UK Government

Accelerating Smart Power & Renewable Energy in India (ASPIRE) Programme

India Roadmap for Offshore Wind Power Evacuation and Grid

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Abbreviations

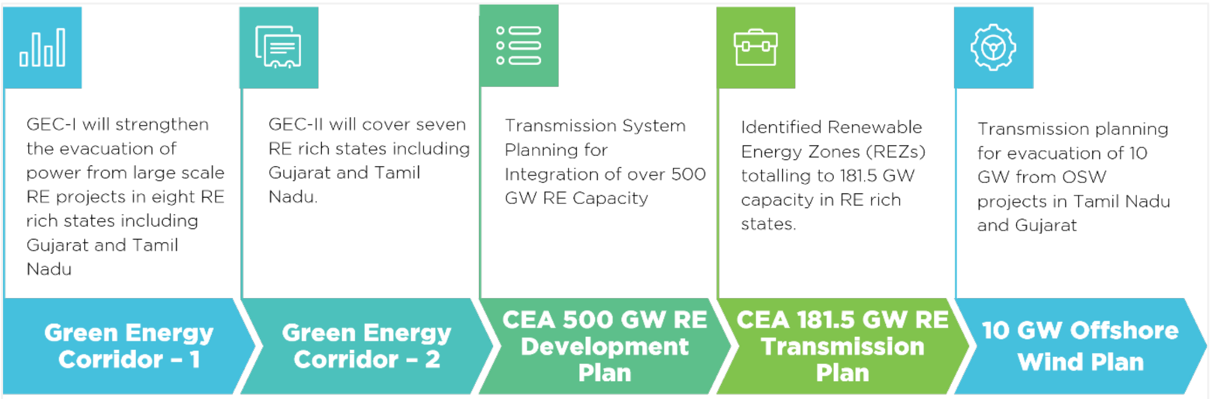
AC	Alternating Current
CAGR	Compound Annual Growth Rate
CBRA	Cable Burial Risk Assessment
CEA	Central Electricity Authority
CERC	Central Electricity Regulatory Commission
CFA	Central Finance Assistance
Ckm	Circuit kilometre
CPZ	Cable Protection Zone
CTUIL	Central Transmission Utility India Ltd
D/c	Double circuit
DEA	Danish Energy Agency
EIA	Environmental Impact Assessment
EAC	Expert Appraisal Committee
EU	European Union
FACTS	Flexible AC Transmission System
FOWIND	Facilitating Offshore Wind in India
GEC	Green Energy Corridor
GOI	Government of India
GW	Gigawatt
GWEC	Global Wind Energy Council
GPS	Global Positioning System
HVAV	High Voltage Alternating Current
HVDC	High Voltage Direct Current
InSTS	Intra State Transmission System
ISTS	Inter State Transmission System
kV	Kilo Volta
LCoE	Levelized Cost of Energy
LDC	Load Despatch Centre
LILO	Line-in Line-out
MLLW	Mean Lower Low Water
MNRE	Ministry of New and Renewable Energy
MSC	Mechanically Switched Capacitors

MSCDN	Mechanically Switched Capacitive Damping Networks
MSR	Mechanically Switched Shunt Reactors
MVA	Megavolt-Amperes
MVAr	Mega Volt Ampere Reactive
MW	Mega Watt
MWS	Marine Warranty Surveyors
NIWE	National Institute of Wind Energy
NLDC	National Load Dispatch Centre
O&M	Operations and Maintenance
OSS	Offshore sub-station
OSW	Offshore Wind
OTM	Offshore Transformer Module
OWA	Offshore Wind Accelerator
OWF	Offshore Wind Farm
OWZ	Offshore Wind Zone
PS	Pooling Station
RCS	Reactive Compensation Station
RE	Renewable Energy
ROV	Remotely Operated Vehicle
RLDC	Regional Load Dispatch Centre
S/c	Single circuit
SIA	Social Impact Assessment
SEAC	State Expert Appraisal Committee
SLDC	State Load Dispatch Centre
STATCOM	Static Compensator
STU	State Transmission Utility
SVC	Static Var Compensators
TSO	Transmission System Operator
UK	United Kingdom
UXO	Unexploded Ordnance
VCS-HVDC	Voltage Source Convertor-HVDC
VGF	Viability Gap Funding
WTG	Wind Turbine Generator
WTIV	Wind Turbine Installation Vesesl
XLPE	Cross-Linked Polyethylene

