABLE 8-12: MATERIAL UNIT COSTS FOR FOUNDATION COMPARISON

	European rates	India rates	Difference
Tower can	136 INR / kg	112 INR / kg	-18%
Tower flange	408 INR / kg	344 INR / kg	-16%
Monopile steel	136 INR / kg	120 INR / kg	-12%
Monopile transition piece steel	280 INR / kg	232 INR / kg	-17%
Jacket steel	288 INR / kg	240 INR / kg	-17%
Jacket piles steel	88 INR / kg	72 INR / kg	-18%
Jacket transition piece steel	320 INR / kg	272 INR / kg	-15%
GBS concrete	250 EUR / m3	200 EUR / m3	-25%
GBS ballast	25 EUR / m3	20 EUR / m3	-25%
GBS reinforcement bars	1.35 EUR / tonne	1.1 EUR / tonne	-23%
GBS pre-stressed tendons	4.0 EUR / tonne	3.5 EUR / tonne	-14%

TABLE 8-13: TAMIL NADU SAND SOIL PROFILE FOR FOUNDATION COMPARISON

Depth from [m]	Depth to [m]	Soil type	Submerged unit weight [kN/m³]	Shear strength from [kPa]	Shear strength to [kPa]	Epsilon 50 [-]	Friction angle [deg]
0.0	3.8	Sand	7.0	-	-	-	20
3.8	10.8	Sand	8.5	-	-	-	25
10.8	21.2	Sand	8.5	-	-	-	20
21.2	To depth	Sand	8.5	-	-	-	25

TABLE 8-14: TAMIL NADU CEMENTED SOIL PROFILE FOR FOUNDATION COMPARISON

Depth from [m]	Depth to [m]	Soil type	Submerged unit weight [kN/m³]	Shear strength from [kPa]	Shear strength to [kPa]	Epsilon 50 [-]	Friction angle [deg]
0.0	To depth	Sand	9.0	-	-	-	45

8.4.4 Results

8.4.4.1 Monopile

Results for monopile support structures are presented in Table 8-15, Table 8-16 and Table 8-17.

TABLE 8-14: MONOPILE RESULTS 4MW TURBINE

Soil Profile Type	Lower Bound	Upper Bound
Transition piece top diameter (m)	4.8	4.8
Transition piece base diameter (m)	4.8	4.8
Monopile top diameter (m)	4.4	4.4
Monopile base diameter (m)	5.5	5.7
Monopile embedded length (m)	41	26
Monopile total length (m)	61	46
Support structure and turbine natural frequency (Hz)	0.28	0.30
Monopile primary steel mass (te)	471	364
Transition piece primary steel mass (te)	134	134
Total support structure mass (te)	605	498
Transition piece cost (kINR)	56,490	43,700
Monopile cost (kINR)	31,050	31,050
Total support structure cost (kINR)	87,540	74,750

TABLE 8-15: MONOPILE RESULTS 6MW TURBINE

Soil Profile Type	Lower Bound	Upper Bound
Transition piece top diameter (m)	6.6	6.6
Transition piece base diameter (m)	6.6	6.6
Monopile top diameter (m)	6.2	6.2
Monopile base diameter (m)	6.6	6.7
Monopile embedded length (m)	47	30
Monopile total length (m)	67	50
Support structure and turbine natural frequency (Hz)	0.26	0.28
Monopile primary steel mass (te)	715	542
Transition piece primary steel mass (te)	203	203
Total support structure mass (te)	919	745
Transition piece cost (kINR)	85,860	65,070
Monopile cost (kINR)	47,150	47,150
Total support structure cost (kINR)	133,000	112,220

TABLE 8-16: MONOPILE RESULTS 10MW TURBINE

Soil Profile Type	Lower Bound	Upper Bound
Transition piece top diameter (m)	8.7	8.7
Transition piece base diameter (m)	8.7	8.7
Monopile top diameter (m)	8.3	8.3
Monopile base diameter (m)	8.7	8.7
Monopile embedded length (m)	55	34
Monopile total length (m)	76	55
Support structure and turbine natural frequency (Hz)	0.26	0.27
Monopile primary steel mass (te)	1,200	853
Transition piece primary steel mass (te)	330	330
Total support structure mass (te)	1,530	1,183
Transition piece cost (kINR)	144,010	102,320
Monopile cost (kINR)	76,550	76,550
Total support structure cost (kINR)	220,560	178,870

8.4.4.2 Jacket

Results for jacket support structures are presented in Table 8-18, Table 8-19 and Table 8-20.

TABLE 8-17: JACKET RESULTS 4MW TURBINE

Soil Profile Type	Lower Bound	Upper Bound
Jacket footprint side length (m)	18	18
Number of bracing bays	3	3
Leg diameter (m)	1.2	1.2
Brace diameters (top to bottom) (m)	0.7	0.7
	0.5	0.6
	0.7	0.7
Pile diameter (m)	1.2	1.2
Pile length (m)	50	26
Support structure and turbine natural frequency[6] (Hz)	0.46 (outside frequency window)	0.46 (outside frequency window)
Jacket primary steel mass (te)	248	248
Transition piece primary steel mass (te)	116	117
Piles mass (te)	118	62
Total support structure mass (te)	482	426
Jacket cost (kINR)	59,520	59,440
Transition piece cost (kINR)	31,640	31,690
Piles cost (kINR)	8,480	4,430
Total support structure cost (kINR)	99,640	95,560

(outside frequency window)

6. Assumes rigid ground connection.

TABLE 8-19: JACKET RESULTS 6MW TURBINE

Soil Profile Type	Lower Bound	Upper Bound
Jacket footprint side length (m)	19	18
Number of bracing bays	3	3
Leg diameter (m)	1.6	1.6
Brace diameters (top to bottom) (m)	0.9	0.9
	0.7	0.7
	0.8	0.8
Pile diameter (m)	1.6	1.6
Pile length (m)	54	29
Support structure and turbine natural frequency (Hz)	0.38 (outside frequency window)	0.38 (outside frequency window)
Jacket primary steel mass (te)	400	398
Transition piece primary steel mass (te)	158	158
Piles mass (te)	231	123
Total support structure mass (te)	788	678
Jacket cost (kINR)	95,920	95,490
Transition piece cost (kINR)	42,880	43,010
Piles cost (kINR)	16,640	8,820
Total support structure cost (kINR)	155,440	147,320

TABLE 8-20: JACKET RESULTS 10MW TURBINE

Soil Profile Type	Lower Bound	Upper Bound
Jacket footprint side length (m)	22	20
Number of bracing bays	3	3
Leg diameter (m)	2.2	2.2
Brace diameters (top to bottom) (m)	1.2	1.2
	0.9	0.9
	1.1	1.1
Pile diameter (m)	2.2	2.2
Pile length (m)	53	31
Support structure and turbine natural frequency[8] (Hz)	0.33 (outside frequency window)	0.33 (outside frequency window)
Jacket primary steel mass (te)	687	678
Transition piece primary steel mass (te)	191	193
Piles mass (te)	422	248
Total support structure mass (te)	1,300	1,119
Jacket cost (mINR)	164,810	162,710
Transition piece cost (mINR)	52,080	52,530
Piles cost (mINR)	30,400	17,850
Total support structure cost (mINR)	247,280	233,090

7 & 8. Assumes rigid ground connection.

8.4.4.3 Gravity Base Structure

Results for gravity base structures are presented in Table 8-21. Gravity base results are only provided for the cemented soil profile because it was found it was infeasible to produce structures that passed design checks for the weaker sand soil profile.

8.4.5 Comparison

A comparison of the jacket and monopile support structure predictions is presented in terms of mass as Figure 8-8 and Figure 8-9. A comparison in terms of fabrication cost is presented as Figure 8-10.

TABLE 8-21: GBS RESULTS

Turbine Rating	4MW	6MW	10MW
Soil Profile Type		Cemented	
Base diameter (m)	28.2	32.0	36.3
Shaft diameter (m)	4.8	6.6	8.7
Concrete thickness (m)	0.5	0.6	0.7
Concrete mass (te)	2,921	4,002	5,437
Ballast mass (te)	5,988	8,629	12,427
Total on seabed mass (te)	9,204	13,034	18,410
Concrete cost (kINR)	18,700	25,620	34,800
Ballast cost (kINR)	4,270	6,160	8,870
Total cost (kINR)	55,190	75,680	103,080

FIGURE 8-8: JACKET AND MONOPILE MASS COMPARISON

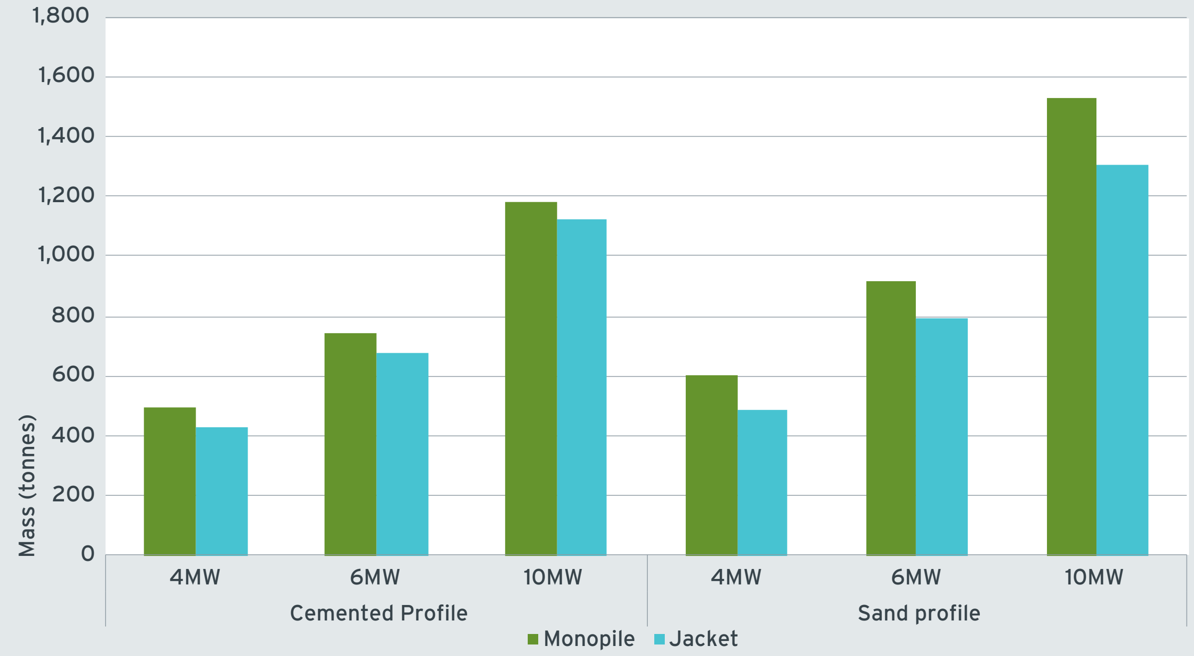


FIGURE 8-9: GBS ON SEABED MASS

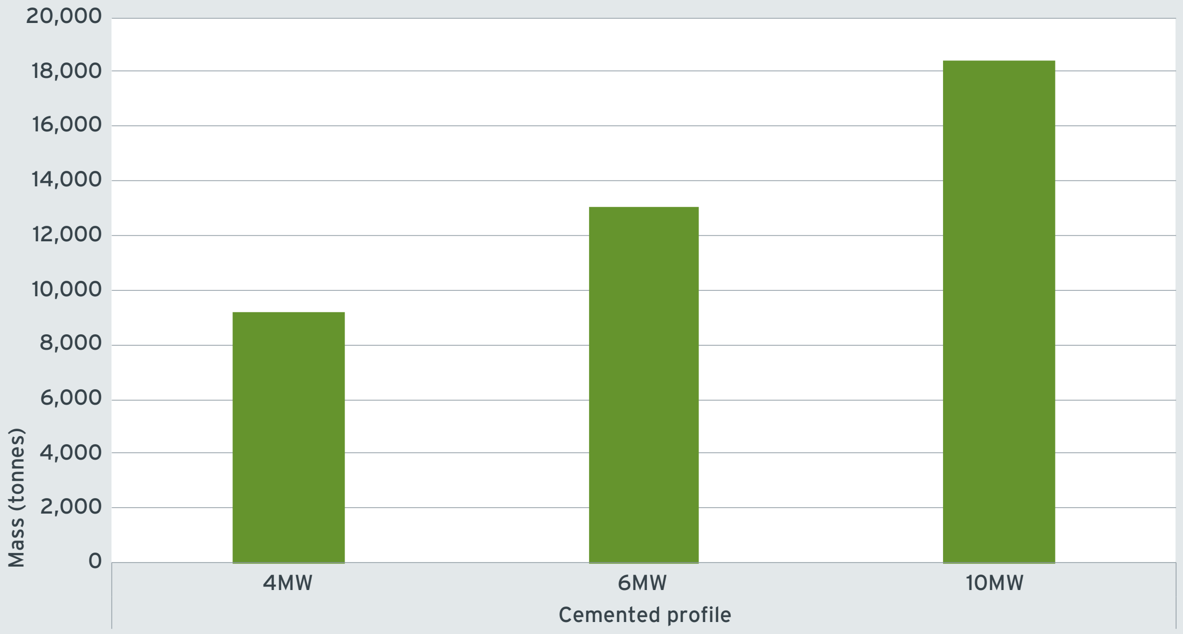
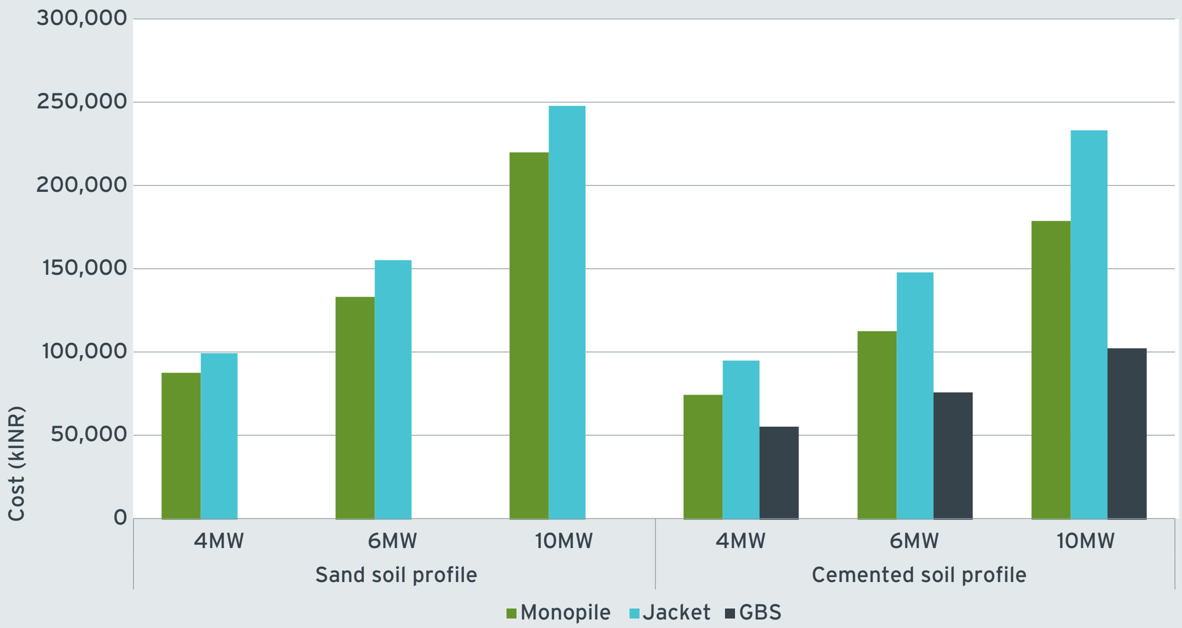
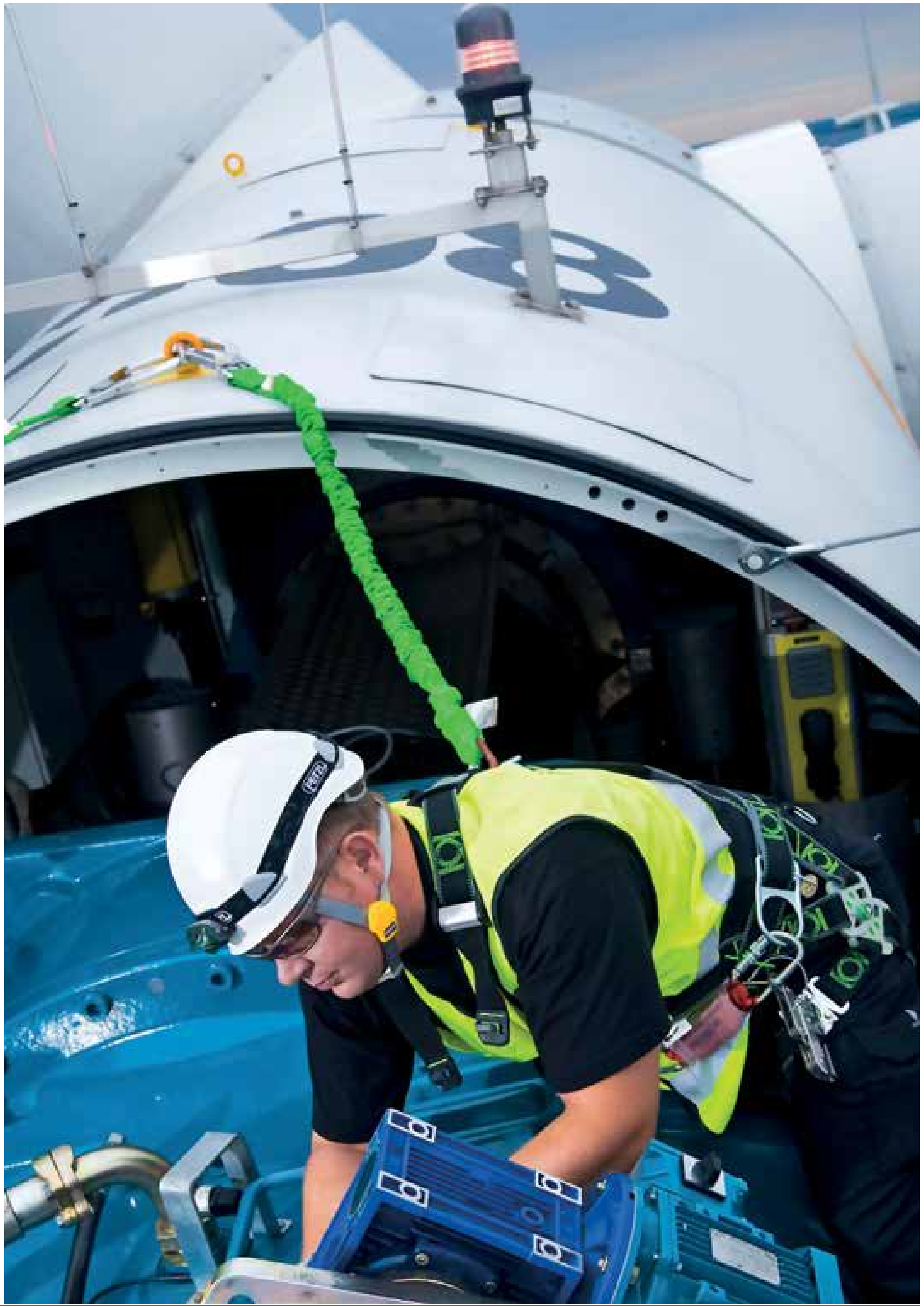


FIGURE 8-10: SUPPORT STRUCTURE COST COMPARISON





8.4.6 Conclusions

Preliminary assessments of jacket, monopile and gravity base support structures have been completed for the A3 sub-zone selected during the Spatial Analysis (Section 4.4).