Executive Summary

India has over 7,600 km of coastline with significant potential available for Offshore Wind (OSW) development. During the initial assessment of the National Institute of Wind Energy (NIWE) in the identified zones, there is a potential of almost 70 GW of OSW that exists off the coast of Tamil Nadu and Gujarat. Considering the OSW potential available along its coastline, the Government of India (GoI) has announced to install 37 GW of OSW generation capacity by 2030 with a defined trajectory for the auction of OSW projects discussed in Chapter 1.

Chapter 2 provides the long-term transmission planning development initiatives in India and discusses the planning and development of an Inter-State Transmission System (ISTS) for the Renewable Energy (RE) projects and the 10 GW offshore wind power evacuation under the ambit of various initiatives by CEA such as National Electricity Plan (NEP), Green Energy Corridor (GEC) and the 181 GW transmission plan for evacuation of Renewable Energy (RE).



OSW is a capital-intensive technology with a high per MW cost because of the stronger structures, foundations, and power evacuation grid infrastructure needed in the marine environment. This is not the case with the onshore wind projects. The Government of India has decided to socialise the evacuation and transmission infrastructure cost of offshore wind power for all OSW capacities bided up to FY 2029/30 to make it a commercially deployable technology. As the OSW sector is in its nascent stages in India, an integrated planning approach is needed to gain the advantages in cost savings through regional & inter-regional planning, environmental & community benefits, employment benefits, using standardized, modular offshore transmission facilities, and most importantly no part of the transmission system is unused later.

Chapter 3 analyses the international experiences in UK to put forth the planning paradigm to follow the OSW transmission planning approach for the Indian context. The integrated planning approach is proven internationally to bring in cost efficiencies and optimise the country's resources such as land for onshore sub-stations, submarine cable corridors, offshore substation platforms, and the environmental footprints for sustainable development of the sector. The integrated planning approaches further bring visibility of the scale of operations to facilitate the establishment of an indigenous supply chain and increase the employment opportunities and capacity building of the persons in the development cycle. The integrated planning for the transmission system is a must for immediate 5 GW OSW projects in Gujarat and Tamil Nadu, which needs to align with the long-term planning for the evacuation of 30 GW OSW capacity in these states.

The chapter discusses the evacuation options investigating the applicability of HVAC and/or a combination of HVDC for offshore transmission systems while working out long-term transmission planning approaches considered based on zone potential, physical distances of OSW projects from the shore, and its compatibility with onshore transmission for effective integration, auction strategy, the technology readiness, indigenisation opportunities gain, capacity building measures and investment channelisation for the transmission system. These evacuation options are further grouped to devise the Configuration Options and evolve an integrated planning approach while qualitatively validating each of the Configuration Options with the physical, technology, development, and environment parameters. The key findings include broader configuration options which are discussed with a brief of each of these options with the physical, technology and developmental attributes and environmental footprint. The suitability of each of these configuration options is discussed in detail in the chapter 3. However, a brief of these options is described below.

- Configuration Option 4 comes out with a clear advantage for an integrated approach to implement for its effectiveness for uprating possibilities i.e., to charge the 400 kV line at a lower voltage 220kV during the initial phase and later with OSW capacity enhancement, the same transmission corridor capacity could be used to cater for subsequent phases. The only cons would be the upfront loading of capital costs for the initial phases. With the OSS cost to be socialised, the integrated approach favours a 400 kV OSS system under Configuration Option 4 over 220 kV OSS under Configuration Option 3.