Results show jackets as being lighter than monopiles for all turbine sizes and soil conditions at the A3 sub-zone. In terms of cost the results show monopiles as being more economical for both ground conditions modelled.

GBS results are shown only for the stronger, cemented soil profile because it was found the weaker soil profiles were not suitable for gravity base structures of the structural form considered. For the soil profile where gravity base structures are suitable they are shown to have significant economic advantages over jackets and monopiles.

Assessments of the natural frequency of the structures show jackets exhibiting frequencies above the turbine's permissible frequency window for all turbine sizes. This is especially true of the 4MW turbine where the shallow water depth, comparatively light RNA, and stiff support structure results in a very high frequency.

It should be noted that the assessment of natural frequency for jackets considers them to be rigidly fixed to the seabed whereas there will be some level of flexibility at the connection in reality. This flexibility is due to the fact the soil has low lateral resistance near seabed. This will lower the natural frequency but it is not expected to bring it to within acceptable limits.

For the purposes of this study, constraints on natural frequency for jackets have been disregarded. In practice this removes constraints on jacket footprint size because footprint size is the jacket variable with the most effect on frequency. Justification for removing constraints on natural frequency are that in practice offshore wind projects commonly make the decision to allow modifications to the turbine's control system which mitigate against the detrimental effects of high frequencies (i.e. resonant excitation of the support structure by the turbine). Mitigative actions may include wind speed "exclusion zones" or an increase to the wind turbine's cut-in speed, both options involve causing the turbine to avoid operating at rotor frequencies which clash with the support structure's natural frequency. Compared with typical north European pile embedment, the predicted embedment depth for monopiles and jackets in Tamil Nadu are not overly onerous. If very hard, cemented or rocky soil conditions are encountered then there is risk that alternative installation methods to pile driving will be required. In these scenarios piles can be installed with the assistance of drilling equipment, either to drill a cavity in rock into which the pile is then grouted, or drilling during a pause in pile driving to remove hard ground beneath the pile tip before pile driving resumes. Both of these options are time consuming, costly and present risks to installation.

Gravity base structures are shown as a highly competitive solution but only when the soil conditions are suitable. Their attractiveness is a result of the relatively cheap cost of materials in comparison to steel. The variation in soil conditions over sub-zone A3 is not known and therefore, it is not clear how applicable gravity base structures are. It is expected that cemented soils, or very dense surface sands, will not be found to extend over a large proportion of sub-zone A3. Installation of the gravity base structures needs careful consideration. The form of the GBS considered for this study is assuming lifted installation. Results suggest it should be possible to design both lifted and floated GBSs (soil conditions dependent), however lifted GBS require crane-vessels capable of lifting weights of at least 6000 tonnes, depending on the WTG being used. The form, mass and cost of a GBS capable of being towed to site and sunk into position will vary, however the variation is not expected to impact the conclusions reached in this study. Of greatest importance is the variation in ground conditions at Tamil Nadu sub-zone A3.

The foundation studies completed thus far should be treated as preliminary only. The level of detail is applicable for preliminary costing studies and CAPEX estimates cost modelling. More detailed design exercises should be completed before forming firm conclusions regarding foundations. A detailed understanding of the local ground conditions in terms of its geospatial variation should be obtained as this will lead to a better understanding of the applicability of gravity base foundations. Consideration of the interaction between the dynamics of the wind turbine and wave loading have not been considered in detail during this exercise. This may have an impact on the cost of support structures, depending on the strength of the interaction.

9. FURTHER TECHNICAL STUDIES

9.1 INSTALLATION AND LOGISTICS

The FOWIND consortium provided a high-level overview for key installation considerations and methodologies for optimisation as part of the Supply Chain, Port Infrastructure and Logistics Study [2] Section 3.2 and the Pre-feasibility Study [4] Section 6.3. The key areas of focus for installation studies are offshore wind port types, vessels and strategy planning.

Besides the main wind farm infrastructure, the port is one of the most important components in offshore wind construction. The key parameters for selection include; distance to shore, maximum vessel dimensions, storage areas and inter-connections.

The characteristics of available ports and vessels are critical for defining and optimising offshore wind installation strategies and logistical operations. The Supply Chain, Port Infrastructure and Logistics Study [2] detailed the port infrastructure and logistics required from manufacturing (i.e. wind turbines and foundations) to installation and the subsequent operation and maintenance (O&M) phase of an offshore wind farm.

In the FOWIND Supply Chain, Port Infrastructure and Logistics Study [2] Section 3.9.2.3 a total of three major and 22 minor ports have been identified in the Tamil Nadu region. Out of the total 22 in the Tamil Nadu region, a selection of ports were initially screened and considered potentially suitable for construction activities. Three ports have been identified with some potential, namely:

- **Kattapalli** - the deep water port of Ennore is provided with a dedicated terminal for handling coal, general and liquid cargo and a vast hinterland. Closest development zone is H, which is approximately 310 km;
- **Chennai** - the deep water port of Chennai is provided with a dedicated terminal for oil, iron ore and general cargo and 24 hour 7 day operations, and a passenger terminal. Closest development zone is H, which is approximately 290 km;
- **Tuticorin** - the port of Tuticorin is provided with an oil & coal handling jetty and 24 hour 7 day operations, general, break-bulk, container and bulk cargo handling facilities, dry and liquid cargo storage facilities and a passenger terminal. Closest development zone is A, which is approximately 20 km.

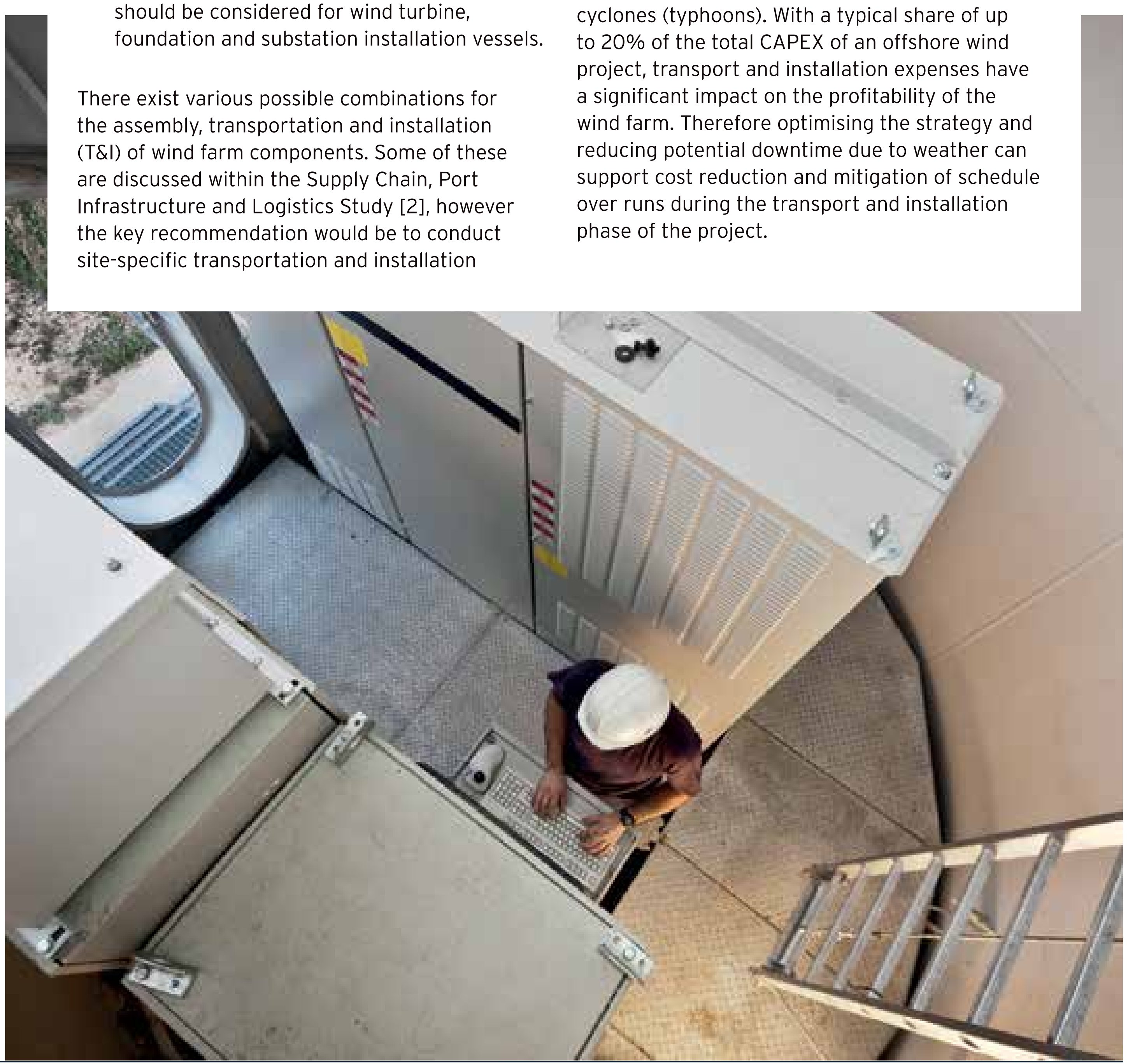
Construction of offshore wind power project requires specialised vessels. In regions where the industry is well developed vessels built specifically for offshore wind requirements are now common, however in newly developing regions such as India it is anticipated that utilisation and modification of vessels from adjacent sectors will be required until a sufficient supply chain develops. Up to 11 different types of vessels can be required during the offshore wind farm project life (typically 20 years) and some of the major types have been discussed in Supply Chain, Port Infrastructure and Logistics Study [2] section 3.6.

The key parameters for vessel selection can be summarised as follows; metocean conditions, soil conditions, component size and distance from shore. India has a total of over 700 offshore vessels with a total gross tonnage of over 800,000, however most of these are related to the oil and gas industry and are not optimised for offshore wind. This will likely leave India with three main vessel supply options:

- Modifications of the existing oil and gas, fishing or civil engineering vessels specific to the requirements for both construction and operation and maintenance phases of offshore wind projects. This option should be considered at least for offshore support vessels and work boats.
- Design of specialised vessels for offshore wind project installation. The development of specialised vessels is largely dependent on the scale of deployment of offshore wind in India.
- Using the services of the existing European or Asian offshore wind vessels may be a favourable short term solution. This option should be considered for wind turbine, foundation and substation installation vessels.

There exist various possible combinations for the assembly, transportation and installation (T&I) of wind farm components. Some of these are discussed within the Supply Chain, Port Infrastructure and Logistics Study [2], however the key recommendation would be to conduct site-specific transportation and installation planning during the early project development stages, before critical design decisions are made. The transport and installation strategy should be optimised for the specific conditions of each individual project site. Careful consideration of the metocean conditions, transit distances and vessel characteristics is necessary.

Considering Tamil Nadu's climatic conditions, the summers are extremely hot and dry, while the monsoons are quite strong and can cause severe floods. Therefore it is important to consider an adequate amount of weather downtime within the overall transport and installation schedule. Furthermore, schedule planning should consider monthly weather fluctuations during the year, like cyclones (typhoons). With a typical share of up to 20% of the total CAPEX of an offshore wind project, transport and installation expenses have a significant impact on the profitability of the wind farm. Therefore optimising the strategy and reducing potential downtime due to weather can support cost reduction and mitigation of schedule over runs during the transport and installation phase of the project.



The CAPEX for installation and logistics is calculated using Turbine.Architect's installation module which estimates the costs for the installation of turbines, foundations and electrical substations. Turbine and foundation installation strategies depend on the turbine size, the selected foundation type, the depth and the selected metocean climate, the installation module finds the appropriate vessel and installation durations from pre-processed installation data. The installation data is a database of simulation results from DNV GL's O2C tool for different scenarios. For electrical substations, the lifts are more problematic and may require a Heavy Lift vessel and as such day rates are very elastic, ranging by a factor of ten depending on market conditions. This results in a greater uncertainty for offshore substation CAPEX. See Table 9-1 for the estimated installation and logistics CAPEX for the different combinations of project capacity and turbine MW for Tamil Nadu's sub-zone A3. These results are for monopile foundations which were selected in Section 8.4. Table 9-2 presents the same information but for turbine installation.

Installation CAPEX per location is seen to decrease as wind farm increases. This effect is due to fixed costs, i.e. mobilisation costs, being spread over a larger number of locations. It's possible this effect would be lessened by the installation period extending over seasons where weather is less suitable for installation, which is more likely to take place with larger numbers of turbines. The effect of installation seasonal effects on installation durations has not been considered in the course of this study.

9.2 OPERATION AND MAINTENANCE STUDY

As the name suggests Operations and Maintenance activities can be divided into two main tasks:

1. Monitoring, controlling and coordinating the wind farm operations; and
2. Maintenance activities of the turbines and the balance of plant (BoP), which are typically sub-categorised into; scheduled and unscheduled maintenance.

TABLE 9-1: FOUNDATION INSTALLATION CAPEX

Config Name	Wind Farm Capacity (MW)	WTG Rating (MW)	Total installation CAPEX (mINR)	Installation CAPEX per location (mINR)
T1	152	4	2,100	55.3
T2	150	6	1,350	54.1
T3	150	10	1,190	79.5
T4	504	4	6,380	50.6
T5	504	6	3,910	46.6
T6	500	10	3,180	63.7

TABLE 9-2: TURBINE INSTALLATION CAPEX

Config Name	Wind Farm Capacity (MW)	WTG Rating (MW)	Total installation CAPEX (mINR)	Installation CAPEX per location (mINR)
T1	152	4	1,870	49.2
T2	150	6	1,250	49.9
T3	150	10	790	52.9
T4	504	4	5,770	45.8
T5	504	6	3,760	44.7
T6	500	10	2,220	44.3

TABLE 9-3: OPEX AND AVAILABILITY ESTIMATES FOR TAMIL NADU ZONE A3

Config. no.	Project configurations	OPEX (mINR per annum)	Wind farm availability (%)
T1	150 MW wind farm (generic 4 MW turbine)	1,419	94.3
T2	150 MW wind farm (generic 6 MW turbine)	1,201	94.3
T3	150 MW wind farm (generic 10 MW turbine)	1,041	94.3
T4	504 MW wind farm (generic 4 MW turbine)	4,643	93.8
T5	504 MW wind farm (generic 6 MW turbine)	4,036	94.0
T6	504 MW wind farm (generic 10 MW turbine)	3,521	94.0

The access logistics associated with these maintenance activities, are one of the most significant operational challenges facing the offshore wind energy market. Access strategies can be categorised into three main types; onshore-based marine access, helicopter access and offshore-based marine access. Onshore-based marine access (e.g. workboats) is the most common approach to date, however is heavily restricted by the sea-state during transfer onto the structures. This section presents a preliminary investigation into suitable O&M strategies for Tamil Nadu and estimates for OPEX (Operational Expenditure). Common access vessels were introduced and minimum typical requirements for O&M ports are discussed in the Supply Chain, Port Infrastructure and Logistics Study [2] Section 3.9.5. The top 3 O&M ports considered suitable for zone A have been identified, namely; Punnakayal, Koodankulam and Valinokkam which are 13.5 NM, 13.5 NM 16.2 NM away respectively.

In order to select the most suitable O&M Strategy DNV GL has used its in-house model: "O2M Optimisation of Operations and Maintenance" to simulate a variety of O&M strategies at sub zone A3 for each of the project capacity and wind turbine capacities. The assumed long term annual mean significant wave height at zone A is 1.24 m (Section 5.3.3) and the nearest port Punnakaya (13.5 NM away from zone A3) has been used in the O2M analysis. It has been noted that the use of helicopters or motherships is not envisaged to prove optimal for most scenarios. The inclusion of helicopter operations to support wind farms can be of significant relevance for a large number of turbines but will prove suboptimal for the rest of the configurations with a lower number of turbines (25, 38 and 84). However, due to the significant logistical and regulatory complexity added to a project and related to helicopter operations, it has been deemed appropriate to rule out these strategies and assume that all first offshore wind projects in India will be based on the most proven work boats access methodologies. Considering only workboat access methods preliminary estimates for OPEX and availability have been presented for each identified project configuration in sub-zone A3, farm capacities (150 to 504 MW) and generic turbine MW classes (4,6 & 10 MW).

The results of the analyses, considering only work boats operations, are presented in Table 9-3 for these project configurations under consideration.

10. OUTLINE PROJECT COSTING

10.1 INTRODUCTION

An outline project costing exercise has been completed and this section presents the results and provides high-level Levelised Cost of Energy (LCOE) estimates for the various project configurations in the selected Tamil Nadu sub-zone A3. A discussion on the cost modelling approach and assumptions is provided in Section 10.2 and Section 10.4 presents a breakdown of the cost modelling results and a summary of overall LCOE.

The LCOE can be defined as the "net present value of the unit-cost of electricity over the lifetime of a generating asset". It is used to consistently compare different power generation sources and in this context, is an economic assessment of the average cost to construct and operate an offshore wind farm over its lifetime divided by the total energy output generated over its life. It considers capital expenditure (CAPEX), operational expenditure (OPEX), annual energy production (AEP) and financial discount rates. It could also be defined as the minimum average cost that electricity must be sold at (including subsidies) in-order for the project to "break-even" over its lifetime.

10.2 METHODOLOGY AND KEY ASSUMPTIONS

DNV GL's Turbine.Architect [7] has been used for the cost modelling calculations. Turbine.Architect is an automated cost modelling tool that executes engineering calculations to derive the physical properties (e.g. section properties, masses and costs) of the sub-components of a wind turbine, its support structure and other components of a wind farm. These engineering outputs are combined with financial calculations and an economic model to calculate an overall LCOE.

The inputs into Turbine.Architect include parameters describing environmental conditions, material properties, layout of the turbine, foundation type, as well as cost data and general information about the wind farm.

The following key assumptions and caveats have been made and must be taken into account when viewing the results:

- The modelling calculates an average LCOE for the selected sub-zone based on the parameters of each modelled location i.e. assuming that the complete project exhibits the same water depth, metocean conditions and wind climate as that defined at the reference point. The LCOE results can be considered applicable for a wind farm situated in the sub-zone only if there is no variation in parameters between the reference point and throughout the wind farm area.
- The optimised LCOE is representative and should not be considered to necessarily represent the actual Cost of Energy of a realised project. For example, effective development and front end engineering studies can yield a significant reduction in cost of energy when compared to the generalised modelling undertaken here.
- Site climate conditions, such as wave characteristics, used in the modelling are based on publicly available information and DNV GL's preliminary metocean study.

10.2.1 Financial Modelling

This section provides a general overview of the financial modelling methodology, used within DNV GL for engineering purposes. For this study Turbine.Architect has been used to calculate the relative financial attractiveness of wind farm project configurations in terms of LCOE.

The calculation of this parameters is achieved by linking several engineering and financial models, as illustrated in Figure 10-1.

LCOE

Levelised cost of energy (LCOE) is a much-used number in wind energy analysis, and is calculated in Turbine.Architect based on the methodology used in Section 10.4 as:

$$LCOE = \frac{\sum [(CAPEX_t + OPEX_t + D_t) * (1+r)^{-t}]}{\sum AEP * (1+r)^{-t}}$$

where:

- $CAPEX_t$ = total capital construction costs in year t;
- $OPEX_t$ = operation and maintenance costs in year t;
- D_t = decommissioning costs in year t;
- AEP = annual electricity production by the farm $(MWh/annum)$;
- $(1+r)^{-t}$ = discount factor for year t.