- The Configuration Option-5 with the HVDC system, can be advantageous considering its modularisation flexibility in OSW capacity augmentation and enhanced reliability as against Configuration Option 4, however, needs to dwell into detail on cost-effectiveness for the involvement of additional converter stations and environmental footprint.
- The Configuration Option 1 and 2 involving 66 kV and 132 kV systems are not the right candidates for integrated planning considering their development will lead to fragmented planning and will cost heavily on environmental and social aspects. While Configuration Option 6 cannot be validated considering its commercial unavailability as of date.
- The Configuration Options developed are indicative and need further investigations through technical pre-feasibility studies and cost assessment, environment, and social impact assessment to undertake relative assessment between Configuration Options 4 and 5.

Chapter 4 compiles the details of key components of OSW transmission infrastructure like offshore substations, reactive power compensation equipment, and submarine cables which constitute the balance of the plant. The balance of the plant includes all components of the wind farm except the turbine. This chapter provides insights into the detailed elements, available technology, design considerations and configuration that can be selected for the Indian context, the development of components in the international market and the maturity of components and the details of suppliers in India as well as international markets. HVDC and HVAC transmission are discussed in detail in this chapter.

The Chapter further dwells into international experiences, technology maturity, and technical data sheet to assess technology readiness to shift to an integrated planning approach discussed in Chapter 3.

Chapter 5 compiles the operation and maintenance aspects of OSW Evacuation. It provides an understanding of the key areas of O&M in OSW evacuation and the international experience in it. It indicates key aspects which are essential for effective O& M management, which include,

- operational performance parameters and standards for key components,
- spare parts and inventory management practices,
- port logistics support requirements and
- requirements of Service providers.

The chapter highlights the operations related to OSW, which include the a) assurance of health and safety of the assets, b) control and operation of assets which include wind turbine, balance of plant, c) remote monitoring of OSW, d) electricity sale, administration and supervision of marine operations, e) operation of vessels and infrastructure, and f) back-office works. OSW industries are focused on optimization of the maintenance activities which can reduce operational costs without compromising the performance of the OSW.

To facilitate operations and maintenance, ports and vessels play a crucial role in the overall execution and management of activities. Power evacuation is an essential component of OSW, it needs certain types of ports that provide specific services across various stages of development. The important point this report tries to emphasise is that it is not one type of port that can serve all the requirements of OSW projects or specifically power evacuation within OSW also. Further, to bring the very point that the identified candidate ports would have to be suitably considered to be re-planned and utilised as one of these categories of ports and/or as combination ports that cater to more than one service. Ports have a critical and continuous role in OSW stages and activities, which are mostly supported through vessel services. Like ports, the type of vessels required across the various stages of OSW development is different. While executing the OSW projects, and with regular operation and maintenance, there is a certain level of risk to the environment and the socio-economic aspects of the region. The possible impacts and mitigation measures are activity-dependent; however, a micro-level study of possible effects would be important while trying to reach the targets of OSW capacities in the two states, Tamil Nadu, and Gujarat. The possible impacts in both these states are highly dependent on the baseline conditions in terms of the geography, climate, biodiversity, environmental regulations and governance, and other agents of negative and positive effects on the environment, for example, coastal areas surrounded by large industrial bases, which may add to the offshore wind project effects, ultimately causing diverse and cumulative effects. The central approach must be that the planning should be inclusive, considering the long-term perspective. The positive impacts that OSW as an industry may offer can be gained as an opportunity for the overall development in a holistic manner.The suggested Configuration Options are proposed to be deliberated with key stakeholders, under this ASPIRE program, for bringing in consensus on the most suitable long-term planning approach as a way forward to develop the Roadmap for Offshore Wind Power Evacuation and Grid Integration, 2030 for India.

1. Introduction

1.1 Background

India pledged a target of Net Zero emissions by 2070 in COP26 and has also set an ambitious target of 50 percent cumulative electric power installed capacity from non-fossil fuel-based energy resources by 2030. As on February 2022, India has an installed RE capacity (including large hydro)[1] of 167.2 GW comprising 63.3 GW from solar energy followed by 41.9 GW from the onshore wind energy sources. The present share of RE capacity in the generation mix is about 40.7%, and India aim at taking up this to 50% by 2030.

The installed wind capacities comprise only the onshore wind. Further, between 2010-2011 to 2015-2016, wind energy in India experienced a CAGR of 11.39%, while the overall electricity capacity installation witnessed a CAGR of 8.78%. However, in the recent past, it has slowed down to 5% between 2016-17 to 2020-21. During 2022, India has announced wind RPO of 0.81 % for FY2022/23 and increasing to 6.94% in FY2029/30. This shall add up around 60 GW wind power capacity in the country taking wind power total beyond 100 GW by 2030.

According to the National Institute of Wind Energy (NIWE), India has a total wind energy potential of 302 GW at 100 m and 695 GW at 120 m hub height, concentrated in seven windy states (Andhra Pradesh, Gujarat, Karnataka, Madhya Pradesh, Maharashtra, Rajasthan, and Tamil Nadu). However, most of the best windy sites in these states are already exploited. Hence, to accelerate the wind capacities installations, the Government of India (GoI) has decided to explore the inherent offshore wind (OSW) potential, spread over the western and southern coastline of India to achieve its commitments. During 2015, the Ministry of New and Renewable Energy (MNRE) has come out with the

[1] National power portal https://npp.gov.in/

National Offshore Wind Power Policy (NOWEP), This was followed by the sea-bed lease rules (Draft) and offshore wind survey guidelines. In 2022, MNRE published a "Strategy Paper for Establishment of Offshore Wind Energy Projects" in line with the NOWEP-2015. The strategy paper aims at auction of 37 GW of OSW capacities by 2030. The figure 1 provides the timeline and auction capacities under three development models as proposed by the MNRE strategy paper. Most of these auctions are likely to be in the state of Tamil Nadu; as the wind resources in the state are relatively better than Gujarat coast wind resources.

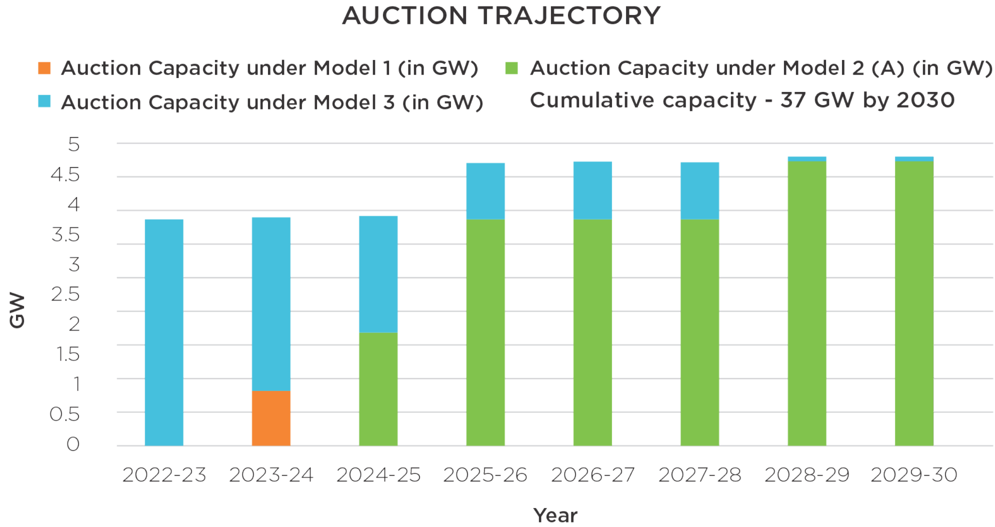


Figure 1: Offshore wind auction capacity planned during 2022-2030 in India.