It is assumed that the discount rate r is stable during the project lifetime. DNV GL has assumed a 10% discount rate based on OECD's guideline that a 10% discount rate "[corresponds] approximately to the market rate in deregulated or restructured markets" [47].

CAPEX

Total wind farm CAPEX is defined as the sum of turbine CAPEX multiplied by the number of turbines, plus the Balance of Plant CAPEX.

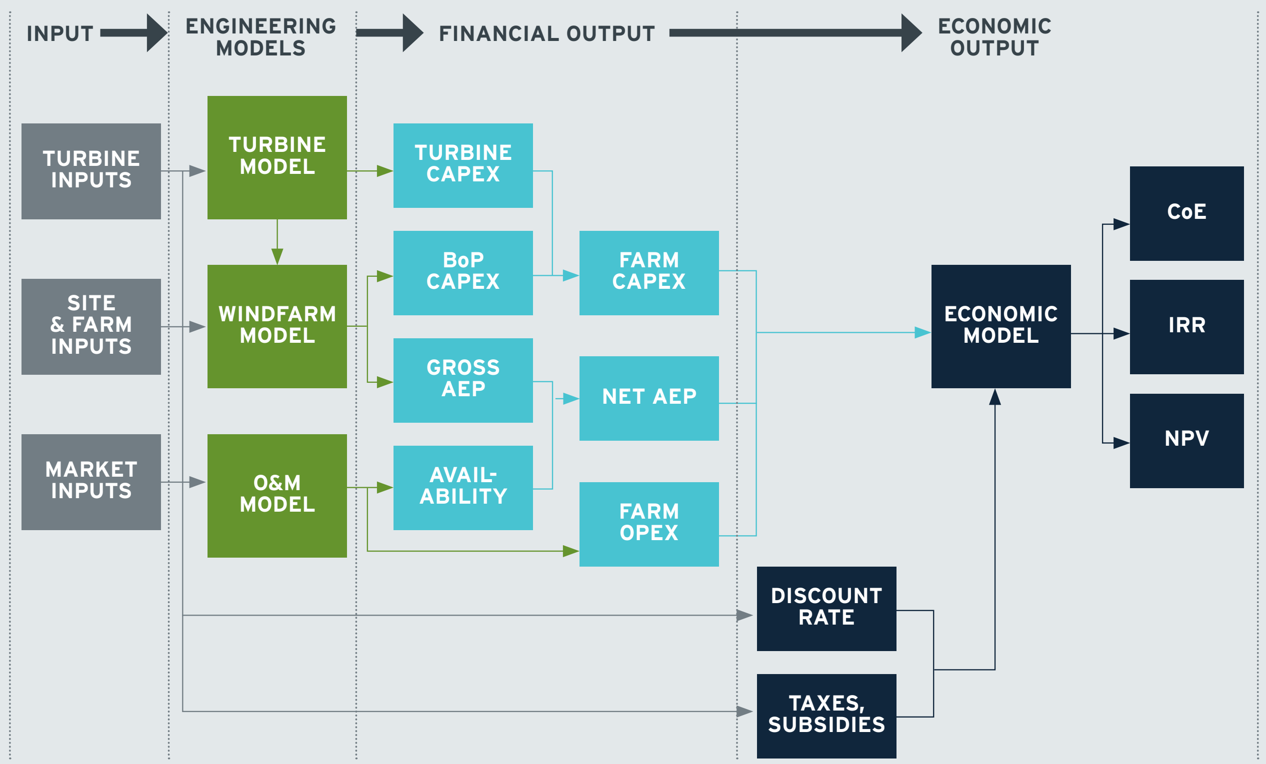
Turbine CAPEX is calculated by the tool via a bottom-up approach, combining component sizing calculations and material unit costs.

Balance of Plant CAPEX includes the following elements:

- Turbine support structures, as described above;
- Electrical infrastructure:
  - Array cabling;
  - Export cabling;
  - Offshore substation;
- Installation of all components;
- Project costs.

9. Decommissioning costs have not been included in the modelling; however, as these costs are incurred at the very end of the project life, their net present value is very small and their impact on LCOE is typically less than 1%.

FIGURE 10-1: TURBINE.ARCHITECT PROCESS



10.3 TURBINE.ARCHITECT INPUT PARAMETERS

DNV GL has used its offshore Cost of Energy (COE) model with site condition information based on publicly available information to calculate preliminary LCOE estimates. Regional conditions in Table 10-1 have remined constant during analysis. Turbine and project configuration parameters in Table 10-2 and Table 10-3 have been varied.

TABLE 10-1: REGIONAL CONDITIONS FOR PROJECT COSTING

Tidal level HAT	0.8 m
50-year maximum wave height	11.0 m
50-year storm surge elevation	1.4 m
Annual mean significant wave height	1.24 m
Wind climate Weibull shape factor	2.0
Wind shear calculation method	Roughness wind shear
Roughness height	0.001 m

TABLE 10-2: TURBINE PARAMETERS FOR PROJECT COSTING

Rating	4 MW	6 MW	10 MW
Rotor diameter	120 m	154 m	190 m
Hub height	83 mLAT	100 mLAT	118 mLAT
RNA mass	205 tonnes	365 tonnes	605 tonnes
Drive train configuration	Geared	Direct drive	Geared
Wind speed and turbulence class	1B		
Cut-in wind speed	3 m/s		
Cut-out wind speed	25 m/s		

TABLE 10-3: PROJECT CONFIGURATIONS FOR PROJECT COSTING

Config Name	Wind Farm Capacity (MW)	WTG Rating (MW)	Foundation Concept	Inter-array Cable Voltage (kV)	Electrical Connectivity
T1	152	4	Monopile	66	Offshore substation
T2	150	6	Monopile	66	
T3	150	10	Monopile	66	
T4	504	4	Monopile	66	
T5	504	6	Monopile	66	
T6	500	10	Monopile	66	

10.4 PROJECT COST ESTIMATES

10.4.1 CAPEX Comparison

Figure 10-2 presents a comparison of CAPEX for the following items:

- Turbines & towers;
- Foundations;
- Electrical; and
- Development costs.

10.4.2 OPEX Comparison

Total annual OPEX is presented in Figure 10-3 for each wind farm capacity and turbine rating.

FIGURE 10-2: PROJECT COSTING: CAPEX COMPARISON

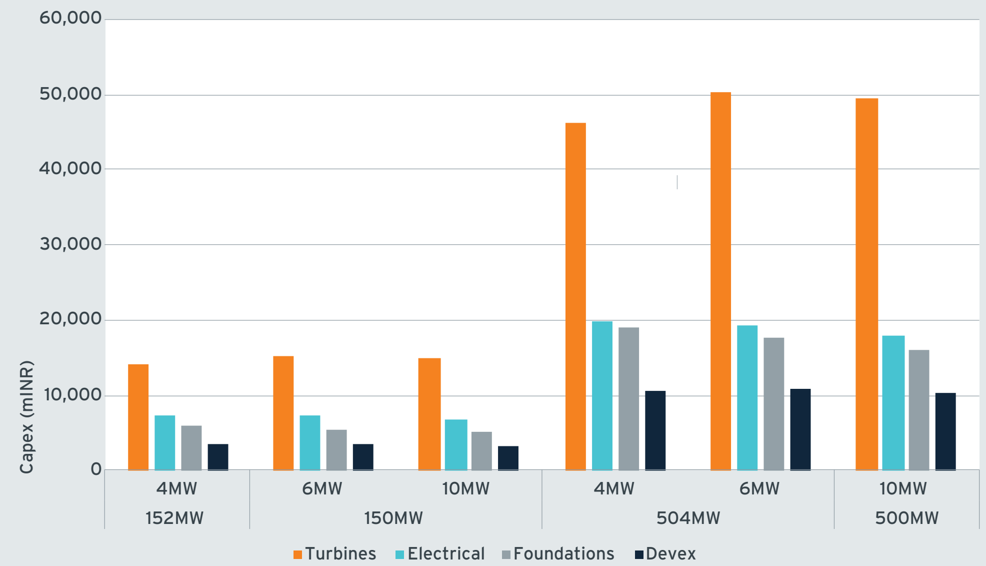
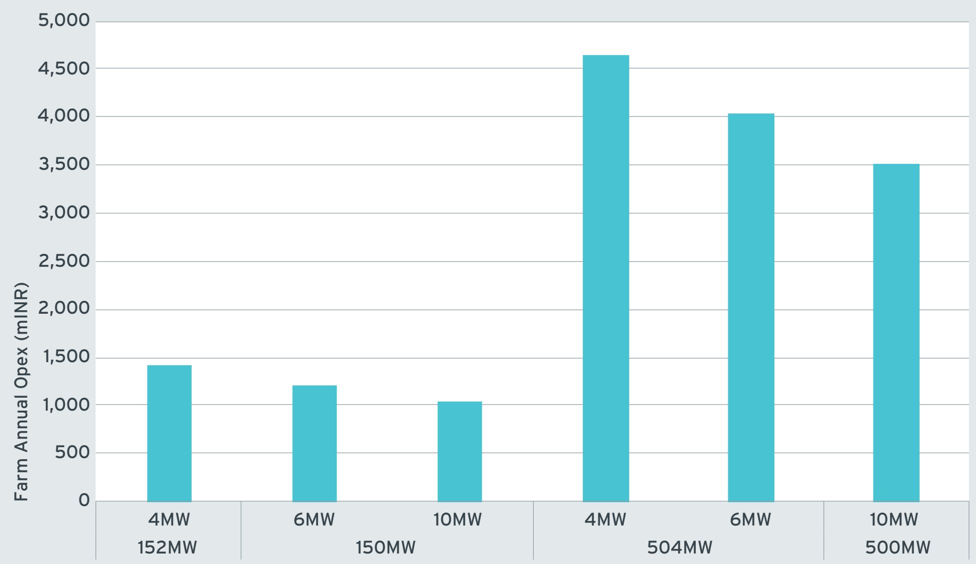


FIGURE 10-3: PROJECT COSTING: OPEX COMPARISON



10.4.3 Annual Energy Yield Comparison

FIGURE 10-4: PROJECT COSTING: ANNUAL ENERGY YIELD COMPARISON

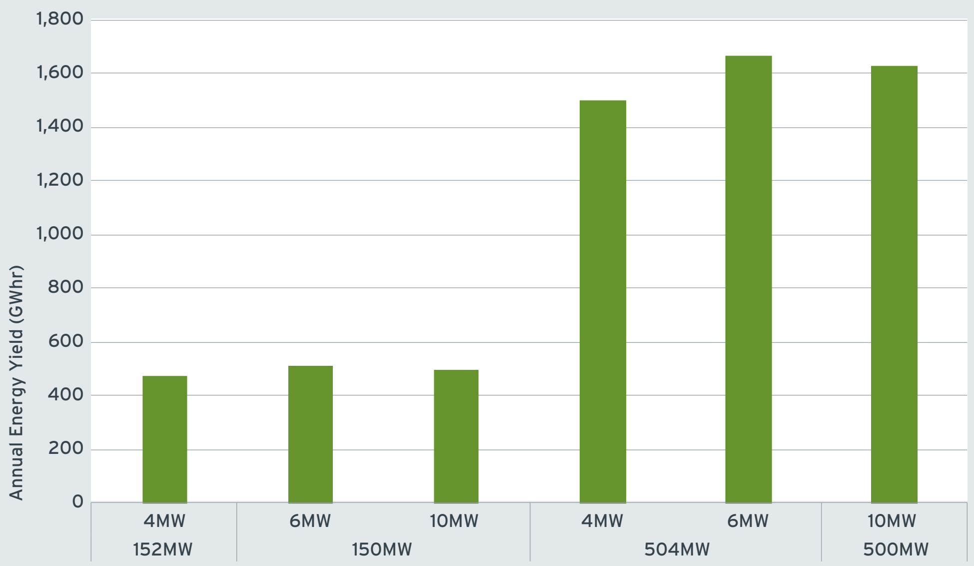


TABLE 10-4: 150MW TO 152MW WIND FARM COST OF ENERGY MODELLING RESULTS

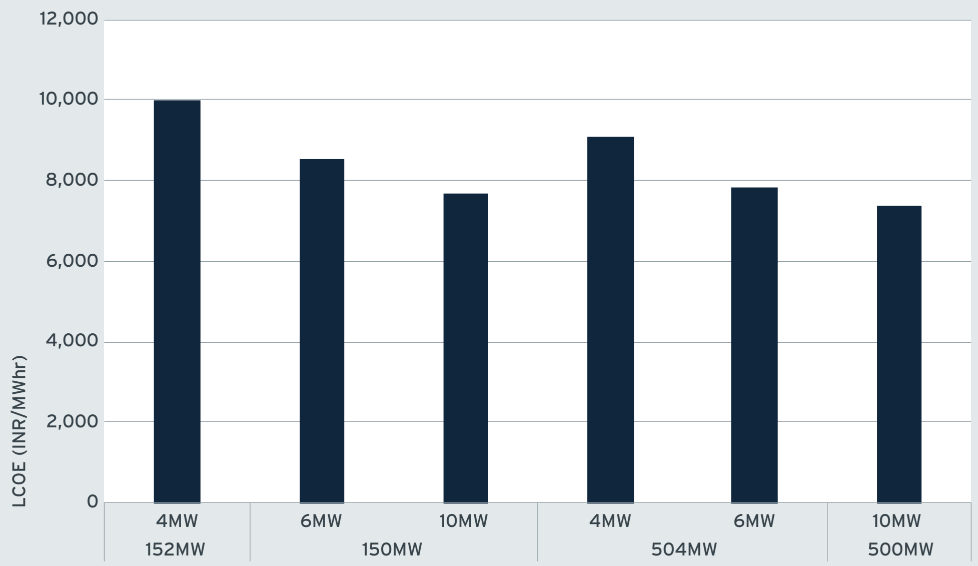
Configuration Name	Turbine Rating	LCOE (INR/ MWh)	Devex (mINR)	Foundation CAPEX (mINR)	Electrical CAPEX (mINR)	Turbine CAPEX (mINR)	OPEX (per annum mINR)	AEP (GWh/ annum)
T1	4MW	9,965	3,660	6,230	8,500	14,270	1,419	471
T2	6MW	8,515	3,470	5,450	7,100	15,210	1,201	508
T3	10MW	7,675	3,080	5,250	4,400	15,060	1,041	498

TABLE 10-5: 500MW TO 504MW WIND FARM COST OF ENERGY MODELLING RESULTS

Configuration Name	Turbine Rating	LCOE (INR/ MWh)	Devex (mINR)	Foundation CAPEX (mINR)	Electrical CAPEX (mINR)	Turbine CAPEX (mINR)	OPEX (per annum mINR)	AEP (GWh/ annum)
T4	4MW	9,087	10,050	20,060	12,900	46,880	4,643	1,502
T5	6MW	7,832	9,920	17,670	11,400	50,660	4,036	1,661
T6	10MW	7,362	9,270	16,720	8,700	49,760	3,521	1,627

10.4.4 Cost of Energy Summary

FIGURE 10-5: PROJECT COSTING: COST OF ENERGY



Total annual energy yield is presented in Figure 10-4 for each wind farm capacity and turbine rating.

The contributions of each wind farm element (turbines, foundations, electrical BoP) to the total CAPEX is shown in Figure 10-2. The results (Figure 10-5, Table 10-4 and Table 10-5) show that increasing the array capacity from a small scale 150 MW "demonstration" project to a larger 500 MW "utility-scale" project will yield some cost of energy benefits. Although larger wind farms typically exhibit lower array efficiency, due to impact of wake accumulation on the downstream turbines; the impact of this effect is minimised in higher wind climates such as that at the Tamil Nadu site. Accordingly, in this study, the reduction in array efficiency from the smaller to the larger project is not sufficient to counter the benefits of increased scale, in which costs such as vessel mobilisation and onshore facilities are shared over a larger number of units and hence the effective cost per unit is reduced.

The results also show that increasing turbine size results in decreasing cost of energy; the effect is particularly noteworthy in moving from a 4MW WTG to one of 6MW capacity, but less so from 6MW to 10MW. In the case of the turbines assumed for this study, the 4MW and 6MW configurations are based on commercial models, whereas the 10MW design is conceptual; the rotor diameter chosen for the 10MW turbine is based upon the power density of typical current commercial offshore wind turbines. The power density of the 4MW and 10MW turbines is somewhat higher than that of the 6MW machine, hence the 6MW turbine will exhibit better low-wind performance. In a relatively low-wind environment, such as Tamil Nadu, this will be manifested as an increased capacity factor, and hence increased energy production for a given installed capacity; this in turn contributes to a lower cost of energy. If the modelling undertaken for this study were to be repeated using three conceptual turbine designs of equal power density, the reduction in cost of energy with increasing turbine size from 6MW to 10MW would be expected to be more pronounced. This also presents a useful note with regard to the development of offshore wind in low-wind environments, in that the deployment of turbines with a lower power density (i.e. a larger rotor for a given generator capacity) may contribute to a lower cost of energy.

Figure 10-5 shows that the cost of energy from an offshore wind farm reduces as turbine size increases; this mirrors general industry experience to date, primarily in European waters, in which technological development of larger commercially-available turbines has been the most significant driver behind the notable reductions in cost of energy from utility-scale offshore wind farms.

Increasing the size of turbines results in fewer units being required for a given wind farm capacity; this in turn results in less foundation steel, fewer installation operations, and fewer O&M transits, all of which contribute to a lower total CAPEX and lower annual OPEX. In addition, larger WTG rotors reach higher, to where wind speeds are typically higher, and hence larger turbines would be expected to yield a higher capacity factor and higher total AEP than an equivalent wind farm comprising more, smaller, turbines. It should be noted that increasing turbine size typically results in cost increases for turbine supply, as shown in Figure 10-2; this is due to the scaling effect of larger rotors, in which turbine loads scale with the square of the rotor diameter, and structural requirements which mean that blade structure, towers etc. scale with the cube of rotor diameter.

Technology developments, such as direct drive transmissions or novel materials, can help reduce the rate of cost increase with scale, however the wind industry has seen in practice that increasing turbine size also increases turbine supply cost. However, in general, the combination of reduced expenditure and increased energy production results in a lower overall cost of energy – as can be seen from the results, increasing the capacity of the wind turbines from 4MW to 10MW results in a cost of energy reduction of approximately 23% (152 MW project config.) and 19% (504 MW project config.).

Some of the factors affecting cost of energy are project-dependent, and the selection (and hence quantification) of these would have to be completed as part of the project development process; furthermore, early projects which perhaps are smaller in scale or closer to shore may offer the opportunity to utilise lower-cost infrastructure. For example, smaller wind farms with short offshore export distances may be able to export power via medium-voltage cables direct to the onshore grid, without requiring an offshore substation platform and high voltage cabling; this would likely be a less costly alternative, however the increased cable installation costs and electrical losses would render such an option unfeasible for a large project.

Whilst the calculations detailed in this section show that increasing turbine size reduces the cost of energy, there are potential advantages to deploying smaller turbines.

Very large turbines may require construction infrastructure that is either not available in some locations, or significantly limited in its availability; selection of these turbines may then result in an undesirable increase in procurement and delay risk. In such a situation, smaller turbines may reduce the risk premium to outweigh some of the cost of energy deficit and hence merit selection for a project. In addition, the use of existing, proven technology, such as a commercial turbine model that has an established track record, may reduce investor risk such that the cost of financing for a project is lower and, again, the apparent cost of energy deficit is outweighed. Deploying new, unproven technologies typically brings an increased cost of financing, as lenders or investors allow for increased risk, which for project-financed developments may significantly reduce the returns to the developer.