However, OSW is a capital-intensive technology with a high per MW cost because of the stronger structures, foundations and power evacuation grid infrastructure needed in the marine environment. Also, OSW being an emerging industry, the government may provide support to encourage the development. The Government of India has decided to socialise the evacuation and transmission infrastructure cost of offshore wind power for all OSW capacities bided up to FY 2029/30 to make it a commercially deployable technology. As on date very few studies are undertaken for offshore wind power evacuation and grid infrastructure development in India. As the sector is in its nascent stages, the long-term planning and development framework for offshore wind power evacuation and grid infrastructure is yet to evolve. This ASPIRE study is probably a first such attempt in the direction to understand the offshore wind power transmission infrastructure development complexities in depth; to evolve and establish the long-term planning mechanism for offshore wind power evacuation in India. There are diverse aspects of power evacuation from offshore to onshore, local and regional conditions in grid integration, involvement of coastal areas and marine environment and other related aspects of OSW power transmission.

1.2 Context

The UK Foreign, Commonwealth and Development Office (FCDO) have initiated the Accelerating Smart Power and Renewable Energy in India (ASPIRE) programme as part of the Forward Action Plan during the 3rd India – UK Energy Dialogue for Growth Partnership. The programme aims to support sustainable development and inclusive growth, for the mutual benefit of both countries. The programme has been divided into two projects- (I) the Smart Power (SP) project to be advanced in collaboration with the Ministry of Power (MoP) and (ii) the Renewable Energy (RE) project to be advanced in collaboration with Ministry of New and Renewable Energy (MNRE).

Smart Power and Renewable Energy (offshore wind theme) are supporting OSW development in India. This multi-year technical assistance program will help the Indian government establish a project and commercial framework for offshore projects in India, based on the UK's expertise and incredible experience in offshore wind space. ASPIRE TA is an ongoing program (Nov.2021 onwards) under which requirement for this 'roadmap for offshore wind power evacuation in India' is identified.

This report attempts to assess the complexities in the planning, development, and execution aspects of offshore wind power evacuation. The report also attempts to establish a roadmap for discussion specifically for offshore wind power transmission infrastructure development in India. The study recognizes India's ambition to target auction and award of 37 GW offshore wind capacity by 2030. This report is built on the previous ASPIRE knowledge base of 'model evacuation framework studies for OSW grid integration for Gujarat and Tamil Nadu and the business models developed'. While developing this roadmap document, the earlier studies carried out under various bilateral and multilateral technical assistance programme on the subject are also reviewed and referred.

The aspects of planning, development, implementation, and operation & maintenance specific to offshore wind power evacuation would be significantly different from onshore power evacuation and transmission network development. Grid integration and power evacuation arrangement forms critical component of OSW development not only because it constitutes around a major share of OSW development cost but there is hardly any experience of offshore substation/evacuation platform development, construction and operations, sub-sea export cable design of suitable configurations, offshore power cable laying, its operation and maintenance, and integration with onshore grid systems in India.

ASPIRE TA programme has earlier covered the planning aspects of OSW evacuation and transmission development requirements in two separate reports for Gujarat and Tamil Nadu. However, several dimensions of technology, supply chain, configuration design considerations, implementation and operational challenges need detailed study and deliberations amongst stakeholders to evolve long term strategy and framework for OSW power evacuation and its grid integration in the Indian context.

This roadmap document may serve the purpose to initiate this needed dialogue around the critical aspects of OSW evacuation and would facilitate planning authorities, transmission licensees, industry participants and OSW developers to envision potential growth areas and initiate advance actions to mitigate potential transmission development challenges in a timely manner.

1.3 Objective

The present report is prepared with the objective to guide the stakeholders involved in the planning of power evacuation infrastructure and transmission aspects of OSW projects. It would serve as a key reference document for OSW transmission infrastructure in India.

The broader objective as described above is to address and facilitate the development of transmission infrastructure and evacuation of OSW power which is set as a target in the strategy paper by the MNRE. The one liner to this may be simply put as 'preparing a path for transmission infrastructure development for OSW in India', which would be in sync with the MNRE's set targets of 30 GW offshore wind by 2030.

While transmission appears to be a broader component of OSW, the other various aspects of supply chain, ports, and logistics, etc. are addressed in this report.

The report captures the needs for long term planning for offshore wind power evacuation planning and grid integration in the potential states of Gujarat and Tamil Nadu. The study also provides the required guidance on planning alternatives for evacuation infrastructure.

1.4 Audience

The present report is prepared considering various stakeholders involved in OSW development in India. While these agencies form an important part of the power evacuation and grid integration stage, the report mayt provide insights o these key stakeholders with respect to OSW

- Ministry of New and Renewable Energy (MNRE)
- Ministry of Power (MoP)

- Central Electricity Authority (CEA)
- Central Electricity Regulatory Commission (CERC)
- National Institute of Wind Energy (NIWE)
- Central Transmission Utility of India (CTUIL)
- Power Grid Corporation of India Ltd (PGCIL)
- State Transmission Utilities (STU)
- National Load Despatch Centre (NLDC)
- Regional Load Despatch Centres (RLDCs)
- State Load Despatch Centres (SLDCs)

RE Developers and Investors

The Chapter 2 describes the Transmission Plan development initiatives in India and status to work towards India Roadmap for OSW evacuation.

2. Transmission Plan development initiatives in India and status

The transmission plan consists of detailed analysis of evacuation of power from generating stations, strengthening of the already existing transmission network for meeting projected growth in load / demand and optimum utilization of distributed generation resources in selected regions. The transmission systems in India consist of two systems - Inter-State Transmission System (ISTS) and Intra State Transmission System (Intra-STS). ISTS are developed by the Inter-State Transmission Licensees. On the other hand, intra-state transmission system is developed by State Transmission Utilities / intra-state transmission licensees. It is necessary to discuss the transmission planning in view of the 30 GW offshore wind capacity to be added by 2030 as envisioned by MNRE.

Transmission planning is a continuous process of identification of transmission system addition requirements, their timing and need.

The transmission requirements could arise from

a) new generation additions in the system,

b) increase in demand

c) System strengthening that may become necessary to achieve reliability as per the planning criteria under change load generation scenario.

Current roadmap study will discuss the planning and development of Inter-State Transmission System (ISTS) for offshore wind power evacuation under the ambit of various initiatives by CEA such as National Electricity Plan (NEP), Green Energy Corridor (GEC) and the 181 GW transmission plan for evacuation of Renewable Energy (RE).