The estimated cost of energy reported in this study is lower than that calculated in the Pre-feasibility Report [1], which is a function of a number of both technical and economic factors.

The focus on the most economically-optimal sub-zone within a designated zone means that the project and site parameters are more specific, and the impact of the less-suitable areas of the zone will have been removed. Industry practice has also developed in the time between the Pre-feasibility Report and this study; such developments include larger turbines and improved pile design methodology, and contribute to the reductions in cost of energy that have been seen in recent European offshore wind auctions. Similarly, as supply chains mature and production volume increases, the unit price of turbines is expected to reduce, and industry evidence appears to support this.

The modelling approach has also been developed and refined, tracking industry developments but also with the focus on particular sub-zones enabling more project-specific system modelling, such as in dedicated electrical system studies which yield a significant reduction in the estimated electrical CAPEX versus that calculated in the Pre-feasibility Study. Local fabrication has been considered for WTG and OSS substructures, hence a -15 to -18 % reduction in fabrication rates per tonne has been assumed compared with typical European rates.

In emerging offshore wind markets, such as India, investors or lenders may demand a higher risk premium. Therefore, a high discount rate (used in the Pre-feasibility Study) has been applied in the economic module of the model. As offshore wind becomes a more established, mature industry and asset class, it will attract lower-cost financing (i.e. lower discount rate seen in European markets) and discussion with potential financing organisations would be recommended.

11. OUTLINE PROJECT RISK REGISTER

11.1 INTRODUCTION

When planning offshore wind farm projects, all decisions have to be made regarding future actions, although outcomes cannot be foreseen with certainty due to incomplete information. This uncertainty associated with all business activity is defined as risk. Therefore the aim of this chapter is to provide a high level qualitative assessment of the principal risks for the potential offshore wind farm zones identified in Tamil Nadu. It is important to ensure that significant risks are managed and mitigation measures are identified.

Table 11-2 undertakes a qualitative assessment of the main risks identified in this report, incorporating potential mitigation measures. It should be noted that all of the risks listed in Table 11-2 are zone related risks that would generally apply but given the high level information obtained for the Tamil Nadu region to date, the uncertainty is considered high. It should be considered non-exhaustive but nevertheless a starting point for project risk consideration. Table 11-1 offers an overview of risk levels, categories and actions required.

11.2 HIGH LEVEL QUALITATIVE ASSESSMENT OF MAIN TECHNICAL RISKS

TABLE 11-1: RISK LEVEL AND CATEGORY

Risk Level	Risk category	Action required
LOW	Acceptable	Low risk level. No risk mitigations required. Check that no other risks can be eliminated.
MEDIUM	Might be reduced to ALARP	Risk identify that will require mitigation measures. Reduce risks as low as reasonably practical (ALARP); Consider alternative design or construction method; If alternatives are not available, specify precautions to be adopted.
HIGH	Not acceptable	Potential major impact. Mitigation is required. Seek alternative solutions or if alternatives are not available, specify precautions to be adopted

TABLE 11-2: QUALITATIVE ASSESSMENT OF MAIN RISKS AND POTENTIAL MITIGATION MEASURES

No# & Risk Level	Issue	Risk	Description	Consequences	Mitigation
1	Consenting	Uncertainty of the regulatory regime	There is currently no offshore wind permitting and consenting regime for the EEZ in India. This leads to a number of uncertainties with regards to the consenting schedule and technical requirements for off- and onshore construction.	This uncertainty may cause delays in the approval process and/ or the installation process with financial consequences on the overall project budget.	A proper defined permitting and consenting process based on suitable regulatory framework forms the basis for any offshore wind development and needs to be setup upfront.
2	Wind resource	Uncertainty of the wind resource assessment	At this stage of the project wind resource assessments are based on mesoscale modelling. This data are generally associated with a relative high uncertainty.	A high uncertainty of the wind resource assessment can have significant financial consequence for the project.	It is common practice to conduct a site specific wind potential analysis and energy yield assessment based on long term wind measurements on the proposed offshore wind farm site.
3	Metocean climate (water)	Uncertainty of the wave and current data	For the design and the installation of the offshore wind farm it is important to fully comprehend the oceanographic conditions in the proposed area. In particular high tidal currents have been identified in several areas around river estuaries in the Tamil Nadu region which need to be considered.	This may impact the foundation design, project costs and project timeline.	To reduce uncertainty a detailed metocean site condition assessment is recommended and should be combined with a validation period from on-site data.
4	Bathymetry	Uncertainty of the bathymetry assessment	The data gathered during the bathymetry desktop study are associated with a relative high uncertainty.	High uncertainty of the bathymetry data could have significant consequences on the foundation costs.	After the selection of potential offshore wind farm sites on-site bathymetry surveys are required to be carried out.
5	Geotechnical conditions	There is only limited information on the seabed geology of the Tamil Nadu region available	The results of the conducted desktop study of the geology of the Tamil Nadu region shows that only limited suitable data for planned offshore wind region exist.	Geological data are essential for the design of the WTG and substation foundation. The limited availability of suitable data increases the uncertainty in the design process of the foundation and could have a significant influence on the foundation costs.	Detailed geotechnical and geophysical site surveys are to be conducted in a later project stage to reduce the uncertain in the foundation design process.
6	Soil conditions and Jack-up vessels	The soil conditions on site indicate loose sands at certain locations	The current desktop study for the proposed offshore wind farm zones shows loose sands at certain location. Jack up vessels usually required for jacking operations require firm soils.	A high level of very loose sand may limit the suitability for jacking operations on site.	If jack-up vessels are considered as part of the offshore installation concept, a full site specific assessment for the proposed offshore wind farm site is required.

No# & Risk Level	Issue	Risk	Description	Consequences	Mitigation
7	Ports and logistics	Uncertainty of the port assessment	The conducted desktop study on suitable construction and O&M ports in the Tamil Nadu region is based on a limited number of available data.	This may impact the sub-zone selection for the potential wind farm developments.	It is recommended to conduct a full port assessment including site visits in a later project stage to reduce uncertainty.
8	Ports and logistics (vessels)	Availability of suitable installation and O&M vessel	So far only a limited number of the offshore wind activities can be observed in the APAC region which leads to a reduced availability of specialist offshore wind installation vessels. The availability of suitable vessels from the oil and gas industry is highly dependent on demand and is subject to high fluctuations.	The general availability of suitable installation vessel can have a significant influence on the overall installation time schedule and budget and may require mobilization of suitable vessels from Europe.	Medium To ensure that installation capacities are available to acceptable costs it is recommended to start negotiating installation contracts in ample time.
9	Shipping traffic	Marine traffic	High density of shipping traffic identified within some of the development zones.	This may risk vessel collisions on the potential wind farm developments.	Is it recommended to conduct a full navigation safety assessment including impact of new developments on marine safety.
10	Environmental and Social Impact Assessment (ESIA)	Uncertainty on the outcome of the ESIA	Construction activities in breeding and feeding seasons may impact marine life.	The occurrence of migrating birds and marine mammals in the proposed offshore wind farm zones can have significant consequences on the construction schedule and the installation methodology, e.g. piling with noise mitigation measure could be required.	Piling noise can be reduced with bubble curtains or using vibration technologies instead of hydraulic hammer. The impact on migration of birds and marine mammals can be mitigated by programming construction activities suitably.
11	Health, safety and environment	Health and safety risk	Working in an offshore environment represents an event with significant requirements on man and material. In particular considering that the offshore wind industry is relatively young industry compared to established industries like offshore oil and gas.	Injury to persons, extensive damage to structures and systems and delay to project, pollution of the environment.	A high safety culture is essential to ensure the project success without having severe incidents. A health, safety and environment management system is to be considered as an important cornerstone of a H&S culture.
12	Electrical design & engineering	Uncertainty of the electrical design	The data gathered during the conducted desktop study are subject to high uncertainty.	The uncertainty of potential grid connection point may cause changes in the electrical design and layout with significant consequences on project costs and the overall project schedule.	The available information needs to be verified to reduce the existing uncertainties

No# & Risk Level	Issue	Risk	Description	Consequences	Mitigation
13	Turbine Technology	Technology risk	The technology of offshore wind turbines is still immature in case of larger capacities. Hence choosing a large capacity turbine can be risky. Furthermore, wind turbine technology has not been tested in Indian offshore conditions.	Technology related turbine breakdowns can cause a significant reduction of the turbine availability.	Given the current status of production and commercial experience of large scale offshore wind turbines with 5 MW and above. Turbines with a suitable track record should be chosen to reduce the technology risk.
14	Grid connection	Grid availability	These existing transmission infrastructures may be utilised to cover small scale offshore wind developments in Tamil Nadu, but not for large scale deployment of offshore wind power plants.	Unavailability of adequate grid infrastructure and grid reliability reduces the amount of electricity feeding into the grid.	For large GW scale offshore wind farm projects new or upgraded transmission infrastructure will be required. A sufficient test programme of the grid infrastructure should be simulated in advance to avoid shut downs during operation.
15	Installation	Weather down time	Weather down time needs to be adequately considered in overall project schedule. In particular the impact of the summer monsoon period on the turbine availability has not been thoroughly assessed.	Not considered weather down time could lead to higher lead times and increased project costs.	It is common praxis within the industry to calculate the weather down time based on statistical weather. However, there is still a risk that the weather down time is above the statistical norm.
16	Installation	Availability of suitable installation equipment	The monopile is one of the preferred WTG foundation designs. The diameter of the monopile designs for up to 30m water depth can exceed 6 m. The size of a hammer required to drive such monopiles are currently limited in availability.	The availability of suitable equipment can have a significant influence on the installation time schedule and budget.	The availability of suitable equipment needs to be considered in the foundation design phase. Installation equipment contracts are to be negotiated right before the start of the installation.
17	CAPEX	Uncertainty of CAPEX	The project CAPEX are estimated based on DNV GL's experience from previous projects and may be subject to significant changes.	The project CAPEX can vary significantly from the estimated figures depending on parameters of the final offshore wind location and layout.	It is recommended to update the CAPEX cost model in a later project stage considering the final offshore wind farm layout.
18	OPEX	Uncertainty of OPEX	Considering the available project parameters the OPEX are relatively uncertain and may be subject to significant changes.	The OPEX can vary significantly from the estimated figures depending on the final offshore wind project parameters.	It is recommended to update the OPEX cost model considering the final layout of the proposed offshore wind farm.
19	DecEx	Uncertainty of decomEx	Based on the current development stage of the offshore wind zones, the decomEx can only be estimates with a high uncertainty.	The decomEx can vary depending on the final installation and decommissioning methodology.	The decomEx should be included in the financial model as a share of the CAPEX. Offshore decommissioning works are assumed to be similar, in cost and effort to the installation work.

12. ENVIRONMENTAL AND SOCIAL IMPACT REGISTER

12.1 INTRODUCTION

The FOWIND Pre-feasibility Study for Tamil Nadu [4] included chapters on Environmental and Social Impact that discussed the potential impacts of offshore wind projects, regulatory mechanisms and protocols for planning consent.

This section discusses the scope, key principles and best practice for Environmental and Social Impact Assessments (EIAs). Key biological, physical and human aspects are discussed.

12.2 SCOPE OF ENVIRONMENTAL AND SOCIAL IMPACT ASSESSMENTS

The European EIA Directive requires an Environmental Impact Assessment (EIA) for certain types of development. In practice these always apply to large offshore wind farms. Similar legislation applies worldwide.

The EIA is required to assess and list the "likely significant effects" on the environment and to consider and describe mitigation measures to prevent, reduce and offset the negative effects and finally to summarise the residual effects. The resulting Environmental Statement forms the basis of the permit application.

In this section, the key principles and scope of typical EIAs for offshore wind farm developments are described, with focus on major potential issues and methods of mitigation.

12.3 KEY PRINCIPLES

The environmental impact assessment (EIA) needs to consider all potential impacts, with the scope including:

- All elements of the offshore wind farm (OWF) development:
  - The offshore wind farm site: the offshore turbines and their support structures, meteorological masts, array cables, offshore substations (topsides and support structures), scour protection;
  - The export cable corridor from the OWF to the shore including any inter-tidal zone;
  - Onshore facilities: onshore export cable route and substation; operations base.
- All stages of the project timeline: construction, operation and decommissioning phases. There may be separate EIAs required for pre-construction work such as erection of met masts and site investigations.
- The potential impact on the biological and physical environment, on other human users of the sea, and socio-economic impacts such as employment.
- Positive and negative impacts, and proposed mitigation measures to address potential negative impacts.
- Plans for monitoring programmes.
- The assessment will typically include:
- Desk-studies and, if warranted, more detailed survey work to provide baseline data.
- Stakeholder engagement: consultation with the public and with interested parties.

From the developer's viewpoint, the EIA will need to consider the environmental risks in relation to the other key drivers of engineering feasibility and technical risk, economics, wind farm energy yield, and Health & Safety. These will be outlined in the submitted documents to provide context.

At the start of the EIA process, there may typically be an initial scoping phase to agree with the authorities which areas require detailed consideration. The intention is to ensure appropriate levels of time and effort are spent on the EIA.

Typically, the permitting process may be split up, for example with separate applications for the offshore wind farm site, for the offshore export cable route and for onshore facilities. The following descriptions focus on the offshore aspects.

12.4 ENVELOPE APPROACH

In many established offshore wind regulatory regimes, it is accepted that the exact details of the proposed OWF are not yet determined when planning permission is granted. The developer's application therefore defines a range (or envelope) of parameters to be considered, sometimes referred to as the "Rochdale Envelope".

By this process, the design of the project is allowed to evolve during the development phase; the developer can take advantage of new technologies becoming available to the market, and can make final technical choices as more detailed site data is amassed, thus benefitting the economics of the project.

Typical parameters that may not be finalised until nearer to construction can be:

- Turbine capacity and dimensions;
- Number of turbines and their exact locations within the site area;
- Foundation type and details (e.g. jacket, suction bucket or monopile);
- Offshore transmission structure design (array cable voltage, design of offshore substation, detailed export cable route).

Through the envelope approach, each environmental impact is assessed according to the maximum adverse scenario within the envelope of parameters. For example, the options may be a large number of small turbines; or a smaller number of large turbines. Some impacts may be most sensitive to the highest tip height, whereas others may be more sensitive to the number of turbines, and they are assessed accordingly. Part of the protocol of this approach is that the developer communicates with the authorities when decisions within the envelope become more firm or options are ruled out.

12.5 BIOLOGICAL ASPECTS

Biological aspects of the EIA will cover all relevant species of flora and fauna. The presence of species may be very location-specific and any impact is often species-specific.

- In Denmark, the initial Danish offshore wind programme selected sites in the North Sea (Horns Rev OWF) and in the Baltic (Nysted OWF), enabling the effects on the species found in the different Danish waters to be explored, with extensive reporting of the findings [48] and ongoing work [49].
- In UK, the COWRIE project between 2005 and 2010 produced a large body of collaborative research [50] and led to the creation of the ongoing Marine Data Exchange portal [51] for sharing of data collected under the permitting process. Results of UK post-consent monitoring programmes were reviewed by MMO in 2014, and incorporated non-UK findings [52].
- In Germany, ecological aspects were studied comprehensively at the Alpha Ventus demonstration project [53] and ongoing studies continue largely through the BFN, the federal bureau for nature conservation.

The main wildlife communities potentially affected will be:

- Benthic communities (flora and fauna in the surface layers of the seabed);
- Fish (commercial or otherwise);
- Reptiles (turtles etc);

- Marine mammals (seals, dolphins, whales etc); and
- Birds (sea-birds or migratory species).

Sensitive flora and fauna in coastal and inter-tidal habitats should also be considered, primarily regarding the route and land-fall of the export cable. Standard onshore EIAs for onshore facilities and onshore cable route may also be needed, and are generally separate from offshore permits. In addition to assessments of potential injury or mortality to the species, consideration is made of the disturbance to different behaviour which may be seasonal (feeding, breeding, migrating, resting, commuting to and from feeding areas).

Designated sites of international, national and local biological conservation importance will be identified in the EIA and may require additional provision.

Common considerations required for offshore wind projects are:

- **Noise impact on fish and sea mammals.** For OWFs, the main impact of noise and vibration is disturbance and displacement, or in the worst case injury to sea mammals.

Sound levels are not thought to ever reach magnitudes considered to be lethal [52]. The impact occurs mainly during construction, though to a lesser extent from marine traffic during all stages of the life of the project. The severity during construction depends on the choice of foundations, with the most noise created by piling (of monopiles or jackets). Position papers [54] [55] describe mitigation measures that include project-specific conditions to avoid piling at critical times or dates, such as the fish spawning season; use of acoustic deterrent devices ("seal-scarers") and soft-start of the pile-hammer to give animals the chance to move away; use piling technology which create lower noise levels; and noise reduction through mufflers and bubble curtains. A marine mammal protocol may be adopted using observers and passive acoustic monitoring equipment to ensure the surrounding area is clear of marine mammals prior to commencement of piling.

Studies have shown no evidence of disturbance caused by the operational noise of turbines [52].

- **Influence on fish and fisheries.** It is generally assumed that fish will be only temporarily disturbed during the construction phase as they can easily move away, provided noise-mitigation measures are in place such as soft-start piling. Any disturbance will only be significant if spawning grounds of a fish species are disturbed. In this case, mitigation generally requires avoiding construction during the spawning season.

  During the operational phase of the OWF, fish monitoring has shown some positive reef effects with the OWF providing more habitats for fish, whilst there is no discernible evidence of vessel noise deterring fish [52]. It is known that fish may be sensitive to electromagnetic fields (EMF), such as around power cables. However, there is little evidence that fish behaviour is changed, and the EMFs will be small for buried cables [52].

- **Influence on other sea-life.** Depending on the location, there may be populations of seabed worms, shell fish, turtles, etc. Seabed surveys are done by grabs and trawl surveys, and video and stills photography. Localised benthic populations may need to be avoided.

- **Influence on birds.** In general, sea-birds tend to avoid wind farms, though there is some evidence from Denmark that over time, birds adapt and return [Ref 2013 follow-up study]. The main potential effects are loss of habitat; disruption to movement for feeding or breeding; barrier effects to migration; and collision with turbines. The effects can vary according to the species, and they need to be assessed separately. Moreover, if multiple projects are to be built in the same area, the cumulative effects need to be assessed.

  When monitoring birds, methods that minimally disrupt the birds are preferred. The early technique of observation from boats is largely being replaced by digital aerial photography from high above, together with improvements in identification methods. Radar methods are also used, particularly for tracking migrating birds.
- **Intertidal zones.** Where export cables make landfall across sensitive habitats such as salt marshes or mangroves, standard cable burial techniques may cause unacceptable disruption to sensitive plant life and feeding or breeding habitats of birds and other species. Mitigation measures include project-specific protocols to avoid certain dates or techniques such as horizontal directional drilling (HDD) or other specialised equipment to minimise the impact.
- **The cumulative effects** of multiple projects in an area need to be assessed. Disruption during a single season may be acceptable to a wildlife population that is temporarily displaced and can quickly recover. However, disruption over multiple seasons, and over a wider geographical area may not be acceptable or need additional mitigation.
- **Positive effects** of offshore wind farms can be provision of marine habitats, for example rock placed for scour protection around subsea foundations may provide refuges and nurseries for juvenile fish if the surrounding seabed is otherwise barren. There is evidence [56] [57] [58] that marine mammals are attracted to offshore wind structures (and also other offshore structures), taking advantage of higher incidence of food around the structures and the refuge from shipping lanes.