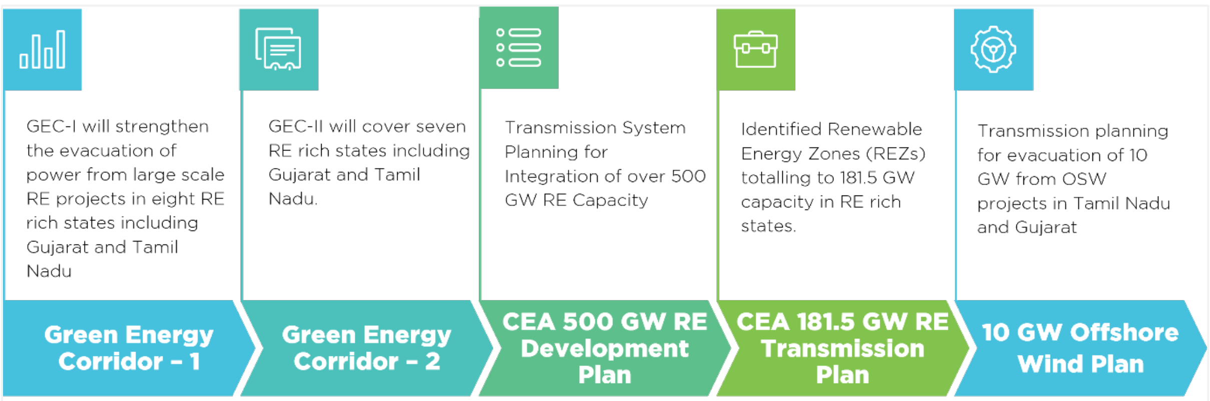


Figure 2: Offshore Wind Transmission Planning

2.1 Overview of CEA National Electricity Plan (2022-2027 and 2027-2032)

The National Electricity Plan for the period April 2022 to March 2027 has envisaged wind sector to grow from current capacity of 40.3 GW (as on 31 March 2022) to 80.8 GW by 2026-27 and to 134 GW by March 2032[2]. Capacity addition of 40.5 GW during 2022-27 is entirely by onshore wind and capacity addition of 53.2 GW during 2027-32 is inclusive of 10 GW offshore wind and 43.1 GW will be from onshore wind. The growth of wind sector beyond 2032 shall be driven majorly by offshore wind given the vast resource potential along India's coastline and MNRE's OSW auction trajectory of 37 GW by 2030 and aim for 30 GW of capacity addition. This huge capacity addition of OSW requires large scale transmission infrastructure development suitable for the offshore at a higher pace.

The expansion of the transmission system depends on the projected load demand and the generation resources addition during a particular time frame. All-India region-wise and state-wise projection of electric demand is considered as per Electric Power Survey (EPS) of the Central Electricity Authority. India's peak load demand was around 203 GW during April-August 2022. Also, the CEA forecasts much higher growth going forward, with peak electricity demand to touch ~340GW by the end of 2030. This implies 6.9% CAGR, compared to 4.5% in last decade. If India's peak demand continues its strong growth trajectory of the last decade, it will remain in the range of 285-300GW by the end of this decade. RE sources including offshore wind will play a key role in fulfilling this demand.

The Transmission system plan in India is guided by the planning philosophy and guidelines given in "Manual on Transmission Planning Criteria", January 2013 by Central Electricity Authority. National Electricity Plan, 2019[3] (NEP) provides guiding principles for all transmission development in India. Based on the same principles, a transmission scheme for evacuation of 10 GW of Offshore wind

[2] DRAFT_NATIONAL_ELECTRICITY_PLAN_9_SEP_2022_2-1.pdf (cea.nic.in)

[3] NEP-Trans1.pdf (powermin.gov.in)

(Transmission Schemes for 5 GW Off-shore Wind farm in Gujarat and Transmission Schemes for 5 GW Off-shore Wind farm in Tamil Nādu) has been planned and published by CEA.

Optimum development of transmission system growth plan requires coordinated planning of the inter State and intra-State grid systems. In respect of development of ISTS, the focus mainly is the interface of ISTS and State grid at drawl point of the State and the ability of ISTS to deliver this power and provide additional reliability to the State grid. In respect of development of Intra-STS, the focus is to enhance ability of State grid to transmit power drawn from ISTS and its own generating stations up to its load centres. The process of integrated planning is being coordinated by the Central Electricity Authority. To fulfil this objective and carry out integrated planning through coordination and consultation with transmission utilities and other stakeholders, CEA has constituted Regional Standing Committees for Power System Planning (SCPSP) to firm up transmission addition proposals. These Standing Committees for Power System Planning have representation of CEA, CTU, STUs of the constituent States, Regional Power Committee (RPC) of the concerned region and representatives of Central Sector Generating Companies in the region.

Following are a few planning criteria by CEA that should be followed for transmission planning.

i. General Principles: The system shall be planned to operate within permissible limits both under normal as well as after more probable credible contingency(ies) (N-0, N-1, N-1-1). To ensure security of the grid,

ii. Permissible normal and emergency limits: Normal thermal ratings and normal voltage ratings voltage limits represent equipment limits that can be sustained on continuous basis and Emergency thermal ratings and emergency voltage limits represent equipment limits that can be tolerated for a relatively short time (one hour to two hour depending on design of the equipment).

iii. Reliability criteria

   a. Criteria for system with no contingency ('N-0')

   b. Criteria for single contingency ('N-1') for Steady-state and Transient-state

   c. Criteria for second contingency ('N-1-1')

iv. Criteria for radially connected generation with the grid.