12.6 PHYSICAL ASPECTS

The main factors to be considered are:

Water pollution, such as from fuel spills or discharges of hazardous materials. Compared with oil and gas facilities there are far fewer potential hazards from offshore wind projects, and the severity of any incident is much lower. Bearing oils and transformer fluids are present in small quantities that should be contained by best practice in design. Fuel and other fluids in construction and maintenance vessels are addressed by good practice design and operation.

Waves, tides and currents should be assessed for potential effects by the OWF. However, monitoring at early OWFs has shown little effect [52].

Sediment movement and coastal processes. There are often likely to be temporary increases in suspended sediments during construction, from the levelling of seabed or burial processes or cables. Knowledge of the mobility of the seabed is required from records of sand waves and water depths over time, to indicate likely changes during the life of the project.

Sea-bed mobility and scour around foundations or cables should be regularly surveyed, especially with sandy seabed that is historically mobile with sand-waves and shifting sand banks. Monitoring is generally done for engineering purposes, to check whether cables or foundation structures are becoming exposed and whether scour protection needs to be added.

12.7 HUMAN ASPECTS

12.7.1 Seascape, landscape and visual

The assessment will typically include visualisations of the proposed Project from selected points on the shore in daylight, and also the impact of aviation lighting on the night sea-scape.

The influence of the new Project is compared with the existing nature of the seascape. Similarly, the effect at shore of any sound warning systems will be assessed.

12.7.2 Marine artefacts

The assessment will consider typically:

Cultural heritage and marine archaeology: wrecks of archaeological significance, other heritage sites such as sunken villages. These may need to be left undisturbed with localised exclusion zones.

Wrecks, unexploded ordnance (UXO), and potentially other dumped objects that may be hazardous to the Project or related activities. The objects may need to be removed, or avoided if left in place.

Cables and pipelines, either disused or active. Even if known, routes may not be charted exactly. In practice, some marine artefacts may only be discovered during detailed site investigations.

12.7.3 Other users of the sea

Typically, this aspect of the assessment will consider primarily the impact of the offshore wind project on other users, whilst taking into account any impact of other users' activities on the offshore wind project. Early consultation is important.

Fishing. The relationship of the Project to fishing grounds and fishing activities is assessed, in addition to consideration of any impact on fish stocks. There may be restrictions to fishing activities during the construction phase, and in some cases, during operation of the project. Typically cables will be sufficiently buried to guard against damage to (and by) fishing gear and ship's anchors, and any scour protection will be designed to allow "overfishing" – so they do not damage fishing gear.

Shipping and Navigation. The distance of the project from shipping lanes needs to be assessed, from the point of view of any disruption to shipping routes and the potential for damage to the OWF should a vessel lose control.

Non-windfarm vessels may be excluded from the site during the construction phase, though movement of smaller vessels may be allowed within the OWF during the operational phase. Clear navigational aids are needed for all weathers.

Oil and Gas facilities (platforms, well-heads etc). This consideration can include buffer zones around existing facilities, access by boats and/or helicopters to the facilities, and the potential for future facilities.

Aviation, Defence, Radar and Telecommunications. Measures may be needed to mitigate potential radar and telecommunications disruption by the moving turbine blades. Aviation lights are fitted as required to selected turbine nacelles at the edges of the OWF. In Germany, turbine blades are required to have red tips for greater visibility to aircraft. Access to certain areas may be restricted due to defence-related activities.

Extraction (minerals, gravel etc.). The extraction of sand and gravel is necessary for a number of onshore activities including land reclamation, beach nourishment and construction. There is typically only limited scope for co-existence with offshore wind energy and extraction has historically taken precedence, though this may be location-specific.

Leisure amenity. In some locations, sailing and other leisure activities may share the sea with the project. Sailors are unlikely to be affected by wind turbine wakes since wind turbine rotors are at least 20 m above the water. Generally, these other users are allowed within the OWF area, though must not land on the OWF structures except in emergency. Although the wind farm vessels create some additional traffic, they are also available and capable for marine rescues.

12.7.4 Socio-economic aspects

The assessment will consider typically:

Stakeholder consultations. Stakeholders will typically include local authorities (including those with coastal and landward jurisdictions which include the development footprint), statutory bodies, local community and interest groups.

Public opinion tests. Typically, information is made available to the local public online and via events and local information points (typically libraries and local authority facilities). The information may include non-technical briefing notes and consultation reports.

Local media. Local media will typically take interest in the development and should be well briefed to prevent the publishing of incorrect or unhelpful information. Local media may also be used to inform the public of the development and where to find consultation information.

Engagement of politicians. As part of the stakeholder engagement and a key objective.

Green and environmental organisations. Again, this would be part of the general stakeholder consultation. The environmental organisation may have a general scope (e.g. Natural England in the UK) or could be more specific (e.g. Royal Society for the Protection of Birds in the UK).

Employment. Offshore wind energy may bring considerable job opportunities to the local area, both during construction and operational phases. This is generally put forward as a key benefit of offshore wind.

Port infrastructure. Local ports may be used as construction and/or operations and maintenance hubs. As such, they may require upgrades for this use, which could have benefits for other port users and the ports themselves.

Transmission infrastructure. Ideally, an offshore wind will connect to a pre-existing strong grid point (an existing or decommissioned power station, for example). However, there may be a need for the appropriate authority to strengthen the transmission infrastructure.

Manufacturing. Some of the employment arising from the offshore wind development could be local manufacturing, whether through indigenous companies or through the establishment of local facilities by foreign manufacturers of wind turbines, support structures, cables, electrical equipment etc.

12.8 RECOMMENDATIONS

Building on the global experience of offshore wind development, the following approaches to the Environmental Impact Assessments (EIAs) and the permitting process are recommended:

- Setting up a single authority to coordinate all the permits and consultations required, and providing a single contact point for developers. This has been done in the expansion of NIWE to cover offshore wind and act as a conduit for applications and clearances.
- Initial data gathering by central authority - for example geophysical surveys, initial geotechnical data, tidal, wind and wave measurement - with the results made available to potential bidders at the pre-tender stage. This reduces the risk to the developers and the cost could be refunded by winner. This is in progress (wind resource) and planned (ground conditions).
- Enable pre-application dialogue between developer and the permitting authorities to ensure appropriate scope and depth of each application.
- Allow an envelope approach in permit applications to give flexibility to the developer.
- Use a transparent process with submitted documents and responses in public domain.
- Employ sufficient staff and resource to avoid delay in addressing applications; and subsequently to ensure compliance with the permitting conditions.
- Require standard methodologies for environmental monitoring and measurement.
- Require an Environmental Management Plan, including designation of a responsible officer at each OWF. During the operational phase, regularly review the OWF monitoring regime and its ongoing suitability.
- Use a central body to receive and collate post-consent data in common format; and review and analyse data from all OWFs to expand the evidence base for all.

13. KEY FINDINGS AND RECOMMENDATIONS

A feasibility study has been completed for a future demonstration project in Tamil Nadu's lowest cost of energy zone, which was identified during the FOWIND Pre-feasibility Study [1]. The study commences with a sub-zone selection exercise which identified sub-zone "A3" as the optimum location in zone A for the demonstration project. This was followed by a preliminary environmental site data study, which defined baseline metocean and geotechnical conditions.

This site data then enabled concept design and outline project costing using DNV GL's Levelised Cost of Energy (LCOE) design tool "Turbine. Architect". Different configurations of project capacity (150 MW to 504 MW) and turbine MW class (4 MW, 6 MW & 10 MW) have been investigated and supported by further technical, social and environmental studies. Where possible these studies have been conducted at a sub-zone feasibility level but should be investigated and analysed further by any potential project developers.

Compared with the established onshore wind industry, offshore wind is a new venture for India and will present many initial challenges, including; technical, logistical, supply chain and political. A proportion of these risks can be mitigated through knowledge exchanges, support and lessons learnt from established European markets. In addition India will see local challenges not seen in the established markets, these include technical risks such as typhoons, earth quakes and weak under-consolidated soils. However, there are newly developing markets in Asia, including China, Taiwan, Japan and South Korea, that are facing similar challenges and are developing new approaches and methods to solve them. This Tamil Nadu Feasibility Study Report, is a key milestone deliverable from the FOWIND project's final year of work and is the consecutive step following the Tamil Nadu Pre-feasibility Study delivered in 2015 [1]. This report is supported by FOWIND's Supply Chain, Port Infrastructure and Logistics Study [2] and the Grid Integration Study [3] delivered in 2016 and 2017 respectively.

The remainder of this chapter presents; short section summaries, the key conclusions drawn from this feasibility study and recommendations for ongoing work.

13.1 SITE CONDITIONS

13.1.1 Wind

There is currently no installed offshore wind measurement in Tamil Nadu. A LIDAR is planned by NIWE. The mesoscale wind resource map modelled during the Pre-feasibility Study has been used. Once 12 months of on-site LIDAR data becomes available, the MNRE may wish to conduct a full energy assessment in support of this feasibility study. The Pre-feasibility Study relied on available satellite data and mesoscale modelling methods. Without offshore measurements available to provide validation points there exists a high level of inherent uncertainty and the presented results must be treated with due caution. Wind speed spatial variation has been presented for projected turbine hub heights of 100 m and 120 m above sea level. For a height of 120 m above sea level modelled mean wind speeds were in the range of 8 to 8.3 m/s. European projects are known to possess mean wind speeds in the range of 8 to 10 m/s hence the values predicted in Tamil Nadu from the mesoscale model are promising.

13.1.2 Waves and Currents

A preliminary metocean study for zone A in Tamil Nadu has been conducted by DNV GL's metocean department, it provides wave, current and tidal data suitable for concept design. Extreme parameters are provided both with and without the presence of typhoons. Consideration of typhoon induced waves is important for both loads analysis and calculating foundation platform elevations. Extreme 50-year return typhoon induced waves are estimated at 11.0 m Hmax, this is comparable with extreme wave conditions seen in some parts of the North Sea. 50-year return currents are estimated at 1.6 m/s at mid-depth, which is in-line with magnitudes seen in some areas of the North Sea. An all-wind speed and omni direction wave scatter table is also provided, this has been used in the calculation of fatigue loads during the foundation comparison studies. During later design stages the effects of full wind/wave misalignments should be considered.

13.1.3 Geotechnical

DNV GL's offshore geotechnical department have developed experience based Geotechnical zone descriptions for the Tamil Nadu offshore region and provided indicative lower/upper bound soil profiles for zone A. This is based on publicly available data and knowledge/experience from working offshore in this region for a number of decades.

The stratigraphy within zone A is believed to generally comprise of a sand and cemented sands with occasional stiff clay seams to depths of around 45m, with relative density of the sands ranging from loose to very dense. A high degree of spatial variation is identified with the limited available data. Profiles range from very firm cemented sands to very loose sands to depth. Both of these extremes present different challenges for foundations.

It should be highlighted all geotechnical findings are still subject to a high-level of uncertainty and any future developer will need to conduct a suitable geophysical and geotechnical survey campaign.

13.2 SELECTION OF POTENTIAL WIND FARM SITE

An optimal location, sub-zone A3, has been identified in Tamil Nadu's most promising offshore wind development area, "zone A", for demonstration projects ranging from 150 to 504 MW.

In total 10 sub-zones were defined in zone A based on the assumption that they could each accommodate a wind farm with a capacity between 150 and 504 MW. Further known hard constraints such as shipping traffic were applied and should be considered in any future spatial planning activities. These 10 sub-zones have been modelled using DNV GL's system design and cost modelling tool Turbine. Architect and evaluated against their normalised levelised cost of energy (LCOE) to establish the optimum demonstration project location.

A3 exhibits the lowest CAPEX costs due to shallow water depth and shorter distance to shore.

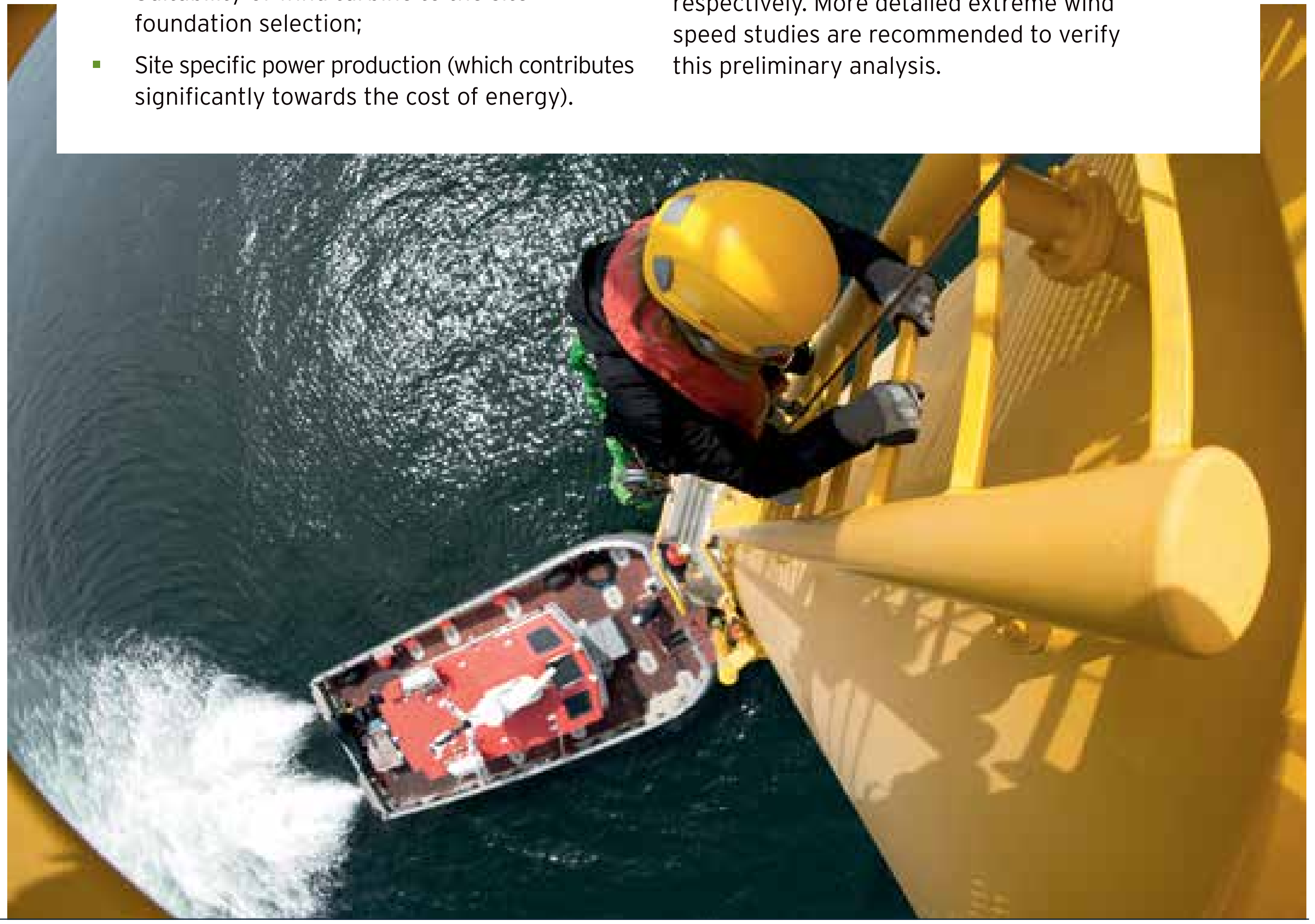
Despite A3 having the second lowest annual mean wind speed and hence one of the lowest energy yields, it still has a lower cost of energy than the other sub-zones. This is due to small variation in wind speeds across the selected zone. A3 was therefore taken forward for further concept engineering and cost of energy studies.

13.3 TURBINE SUITABILITY

The FOWIND consortium has completed a revised review of potential wind turbine offerings for the Tamil Nadu region, given a commercial turbine procurement date target between 2020 and 2025. The objective of this exercise was to review the suitability of these wind turbine offerings considering the key drivers for wind turbine selection, specifically:

- Site suitability (ability to withstand the site climatic conditions over the design operating life);
- WTG track record (a loose measure of wind turbine reliability);
- Suitability of wind turbine to the site foundation selection;
- Site specific power production (which contributes significantly towards the cost of energy).

Consideration was given to the known site-specific climatic conditions within Tamil Nadu and the likely turbine class requirements to meet these conditions (e.g. IEC 61400-1 edition 3 turbine classification). Turbines are classed by three main parameters: the average wind speed, extreme 50-year gust, and turbulence. Mean wind speeds identified from the mesoscale modelling indicate a requirement for IEC Class II and above (noting the uncertainty without a sufficient duration of onsite wind measurements). Regarding extreme wind speeds further investigation is required, especially given the typhoon risks within this region. In lieu of long term measurements, it has been possible to estimate (with noted uncertainties) a 50-year return gust wind speed using two approaches, one by extrapolating extreme wind speeds from the metocean study to hub-height, and the second by applying the Indian Standard relating to Codes of Practice for Design Loads for Buildings and Structures. For zone A (including sub-zone A3) both methods indicate IEC Class I turbines could be sufficient with 3-second gusts of 63.8.8 m/s and 65.4 m/s for hub-heights of 100 mMSL and 120mMSL respectively. More detailed extreme wind speed studies are recommended to verify this preliminary analysis.



Classification of a wind turbine as Class A or B is dependent on the turbulence level within the wind farm. This will be mainly driven by wind turbine array layout and can be quantified and mitigated at a later stage however it is probable Class B will be sufficient offshore in Tamil Nadu. Based on the assessment, Class I or S wind turbines were taken forward for further assessment.

Offshore wind turbines with a significant operating track record are still few and far between in a market dominated by a few suppliers and this effect has been compounded between 2013 and 2017 with significant mergers and formation of strategic joint ventures between the big players. The Siemens G4 platform still has accrued a substantially stronger track record than the other WTG's considered, with the Vestas V112-3MW platform (including onshore experience) still coming in second place. With the successful offshore cost reductions recently seen in Europe and with subsidy-free offshore wind projects on the horizon the next round of bids in Europe are predicted to feature much larger "1x MW" turbine platforms with MW capacities exceeding 10 MW and with rotor diameters more than 200 m. These larger turbines are critical to meet the LCOE targets and as such developers will need to accept "1x MW" platforms with limited operational hours, but likely from suppliers with extensive experience of the design and operation of established smaller platforms. However a strong track record may still come at a price premium and it should be noted that there may be opportunities to partner with organisations which are bringing new WTG's to the market. This may result in more favourable economic conditions with respect to turbine procurement in return for sharing the risk associated with the lack of a proven offshore track record.

13.4 LAYOUT AND ENERGY PRODUCTION

An offshore wind farm layout using the 6MW and a 154m rotor diameter generic offshore wind turbine with a 504MW project capacity has been developed to represent a base case. A minimum inter-turbine constant spacing of 8 x 7 rotor diameters (D) has been assumed for the proposed layout. This layout would be broadly similar for other project configurations and wind turbine capacity. An elliptical exclusion zone around the turbines was generated using DNV GL's WindFarmer software. During the wind farm layout design, the long axis of the ellipse has been aligned with the assumed prevailing wind direction in order to minimise both losses due to wake effects and loads on downwind turbines. It should be noted that the proposed layout is preliminary in nature and should be revised further based on the onsite measured wind resource and detailed grid studies specific to sub-zone A3.

The FOWIND consortium has conducted a high-level energy production assessment for sub-zone A3 in Tamil Nadu. The assessment was undertaken assuming uniform layouts for both 150-152 MW and 500-504 MW wind farm capacity options, using the generic 4 MW, 6 MW and 10 MW wind turbines. It is important to take note of the preliminary nature of these estimates and the uncertainties highlighted within the report.

For the Generic 4 MW turbine, Project Net Capacity Factors were estimated in the range of 30.0 % and 35.3 % (depending on the MW capacity of the farm). When deploying the larger 6 MW and 10 MW Generic turbines Project Net Capacity Factors were estimated in the range of 37.6 % to 38.1 % and 37.1 % to 37.9 % respectively. These values might be considered equivalent to those achieved in recent European projects [97] [98]. Lower capacity factors in early UK projects were largely a result of poor turbine reliability and availability resulting from un-optimised maintenance access strategies and worse than anticipated weather restrictions. Current and future European projects are set to achieve significantly higher capacity factors due to the development of optimised operation and maintenance strategies and improved turbine reliability. For example, recently Danish offshore wind farms have been reported as achieving a total average capacity factor of 41.6 %[59]. The UK average capacity factors have grown significantly over the years and current averages are reported at 37.8% [59].

13.5 CONCEPT ELECTRICAL CONCEPT DESIGN

A preliminary investigation has been conducted into the electrical layouts of the onshore substation and offshore cables for a Tamil Nadu demonstration offshore wind farm, as well as indicative costing and sizing for the equipment. It is assumed that the Tamil Nadu offshore development will not include an offshore substation due to its close proximity to shore.

The offshore wind farm location within zone A is assumed at 15 km away from the shore. The wind farm being near to the shore and by utilising a 66 kV collection system voltage level, FOWIND estimate that direct HVAC connection of the offshore wind farm to the onshore substation could be feasible. This arrangement reduces the overall CAPEX and future operation and maintenance cost. However, towards the detail engineering if the offshore wind farm is finally located more than 20 km from the shore, then the requirement of having an offshore substation should be assessed.

For the propose of the electrical concept design a base case has been established, considering 84 WTGs each of 6 MW capacity. The overall installation capacity is therefore calculated as 504 MW. For the remaining project configurations Turbine.Architect has been used to validate and scale the results from this concept design study. To minimise electrical losses, 66 kV array cables have been assumed for all turbine MW capacities.

13.6 CONCEPT FOUNDATION DESIGN

Turbine.Architect's foundation module has been used to undertake a foundation comparison for sub-zone A3. Monopile, jacket and GBS foundation types have been assessed to determine preliminary estimates of dimensions, masses and costs. Three turbine types have been considered and each combination of foundation and turbine has been assessed using upper and lower bound soil conditions. Monopile, jacket and GBS types have been selected for Tamil Nadu, based on findings from the Pre-feasibility Study [4], Supply Chain, Port Infrastructure and Logistics Study [2] and findings from the site data study.

Results show jackets as being lighter than monopiles for all turbine sizes and soil conditions at the A3 sub-zone. In terms of cost the results show monopiles as being more economical for both ground conditions modelled. GBS foundations are only suitable for the stronger cemented soil profile and for the lower bound weaker sand profile are deemed unsuitable. For the soil profile where gravity base structures are suitable they are shown to have significant economic advantages over jackets and monopiles.

Compared with typical north European pile embedment, the predicted embedment depth for monopiles and jackets in Tamil Nadu are not overly onerous. If very hard, cemented or rocky soil conditions are encountered then there is risk that alternative installation methods to pile driving will be required. In these scenarios piles can be installed with the assistance of drilling equipment, either to drill a cavity in rock into which the pile is then grouted, or drilling during a pause in pile driving to remove hard ground beneath the pile tip before pile driving resumes. Both of these options are time consuming, costly and present risks to installation. Gravity base structures are shown as a highly competitive solution but only when the soil conditions are suitable. Their attractiveness is a result of the relatively cheap cost of materials in comparison to steel. The variation in soil conditions over sub-zone A3 is not known and therefore, it is not clear how applicable gravity base structures are. It is expected that cemented soils, or very dense surface sands, will not be found to extend over a large proportion of sub-zone A3.

The foundation studies completed thus far should be treated as preliminary only. The level of detail is applicable for preliminary costing studies and CAPEX estimates cost modelling. However, more detailed design exercises should be completed before forming firm conclusions regarding foundations. A detailed understanding of the local ground conditions in terms of its geospatial variation should be obtained as this will lead to a better understanding of the applicability of gravity base foundations.

13.7 INSTALLATION CONSIDERATION

The FOWIND consortium provided a high-level overview for key installation considerations and methodologies for optimisation as part of the Supply Chain, Port Infrastructure and Logistics Study [2] Section 3.2 and the Pre-feasibility Study [1] Section 6.3. The key areas of focus for installation studies are offshore wind port types, vessels and strategy planning.

Considering Tamil Nadu's climatic conditions, the summers are extremely hot and dry, while the monsoons are quite strong and can cause severe floods. Therefore it is important to consider an adequate amount of weather downtime within the overall transport and installation schedule. Furthermore, schedule planning should consider monthly weather fluctuations during the year, like cyclones (Typhoons). With a typical share of up to 20% of the total CAPEX of an offshore wind project, transport and installation expenses have a significant impact on the profitability of the wind farm. Therefore, optimising the strategy and reducing potential downtime due to weather can support cost reduction and mitigation of schedule over runs during the transport and installation phase of the project.

The CAPEX for installation and logistics is calculated using Turbine.Architect's installation module which estimates the costs for the installation of turbines, foundations and electrical substations. Turbine and foundation installation strategies depend on the turbine size, the selected foundation type, the depth and the selected metocean climate, the installation module finds the appropriate vessel and installation durations from pre-processed installation data. For electrical substations, the lifts are more problematic and may require a Heavy Lift vessel and as such day rates are very elastic, ranging by a factor of ten depending on market conditions. This results in a greater uncertainty for offshore substation CAPEX.

13.8 OPERATION AND MAINTENANCE CONSIDERATIONS

The access logistics associated with these maintenance activities, are one of the most significant operational challenges facing the offshore wind energy market. Access strategies can be categorised into three main types; onshore-based marine access, helicopter access and offshore-based marine access. Onshore-based marine access (e.g. workboats) is the most common approach to date, however is heavily restricted by the sea-state during transfer onto the structures.

In order to select the most suitable O&M Strategy DNV GL used its in-house model: "O2M Optimisation of Operations and Maintenance" to simulate a variety of O&M strategies at sub-zone A3 for each of the project capacities and wind turbine capacities. It has been noted that the use of helicopters or motherships is not envisaged to prove optimal for most of the demonstration project scenarios. Due to the significant logistical and regulatory complexity added to a project and related to helicopter operations, it has been deemed appropriate to rule out these strategies and assume that all first offshore wind projects in India will be based on the most proven work boats access methodologies. Considering only workboat access methods preliminary estimates for OPEX and availability have been presented for each project configuration in sub-zone A3. OPEX ranges between 1,041 mINR and 1,419 mINR per annum for 150-152 MW farm capacities and 3,521 mINR and 4,643 mINR per annum for 500-504 MW capacities. This variation relates to cost savings seen when operating and maintaining a fewer number of larger capacity WTGs. Larger turbines are a key driver for reducing LCOE.

13.9 OUTLINE PROJECT COSTING

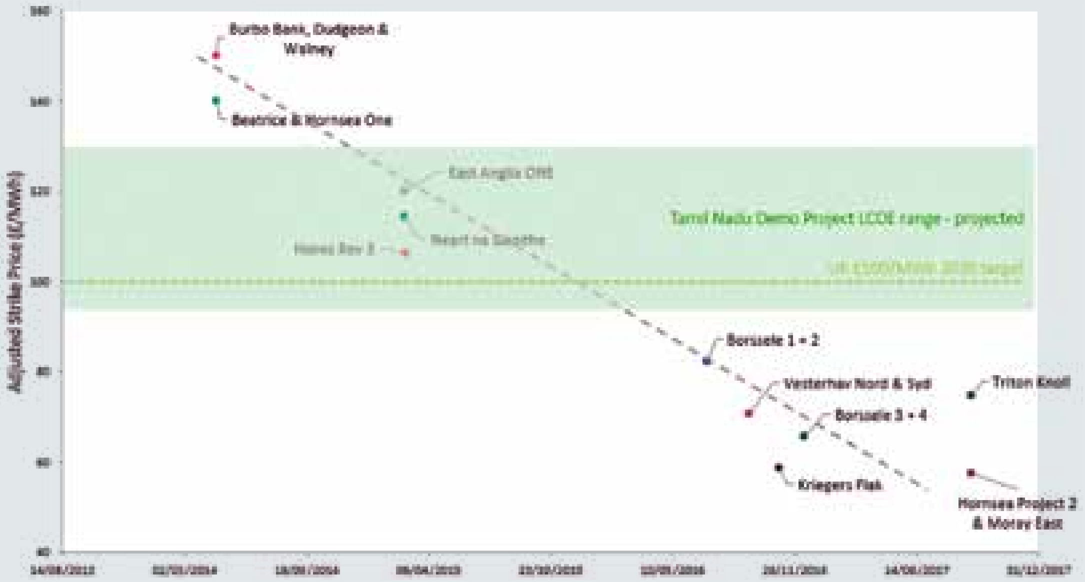
The cost of energy from an offshore wind farm reduces as turbine size increases; this mirrors general industry experience to date, primarily in European waters, in which technological development of larger commercially-available turbines has been the most significant driver behind the notable reductions in cost of energy from utility-scale offshore wind farms. In addition, larger WTG rotors reach higher heights, to where wind speeds are typically higher, and hence larger turbines would be expected to yield a higher capacity factor and higher total AEP. Increasing the capacity of the wind turbines from 4 MW to 10 MW results in a cost of energy reduction of approximately 23% (152 MW project confg.) and 19% (504 MW project config.). It was also noted that, with regard to the development of offshore wind in low-wind environments, that the deployment of turbines with a lower power density (i.e. a larger rotor for a given generator capacity) would likely contribute to a lower cost of energy.

Although increasing turbine size reduces the cost of energy, there are potential advantages to deploying smaller turbines, particularly in new markets with developing supply chains. Very large turbines may require construction infrastructure that is either not available, or significantly limited in its availability; selection of these turbines may then result in an undesirable increase in procurement and delay risk. In such a situation, smaller turbines may reduce the risk premium to outweigh some of the cost of energy deficit and hence merit selection for a project.

The LCOE for the Tamil Nadu demonstration project has been estimated at between 7,675 INR/MWhr and 9,965 INR/MWhr for a 150-152 MW wind farm capacity and between 7,362 INR/MWhr and 9,087 INR/MWhr for a 500-504 MW wind farm capacity. Figure 13-1 compares recently awarded European offshore wind tenders against LCOE projections for the Tamil Nadu demonstration project. It can be seen the lower bound of the projected LCOE figures for Tamil Nadu is broadly in line with the UK 2020 target and the upper bound is slightly above but still tracking LCOE figures for recent European projects. This appears positive for Tamil Nadu, especially considering the demonstration project figures have be calculated based on a higher financial discount rate (i.e. 10% vs. 6-7%).

FIGURE 13-1: EUROPEAN LCOE TRENDS VS TAMIL NADU PROJECTIONS

(Adjusted for grid, development costs and contract length where required)



13.10 PRELIMINARY PROJECT RISK REGISTER

When planning offshore wind farm projects, all decisions must be considered regarding potential future actions, although outcomes cannot be foreseen with certainty due to incomplete information. This uncertainty associated with all business activity is defined as risk. This section provided a high level qualitative assessment of the principal risks for the potential offshore wind farm zones identified in Tamil Nadu. It is important to ensure that significant risks are managed and that mitigation measures are identified. Risks were characterised into three major categories (High, Medium and Low) with "High" indicating the risk is considered "Not acceptable" and mitigation through an alternative solution is likely to be required. Further tasks have been identified as "Medium" indicating that mitigation measures would likely be required to reduce risks to "as low as reasonably practicable" (ALARP) levels. At this preliminary stage the following tasks have been highlighted as "High" risk and are recommended as priorities for mitigation measures in future offshore wind developments:

- **Wind Resource:** high uncertainty of the wind resource assessment (noted LIDAR is planned for Tamil Nadu by NIWE);
- **Geotechnical conditions:** there is only limited information on the seabed geology of the Tamil Nadu region available, and DNV GL's experience in the region indicates high spatial variation from loose/weak to strong highly cemented sand material to depth;
- **Grid connection:** grid availability.

13.11 ENVIRONMENTAL AND SOCIAL IMPACT

The FOWIND Pre-feasibility Study for Tamil Nadu [1] included chapters on environmental and social impact that discussed the potential impacts of offshore wind projects, regulatory mechanisms and protocols for planning consent. In this feasibility study the scope, key principles and best practice for environmental and social impact assessments is discussed. Key biological, physical and human aspects are considered. Along with other permitting recommendations the importance of allowing a design envelope approach in EIA permit applications, to give flexibility to the development, is highlighted.

14. INDUSTRY PERSPECTIVE ON INDIA'S OFFSHORE WIND POLICY

Written by ReNew POWER

The objective of this exercise was to supplement FOWIND's feasibility assessments undertaken for Gujarat and Tamil Nadu with an informed feedback from an experienced renewable energy project developer's perspective on the key areas of offshore wind policy design, regulatory framework, financial mechanism, tariff regime and the supply chain ecosystem.

We structured our discussions under five core areas. During our discussions with the wind industry and project developers in the past months we found that there are recurring threads in their perspective on the current offshore wind policy and the development of a successful offshore wind sector in India. In the following paragraphs we highlight and synthesize our discussions from the industry perspective.

14.1 POLICY SUPPORT:

- For providing long-term clarity and certainty to the sector the Ministry of New and Renewable Energy should declare offshore specific targets (e.g. Renewable Purchase Obligations for the states).
- Further the Ministry in conjunction with the grid companies plan for an expansion of onshore transmission targets to facilitate timely grid integration of all new generation from offshore wind farms.
- With the expectation that the early offshore wind projects will have a very high import requirement for necessary components. Providing exemption from excise duties or GST on offshore wind turbines (WTGs), inverters, transformers, evacuation infrastructure etc. for the early phase projects would make project development possible at reasonable cost.
- The Ministry should consider providing time bound incentives similar to the provisions of Generation Based Incentive, Accelerated Depreciation etc. that supported the creation of India's successful onshore wind sector. The incentives would have to be designed keeping in mind the unique conditions associated with the complex range of actors within the offshore wind sector.
- The Ministry of New and Renewable Energy should work with the Ministry of Power, Ministry of Finances, the Central and State Electricity Regulatory Commissions, and lastly the Central and State Transmission Utilities to provide a comprehensive polity roadmap for offshore wind development in India.

14.2 REGULATORY SUPPORT:

- The Ministry of New and Renewable Energy in collaboration with the relevant state authorities should pre-identify dedicated offshore wind development zones within the Indian SEZ.
- The industry sees the UK's Crown Estate Model [60] as a desired seabed use and management model that the government could consider towards developing India's offshore wind specific assets.
- The industry applauds the current policy's intent to undertake 'Single Window Clearance' system for all necessary approvals and permits, by its nodal agency the National Institute of Wind Energy. This facility should comprise all relevant aspects including environmental clearances to onshore power evacuation approvals. This is a crucial element within the supporting regulatory ecosystem as it is expected a multitude of ministries and regulatory bodies, both at central and state levels, would have to be involved for securing the necessary project development clearances.
- Given the initial cost of early offshore wind projects, these wind farms should include the obligation from the offtaker as "Must Run" status.
- Further for these 'first of its kind projects' in India – the regulators must ensure measures are taken to safeguard them against losses from curtailment by the state or regional grid operators, as witnessed by land-based renewable energy generators. To make the projects viable offshore wind must be granted the "deemed generation provision" to offset any curtailment.
- Further, in line with the expected high investment needs for offshore projects, priority payments from DISCOMs must be ensured.

14.3 FINANCING SUPPORT/TARIFF REGIME:

- With higher expected cost of energy from the early projects, the financial viability of projects can be improved by securing lending from public sector banks/government backed special purpose funds (e.g. similar to the Green Investment Bank in the UK) to promote the inception of this industry in India.
- The government can seek tie-ups with the European Investment Bank who have provided significant lending to offshore wind projects in Europe over the last decade, the KfW that has an offshore wind lending program, the World Bank and other sister development banks for low-cost funds for offshore wind projects. Similar to the State Bank of India's recently availed US$ 625 M facility from the World Bank for promotion of grid connected rooftop solar projects.
- The Ministry could also consider ensuring that a Feed-In Tariff with mandatory procurement by the DISCOMs is available to the offshore wind projects. The industry had recommendations for the design of this tariff regime:
    - Offshore tariff could be structured to factor in the nature of each specific project. The tariff bands could be built to consider the impact of water depth, distance from shore, capital cost involved etc. This would be similar to onshore wind policy developed by states where tariff is determined based on wind power density, capital cost of installation, O&M cost etc.
    - Tariff could also be differentiated based on project size.
    - Tariff should be worked out based on a 'Front Loaded' payment method, wherein instead of having a constant tariff level over the complete duration of support, the tariff structure could pay higher tariff for the early years of a project, with a tapering out of the tariff towards the end of the tariff agreement period. This can help to reduce financing cost without increasing the total sum of financial support for the early offshore wind projects.

14.4 GRID INTEGRATION SUPPORT:

- The state governments could provide significant risk management benefits for offshore wind projects by improving the onshore existing grid infrastructure by floating concurrent tenders for connection of offshore plants to the onshore grid.
- The Ministry of New and Renewable Energy in collaboration with the CTU should initiate a review of the current grid-code for the need of a separate grid code or modifications specifically for offshore wind. Future grid code modifications should be reviewed in light of the specific characteristics and quantum of power from offshore wind farms and the capacity addition envisaged under long-term plans for the offshore sector of the government.
- The state and central agencies must clarify the compliance boundary of offshore wind farms under the individual grid code requirements, as applicable.
- Development of underwater/seabed power evacuation infrastructure and setting up of offshore sub station to be PGCIL's responsibility. This reduces significant project risk for the offshore wind farm developer(s).
- Training of PGCIL personnel in key offshore countries such as the UK, Germany, Denmark etc. as underwater/seabed power evacuation and cabling expertise is currently not available in India.
- National Clean Energy Fund allocation could be utilized for investments in the relevant transmission sector improvements.

14.5 SUPPLY CHAIN SUPPORT:

- Recommendations provided under the FOWIND Supply Chain, Ports and Infrastructure Study should be looked at by the Ministry.
- The government should undertake the development of ports and make them ready for offshore wind project delivery. Current port infrastructure in India will be a limiting factor.
- Early assistance from public sector specialist companies like the Oil and Natural Gas Corporation could be extremely beneficial both for operational and in competency development for offshore wind project development. This could include help from lending of jack-up rig vessels to drilling and foundation casting. A government directive to this effect would greatly expedite collaboration between the ONGC, its suppliers and offshore project developers. This would expedite the build-up of Indian offshore wind sector's competency indigenously.
- Development of offshore focused R&D by government for long-term LCOE reduction. This could include bilateral MoUs with the relevant European agencies and governments etc. for sharing of expertise, training of key technical personnel etc. in order to have a long term development plan for the sector.
- Ensure a transparent system for acquisition of approvals and all related information through dedicated online portals that are regularly updated. Also, NIWE as the nodal agency under the policy framework must work towards ensuring effective collaboration between involved/affected parties during the planning stages to minimise execution challenges later on.

15. FIRST OFFSHORE WINDFARM PROJECT IN INDIA (FOWPI)

Written by FOWPI

FOWIND has paved the way for offshore wind in India in general and specifically in Gujarat and Tamil Nadu. Next step is to start construction works, and the EU-funded "First Offshore Windfarm Project for India" is for this purpose preparing technical documents for a first 200 MW demonstration windfarm in Gujarat as well as providing capacity building for the implementation.

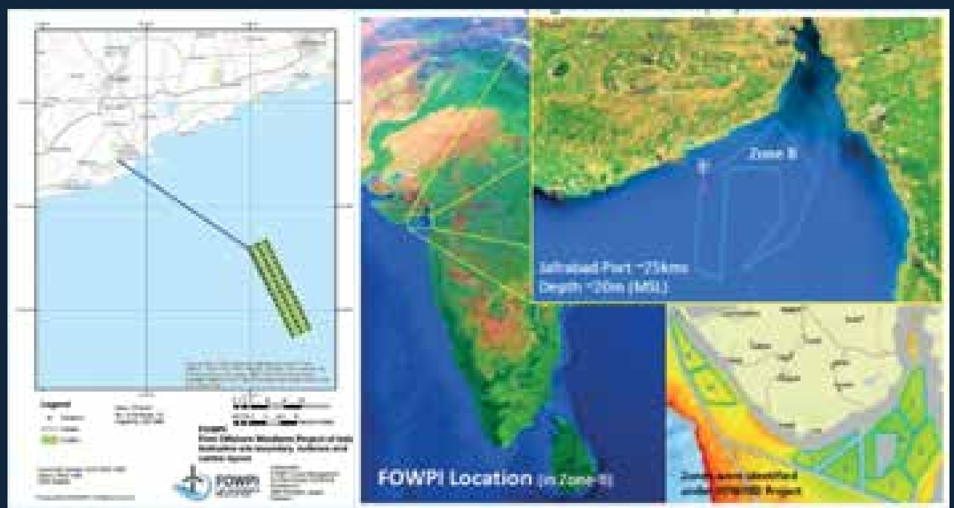
The planned 200 MW demonstration windfarm is to be located in the Zone B, ref. Figure 15-1.

Introduction of the offshore wind technology brings challenges. Some challenges are technical such as availability of design capacity, manufacturing facilities and installation equipment. Other challenges are non-technical such as legal and procedural regulations for permitting, financing and use of infrastructure. Worldwide an early step in the learning process is implementation of one or a few demonstration offshore wind farms to test and improve the local capability before large scale commercial implementation. Denmark got in 1991 5MW Vindeby, in 1996 5 MW Thunø and in 2000 40 MW Middelgrunden demonstration windfarms. Germany installed 60 MW AlphaVentus in 2009 and Sweden, UK and the Netherlands in similar way have had their demonstration windfarms.

Professional investors assess weaknesses as the mentioned as "risks". Risks of not seeing the scheduled performance and results, and thus of return on investments to become lower than assumed. For this reason, early offshore wind bidding prices of India can be expected to become lower after implementation of a demonstration windfarm, and therefore it is advisable to have a demonstration project as FOWPI before large scale auctioning.

The FOWPI project started in 2016 and is already far developed. The developed technical tender call documents cover design basis input of wind, metocean and soil, as well as advisory design studies for layout, production, foundation and electrical.

FIGURE 15-1 LOCATION IN ZONE B OF GUJARAT (RIGHT) AND LAYOUT (LEFT) OF FOWPI 200 MW WINDFARM IN GUJARAT



15.1 DESIGN BASIS OF FOWPI

A site specific desk top wind study has been developed, which shall be calibrated and adapted according to wind measurements at site initiated by FOWIND and NIWE. The study shall cover operational conditions as well as extreme conditions, governed by typhoons. Wind is the most important parameter for assessment of the cost of power, and thus FOWPI builds on the results of FOWIND.

Metocean covering waves, current, sea-state and more for the site in question is another important part of the design basis. FOWPI has prepared a metocean study for the site, and results are available through reports, which can be found at NIWE's web-page, ref. Figure 15-3. The reports explain the model and shows resulting design conditions as well as calculated operational conditions meant for vessel assessments. The study has one short-coming: On-site measurements with wave-buoy and ADCP for calibrations are not (yet) available.

At site of the LIDAR-platform, ref. Figure 15-2, NIWE has carried out a geotechnical drilling, which is available for FOWPI. It shows around 15 m sea depth, 9 m of incompetent clay (mud) from sea-bed down and then strong sand as far as drilling went (30m from sea bed), ref. Figure 15-4. NIWE and MNRE is considering to implement 1-3 extra drillings at the windfarm site to increase the understanding of the conditions.

Fugro has for FOWPI implemented a full geophysical survey campaign covering the 70 km^2 FOWPI site. The campaign provides output from UHR (Sparker), Side Scan Sonar, Magnetometer and Bathymetry. The campaign results will be analysed and reported for FOWPI.

GETCO will for FOWPI prepare a grid connection study for the area near the FOWPI site. A usable connection point at 220 kV level will be identified for the project. ERM will for FOWPI prepare an ESIA scoping report. The scope for an ESIA will be proposed. A full ESIA will have to be prepared and the project is looking for funding for this.

FIGURE 15-2: OFFSHORE LIDAR PLATFORM

FIGURE 15-3: 50-YEAR EXTREME WAVE HEIGHT, HS(M), FROM FOWPI METOCEAN STUDY

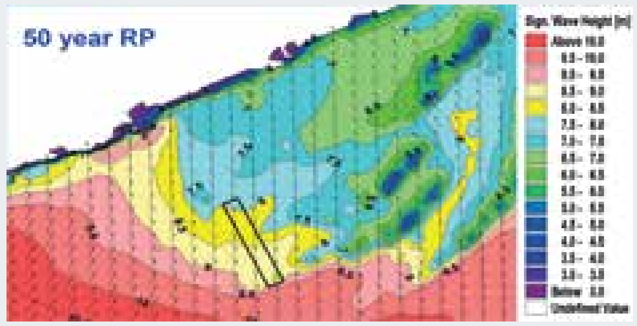


FIGURE 15-5: PRELIMINARY BATHYMETRY AT THE SITE (SHOWN IN BLUE LINE)

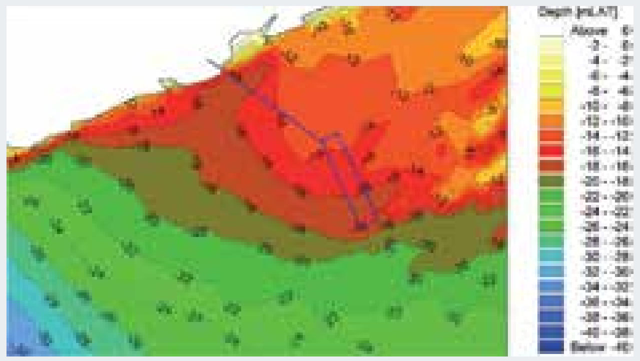


FIGURE 15-4: RESULT OF NIWES GETOECHNICAL DRILLING AT LOCATION OF LIDAR-PLATFORM NEXT TO SITE

15.2 DESIGN FOR FOWPI

FOWPI has prepared a number of design studies to guide project developers in their preparations. All of these studies are advisory only as neither full design basis has been established nor has wind turbine type and size been chosen.

A study on Wind Turbine Technology, Layout and AEP has been prepared. Reference wind turbines of two sizes are defined and desk top based wind resource are provided for the two reference wind turbines. Choice of wind turbine type has to cope with typhoon conditions and low annual mean wind speed exactly as onshore. The wind farm layout is simple and consists of 3 lines of wind turbines perpendicular to dominating wind direction, ref. Figure 15-1.

A study on foundation design for the site recommends to use monopiles. Advisory comments on design of main structure as well as of secondary steel are given. This should give easy access to the technology for Indian designers and decision makers.

A study on electrical design for the site opens for two very different options to be decided upon by eventual project developer. Either an offshore substation will be used, which converts from 33 kV to 220 kV in the windfarm before export via one cable to shore and grid connection. Or an onshore substation will be used, which is fed via multiple (4-6) 33 kV export cables from the windfarm to shore. An offshore substation preparation requires sophisticated marine electrical designers, experienced high quality manufacturers and large installation vessels. The onshore solution on the other hand has large costs for many kilometre of marine cables and marine installation of these. The study gives advises on electrical offshore windfarm design for newcomers and decision makers.

FOWPI is organising workshops and conferences to share the results as fast as possible, ref. Figure 15-7. It will facilitate the fast preparation and implementation of the First Offshore Windfarm Project of India – maybe already by 2020.

FIGURE 15-6 OFFSHORE SUB STATION FOR A EUROPEAN OFFSHORE WINDFARM

FIGURE 15-7 FOWPI SHARES RESULTS AT WORKSHOPS AND CONFERENCES

WIND IS THE MOST COMPETITIVELY PRICED TECHNOLOGY IN MANY IF NOT MOST MARKETS; AND THE EMERGENCE OF WIND/SOLAR HYBRIDS, MORE SOPHISTICATED GRID MANAGEMENT AND INCREASINGLY AFFORDABLE STORAGE BEGIN TO PAINT A PICTURE OF WHAT A FULLY COMMERCIAL FOSSIL-FREE POWER SECTOR WILL LOOK LIKE.

In Europe offshore wind power saw a record 3,148 MW of net additional installed capacity in 2017. This corresponds to 560 new offshore wind turbines across 17 wind farms. There were 14 projects fully completed and connected to the grid, including the first floating offshore wind farm.

Europe now has a total installed offshore wind capacity of 15,780 MW. This corresponds to 4,149 grid-connected wind turbines across 11 countries. 2017 was a record year: twice as much as 2016 and 4% higher than the previous record in 2015."

The numbers show a maturing industry, in transition to a market-based system, competing successfully with heavily subsidized incumbent technologies.

16. REFERENCES

[1] FOWIND, "Pre-feasibility Study for offshore wind farm development in Gujarat," 2015.

[2] FOWIND, "Supply Chain, Port Infrastructure and Logistics Study for offshore wind farm development in Gujarat and Tamil Nadu," 2016.

[3] FOWIND, "Grid Integration Study for offshore wind farm development in Gujarat and Tamil Nadu," 2017.

[4] FOWIND, "Pre-feasibility Study for offshore wind farm development in Tamil Nadu," 2015.

[5] Global Wind Energy Council, "Offshore Wind Development in India: FOWIND Commissions India's First LIDAR for Offshore Wind Resource Assessments in Gujarat," 02 11 2017. [Online]. Available: http://gwec.net/offshore-wind-development-in-india-fowind-commissions-indias-first-lidar-for-offshore-wind-resource-assessments-in-gujarat/#. [Accessed 01 12 2017].

[6] FOWIND, "From Zero To Five GW: Offshore Wind Outlook for Gujarat and Tamil Nadu," 2017.

[7] DNV GL, "Turbine.Architect," [Online]. Available: https://www.dnvgl.com/services/turbine-architect-49342. [Accessed 01 12 2017].

[8] "Cost of Energy Model Theory Guide," DNV GL, 2015.

[9] "Marine Traffic," [Online]. Available: https://www.marinetraffic.com/en/ais/home/centerx:71.7/centery:20.1/zoom:8. [Accessed 15 December 2017].

[10] "Anemoscope User's Guide," Canadian Hydraulics Centre and Environment, [Online]. Available: http://www.anemoscope.ca/Documents/AnemoScope_User_Guide.pdf. [Accessed 18 05 2013].

[11] "Anemoscope Reference Guide," Canadian Hydraulics Centre and Environment, [Online]. Available: http://www.anemoscope.ca/Documents/AnemoScope_ReferenceGuide.pdf. [Accessed 18 02 2013].

[12] "Global Map V.1 (Global Version) – Land Cover (GLCNMO) Download, ISCGM, Geographical Survey Institute, Chiba University and collaborating organizations; http://211.19.49.27/gmd/download/glcnmo.html, accessed 18/02/2013.," [Online].

[13] "Shuttle Radar Topography Mission, Jet Propulsion Laboratory, NASA; http://www2.jpl.nasa.gov/srtm/, accessed 18/02/2013.," [Online].

[14] "NCEP/NCAR Reanalysis dataset, Earth System Research Laboratory, NOAA; http://www.cdc.noaa.gov/data/gridded/data.ncep.reanalysis.html, accessed 18/02/2013.," [Online].

[15] "Modern Era Reanalysis for Research and Applications (MERRA)," NASA GSFC Global Modelling and Assimilation Office , 2008. [Online].

[16] A. Chawla, D. M. Spindler and H. L. Tolman, "30 Year Wave Hindcasts using WAVEWATCH III with CFSR winds, Phase 1," NOAA/NWS/NCEP/MMAB, Maryland USA, 2012.

[17] A. Chawla, D. M. Spindler and H. Tolman, "WAVEWATCH III Hindcasts with Re-analysis winds, Initial report on model setup," NOAA/NWS/NCEP/MMAB, Maryland USA, 2011.

[18] D. Spindler, A. Chawla and H. Tolman, "An initial look at the CFSR Reanalysis winds for wave modeling," NOAA/NWS/NCEP/MMAB, 2011.

[19] Logica, "DUE GlobWave Deliverable D.2 - Technical Specification, V1.3," 2010.

[20] Satellite Oceanographic Consultants, "DUE GlobWave Deliverable D5 Product User Guide, V1.4," 2010.

[21] NASA/GSFC/NOAA, NASA/GSFC/NOAA, 2009. [Online]. Available: http://podaac.jpl.nasa.gov/dataset/CCMP_MEASURES_ATLAS_L4_OW_L3_0_WIND_VECTORS_FLK. [Accessed 2014].

[22] HYbrid Coordinate Ocean Model, Center of Ocean-Atmospheric Prediction Studies, 2010. [Online]. Available: http://www.hycom.org. [Accessed 2014].

[23] DHI, MIKE 21/3 Flow Model FM Hydrodynamic and Transport Module - Scientific Documentation., 2005..

[24] NOVELTIS, 2015. [Online]. Available: http://tips.noveltis.com/.

[25] OSU. [Online]. Available: http://volkov.oce.orst.edu/tides/.

[26] K. Knapp, M. C. Kruk, D. Levinson, H. Diamond and C. Newmann, "The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone best track data," 2010.

[27] NOAA, National Climatic Data Center, NOAA National Climatic Data Center, 2010. [Online]. Available: http://www.ncdc.noaa.gov/ibtracs/. [Accessed 2014].

[28] ISO, "Petroleum and natural gas industries - Specific requirements for offshore Structures, Part 1: Metocean design and operating considerations," ISO, 2005.

[29] American Petroleum Institute, "Interim Guidance on Hurricane Conditions in the Gulf of Mexico," 2007.

[30] The United Kingdom Hydrographic Office, Admiralty Sailing Directions, vol. Various, Taunton, UK: The Hydrographer of the Navy.

[31] P. E. Tucker MJ, "Waves in ocean engineering:," Elsevier Science Ltd, 2001.

[32] Det Norske Veritas, "Environmental Conditions and Environmental Loads," DNV, 2010.

[33] F. J. D., "Nonlinear Wave Theories," Ocean Engineering Science, vol. 9, 1990.

[34] E. Spentza, B. Chicaud and I. Garcia de Andoin, "Parametric Modelling of Cyclonic Winds for Quick Location Assessment," in 22nd International Ocean and Polar Engineering Conference.

[35] C. K. Cooper, "Parametric Models of Hurricane Generated Winds, Waves and Currents in Deep Water," in 20th Offshore Technology Conference, Houston, Texas, 1998.

[36] H. E. Willoughby, R. W. R. Darling and M. E. Rahn, "Parametric Representation of the Primary Hurricane Vortex, Part II: A New Family of," Monthly Weather Review, vol. 134, pp. 1102-1120, 2006.

[37] ONGC, Composite Bouguer Gravity Map of Cauvery Basin, Tamil Nadu, 1993.

[38] Geological Survey of India, Geology and Mineral Resources of the states of India, Chennai, 2006.

[39] NGRI - Natural Geophysical Research Institute, India., Gravity Map Series of India (1: 5,000,000), First Edition, Explanatory Notes., 1978.

[40] S. Badrinarayanan, D. Sasisekaran and K. Sivakolun, New Archaeological sites in the Gulf of Cambay, India , Chennai., Chennai: National Institute of Ocean Technology., 2003.

[41] K. Vasudevan, L. V. Ramana, N. Nagasudha, A. Borthakur and S. K. Das, "Petroleum System and Play Types of Synrift Sequences, Ramand Subbasin, Cauvery Basin.," in 7th Internaitonal Conference and Exposition on Petroleum Geophysics., Hyderabad., 2008.

[42] IEC, "International Standard IEC 61400-1 Third edition 2005-08," 2005. [Online]. Available: http://webstore.iec.ch/preview/info_iec61400-1%7Bed3.0%7Den.pdf.

[43] Bureau of Indian Standards, "Code of Practice for Design Loads for Building and structues," Bureau of Indian Standards.

[44] Building Materials & Technology Promotopn Council (BMTPC); India..

[45] "4COffshore," 4C Offshore Market Overview Report, June 2017. [Online]. Available: http://www.4coffshore.com/.

[46] DNV GL, "FOWIND Offshore Wind Speed Mapping of Gujarat and Tamil Nadu," 2014a.

[47] International Energy Agency; Nuclear Energy Agency; Organisation for Economic Cooperation and Development, "Projected Costs of Generating Electricity," Paris, France, 2015.

[48] DONG Energy; Vattenfall; The Danish Energy Authority; The Danish Forest and Nature Agency, "Danish Offshore Wind - Key Environmental Issues," 2006.

[49] Danish Energy Agency; Danish Nature Agency; Dong Energy & Vattenfall, "Danish offshore wind key environmental issues – a follow-up," 2013.

[50] Collaborative Offshore Wind Research into the Environment, "COWRIE reports," [Online]. Available: http://www.thecrownestate.co.uk/energy-minerals-and-infrastructure/downloads/cowrie/. [Accessed 01 November 2017].

[51] The Crown Estate, "Marine Data Exchange," [Online]. Available: http://www.marinedataexchange.co.uk/. [Accessed 01 November 2017].

[52] Marine Management Organisation, "Review of post-consent offshore wind farm monitoring data associated," 2014.

[53] . A. Beiersdorf and A. Radecke, Eds., Ecological Research at the Offshore Windfarm alpha ventus, Springer Spektrum, 2014.

[54] OSPAR Commission, "Inventory of measures to mitigate the emission and environmental impact of underwater noise," 2014.

[55] Joint Nature Conservation Committee, "Statutory nature conservation agency protocol for minimising the risk of injury to marine mammals from piling noise," 2010.

[56] B. Berwyn, "How do offshore wind farms affect ocean ecosystems?," Deutsche Welle, 22 11 2017. [Online]. Available: http://www.dw.com/en/how-do-offshore-wind-farms-affect-ocean-ecosystems/a-40969339. [Accessed 30 November 2017].

[57] V. L. G. Todd, J. C. Warley and I. B. Todd, "Meals on Wheels? A Decade of Megafaunal Visual and Acoustic Observations from Offshore Oil & Gas Rigs and Platforms in the North and Irish Seas," PLoS ONE, vol. 11, no. 4, 2016.

[58] D. J. Russell, S. M. Brasseur, D. Thompson, G. D. Hastie, V. M. Janik, G. Aarts, B. T. McClintock, J. Matthiopoulos, S. E. Moss and B. McConnell, "Marine mammals trace anthropogenic structures at sea," Current Biology, vol. 24, no. 14, pp. R638-R639, 2014.

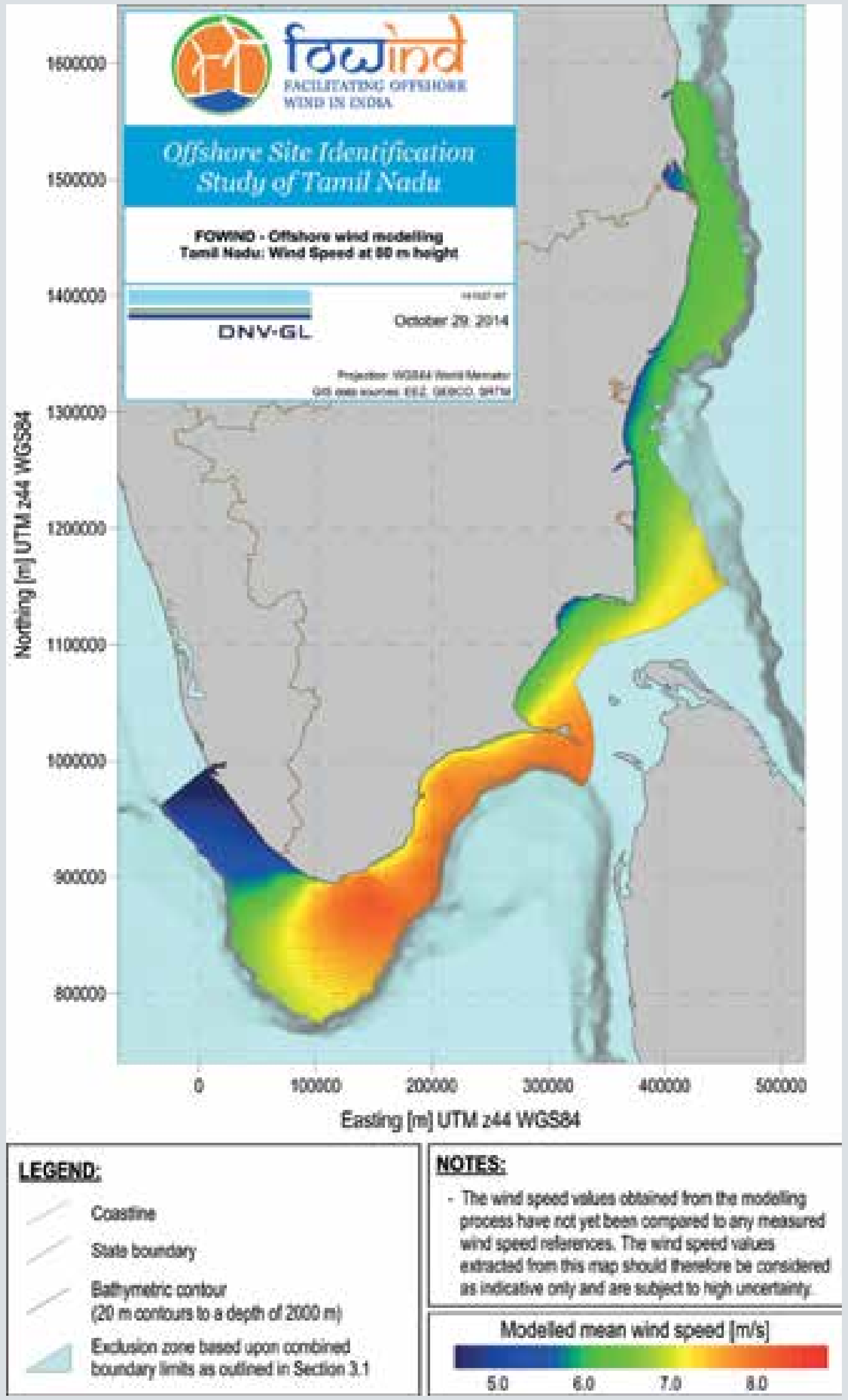
[59] "Energynumbers.info," 18 01 2018. [Online]. Available: http://energynumbers.info/uk-offshore-wind-capacity-factors. [Accessed 27 01 2018].

[60] CROWN ESTATE , "Offshore wind cost reduction: Pathways study.," May 2012. [Online]. Available: http://www.thecrownestate.co.uk/media/5493/ei-offshore-wind-cost-reduction-pathways-study.pdf. [Accessed 27 04 2015].

APPENDICES

APPENDIX 1
MODELLED WIND SPEEDS

FIGURE 16-1: MODELLED WIND SPEED OVER TAMIL NADU AT 80 M ABOVE SEA LEVEL



APPENDIX 1
MODELLED WIND SPEEDS

FIGURE 16-2: MODELLED WIND SPEED OVER TAMIL NADU AT 100 M ABOVE SEA LEVEL

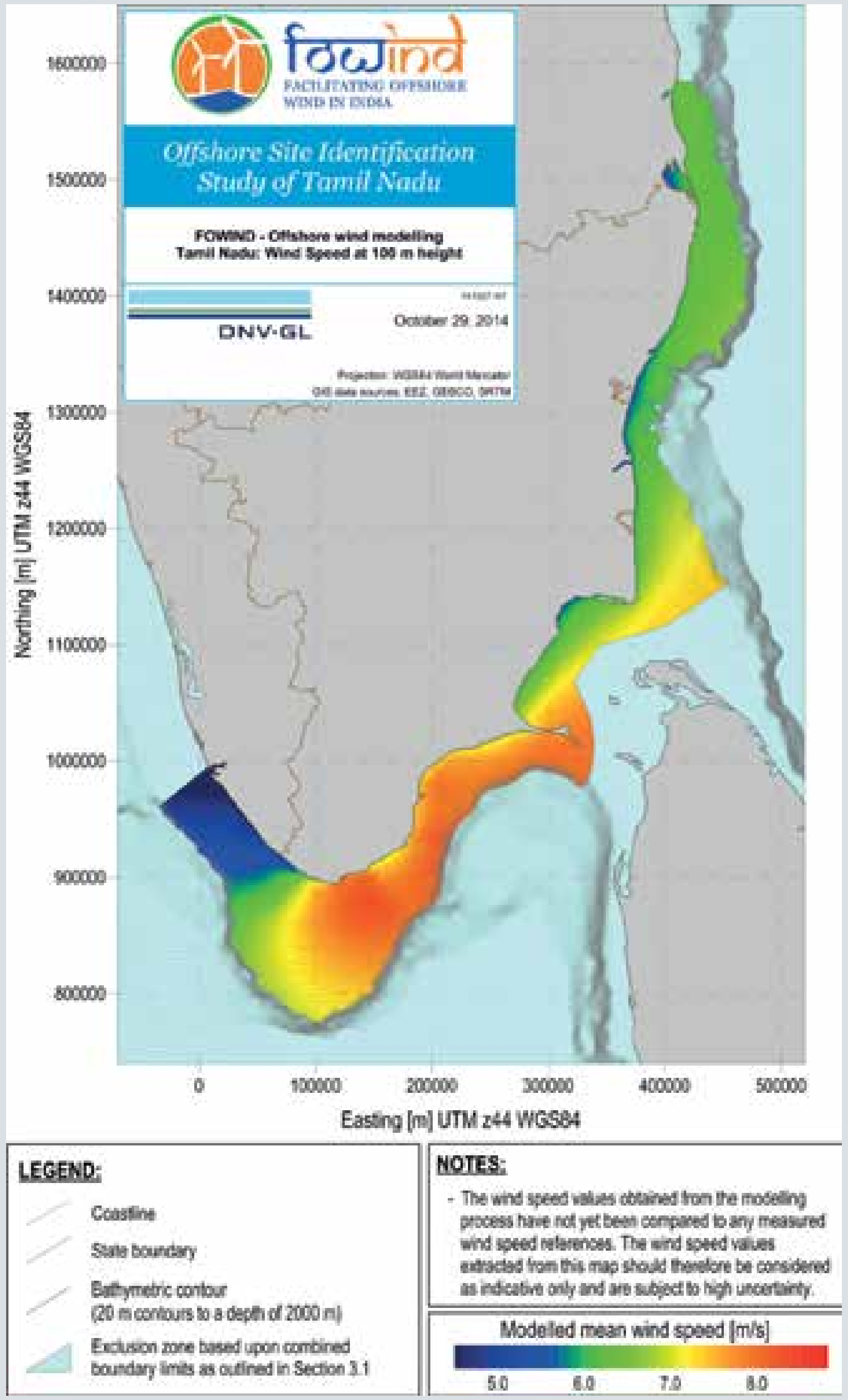
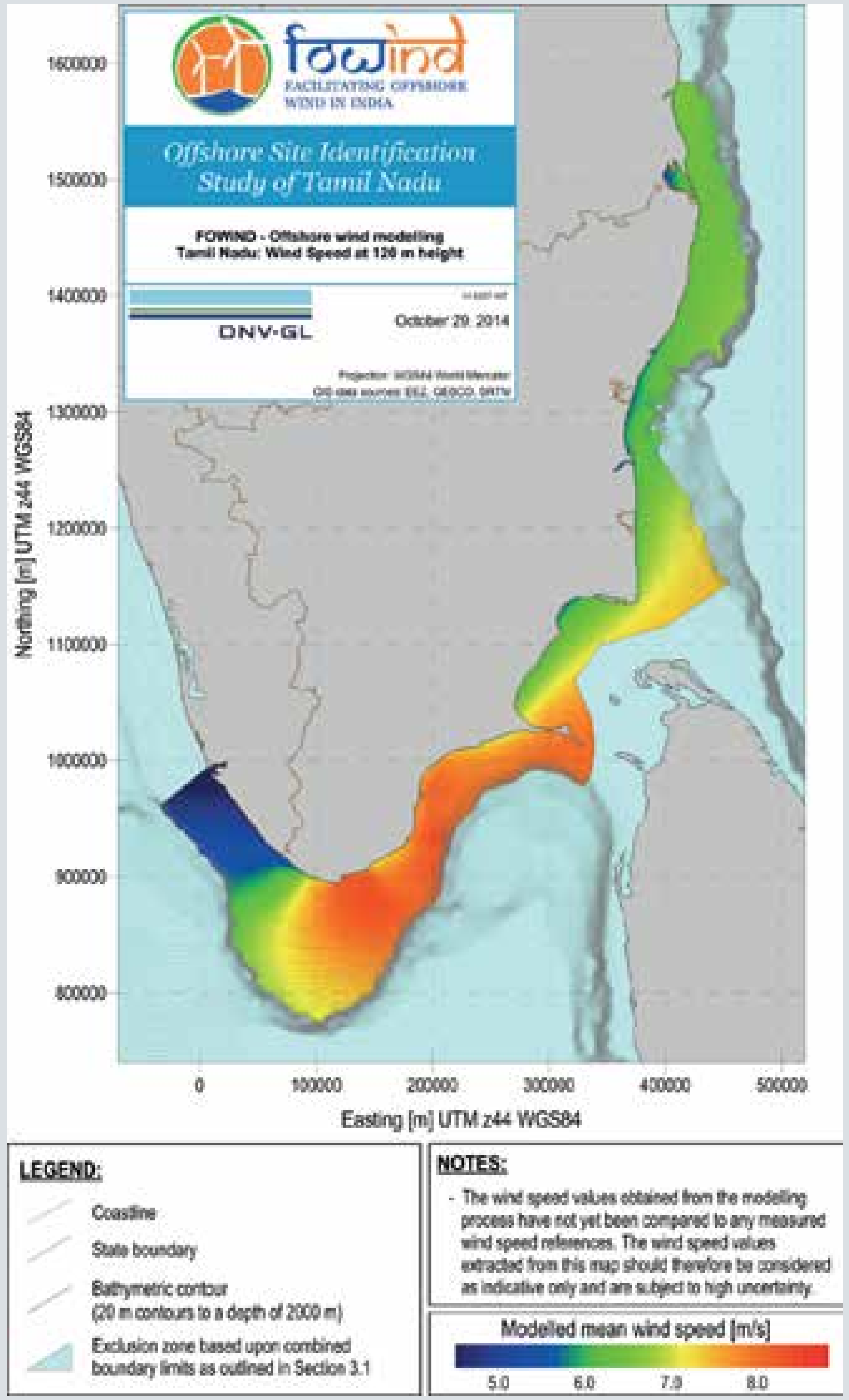


FIGURE 16-3: MODELLED WIND SPEED OVER TAMIL NADU AT 120 M ABOVE SEA LEVEL



APPENDIX 2
HEAT MAPS

FIGURE 16-4: OFFSHORE HEAT MAP WITH POTENTIAL DEVELOPMENT ZONES OF TAMIL NADU

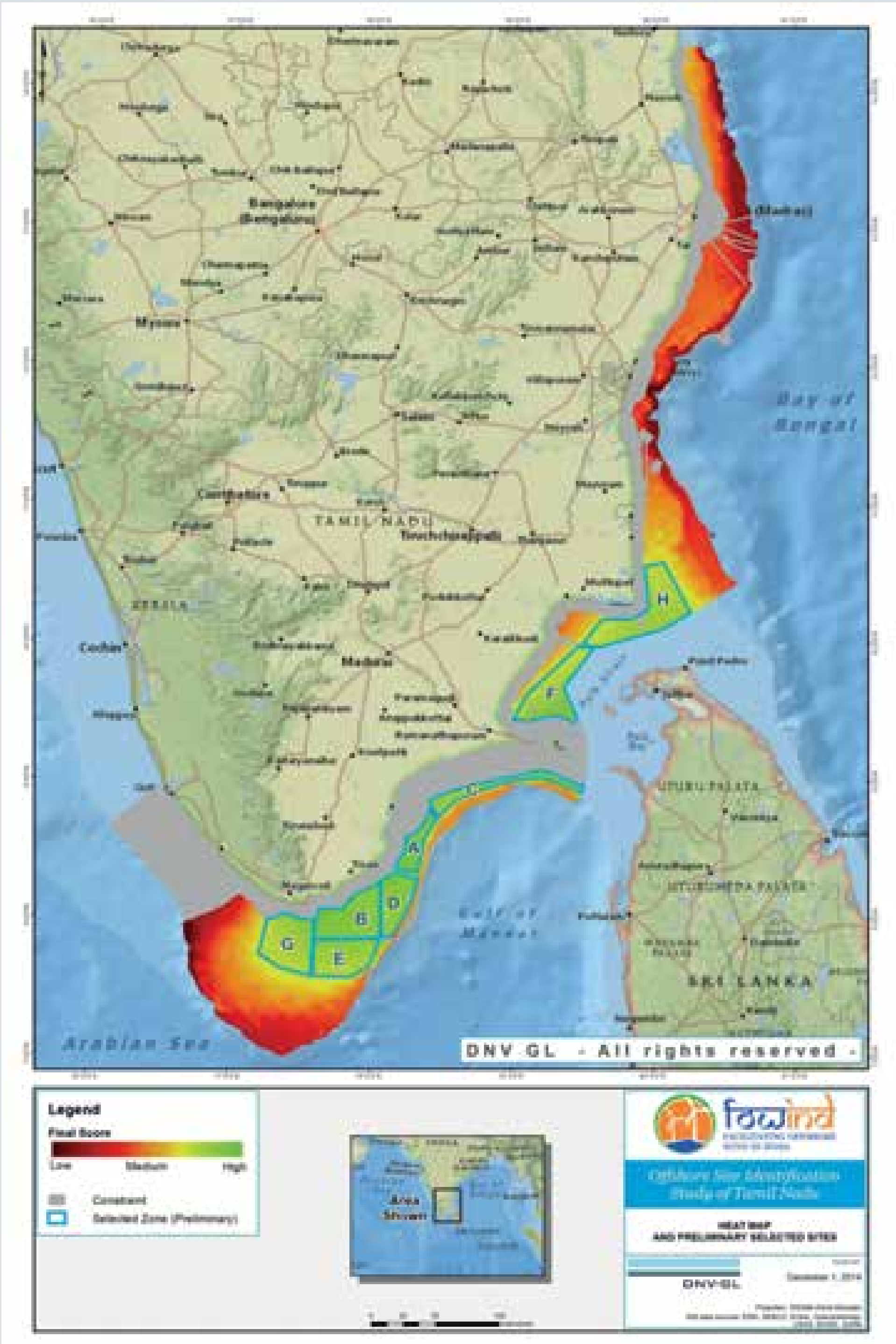


FIGURE 16-5: OFFSHORE POTENTIAL DEVELOPMENT ZONES OF TAMIL NADU

PROJECT PARTNERS

GLOBAL WIND ENERGY COUNCIL

Global Wind Energy Council (Brussels, Belgium) is the international trade association for the wind power industry. The members of GWEC represent over 1,500 companies, organisations and institutions in more than 70 countries.
www.gwec.net

Center for Study of Science, Technology and Policy (Bangalore, India) is one of the largest think tanks in South Asia; its vision is to enrich the nation with technology-enabled policy options for equitable growth.
www.cstep.in

DNV GL is the world's largest provider of independent renewable energy advice. The recognised authority in onshore wind energy, DNV GL is also at the forefront of the offshore wind, wave, tidal and solar sectors.
www.dnvgl.com

Gujarat Power Corporation Limited (Gandhinagar, India) has been playing the role of developer and catalyzer in the energy sector in the state of Gujarat. GPCL is increasing its involvement in power projects in the renewable sector, as the State of Gujarat is concerned about the issues of pollution and global warming.
www.gpclindia.com

World Institute of Sustainable Energy (Pune, India) is a not-for-profit institute committed to the cause of promoting sustainable energy and sustainable development, with specific emphasis on issues related to renewable energy, energy security, and climate change.
www.wisein.org

KNOWLEDGE PARTNER

National Institute of Wind Energy (NIWE) will support FOWIND efforts towards offshore wind feasibility assessments for potential offshore wind project development in the states of Gujarat & Tamil Nadu – with a special focus on wind resource validation. NIWE is an autonomous R&D institution under the Ministry of New and Renewable Energy, Government of India, established to serve as a technical focal point for orderly development of Wind Power deployment in India.
www.niwe.res.in

INDUSTRY PARTNER

ReNew Power Ventures Private Ltd. join as an industry partner. ReNew Power is a leading clean energy IPP with more than 3 GW of commissioned and under-construction clean energy assets, and a pipeline of close to 1.8 GW wind, solar and distributed.

ACKNOWLEDGEMENTS

Authors:

Jack Giles (DNV GL)
Ruben Menezes (DNV GL)
Frederick Davison (DNV GL)
Dheeraj Katkar (DNV GL)
Lucia Vega Fernandez (DNV GL)
Cyril Frelin (DNV GL)
Ramtin Hosseini Kamal (DNV GL)
Marco Beghi (DNV GL)

Reviewers:

Shruti Shukla (GWEC)
Alok Kumar (DNV GL)

Design:

Sweeta Patel

EUROPEAN UNION

fowind FACILITATING OFFSHORE WIND IN INDIA

CONTACT:

For further information,
please contact FOWIND Secretariat at
info@fowind.in

This report is available for download from
www.fowind.in
and the websites of respective project partners.

DISCLAIMER

This publication was produced with the financial support of the European Union. Its contents are the sole responsibility of FOWIND consortium and do not necessarily reflect the views of the European Union.

This report is provided for illustrative purposes only without any representations, warranties or undertakings from GWEC or DNV GL as to the content or any part of this report and the data contained therein, including without limitation in respect of quality, accuracy, completeness, or reliability.

The information contained in the report does not represent endorsement by GWEC, or DNV GL of any particular project, product or service provider. By accessing the report either in a hard copy or electronically, users accept that GWEC, DNV GL or the authors are not responsible for any kind of loss or damage resulting from the use of the information contained in the report or for any reliance placed thereon and the users further acknowledge that the content of the report and data therein are subject to change.