v. Reactive power compensation

vi. Sub-station planning criteria- The requirements in respect of EHV sub-stations in a system such as the total load to be catered by the sub-station of a particular voltage level, its MVA capacity, number of feeders permissible etc.

vii. The 'N-1' criteria may not be applied to the immediate connectivity of wind farms with the ISTS/Intra-STS grid i.e. the line connecting the farm to the grid and the step-up transformers at the grid station.

viii. The wind farms shall maintain a power factor of 0.98 (absorbing) at their grid inter-connection point for all dispatch scenarios by providing adequate reactive compensation

ix. Guideline for planning HVDC Transmission System

x. Guidelines for voltage stability

The NEP also provides guidelines for studies and analysis for Transmission Planning.

i. The system shall be planned based on one or more of the following power system studies:
   a. Power Flow Studies
   b. Short Circuit Studies
   c. Stability Studies (including transient stability and voltage stability)
   d. EMTP studies (for switching / dynamic over-voltages, insulation coordination, etc)

ii. Power system model for simulation studies

iii. Time Horizons for transmission planning

iv. Load - generation scenarios

v. Load demands
   a. Active power (MW)
   b. Reactive power (MVAr)

vi. Generation dispatches and modelling

vii. Short circuit studies

viii. Planning margins – 10% margin for thermal overload and 2% margin for voltage overload is recommended.

Apart from the above planning criteria and guidelines for study and analysis for planning transmission network, the NEP also speaks about technology options and new technologies in transmission system in general.

NEP covers broad transmission corridors capacity requirement during the plan period (2022 – 2027). The generation plants that may come up in these 5 years (2022-27) are not known. The all-India peak demand is expected to rise from the current level of 220 GW to about 298 GW by 2026-27 and to more than 340 GW by 2031-32[4]

In the 19th Electricity Power Survey report the demand for electricity both in terms of peak electric load and electrical energy requirement has been projected. As per 19th Electric Power Survey (EPS) Report, the peak electricity demand 2026-27 is given below[2]:

Northern Region – 97,182 MW

Western Region – 94,825 MW

Southern Region – 83,652 MW

Eastern Region – 35,674 MW

North- Eastern Region – 6,710 MW

Total All India Peak – 298,632 MW

<u>Applicability for OSW planning in Long Term</u>

- A transmission plan for the evacuation of 10 GW of offshore wind (Transmission Schemes for 5 GW Off-shore Wind Farm in Gujarat and Transmission Schemes for 5 GW Off-shore Wind Farm in Tamil Nadu) has been developed and made public by CEA based on the discussed planning criteria.

[4] NEP-Trans1.pdf (powermin.gov.in)

- Relevant ISTS and InSTS system strengthening has been emphasized, which will directly and indirectly help in evacuation of OSW power across the nation.
- The above discussed planning criteria and the transmission planning guidelines will eventually help all the stakeholders for OSW transmission planning based on power system studies, power system model for simulations, time horizon, generation, demand, despatch, and short circuit studies.

2.2 Summary of Green Energy Corridor (GEC-I) schemes and status

The Green Energy Corridor Project intends to synchronise electricity generated from renewable sources like solar and wind with conventional power plants in the grid. The first phase of the project was launched in the year FY 2015-16 with a budget of ~Rs. 10,000 Crores and was scheduled to be completed by the year 2022[5].

The Ministry approved the GEC – I project in 2015–16 for the evacuation of large-scale renewable energy in Tamil Nadu, Rajasthan, Karnataka, Andhra Pradesh, Maharashtra, Gujarat, Himachal Pradesh, and Madhya Pradesh. The State Transmission Utilities (STUs) are carrying out the project in respective states.

The project's updated goal is to complete the installation of approximately 9700 Ckm (circuit kilometre) of InSTS transmission lines and substations with a total capacity of approximately 22600 MVA (Mega Volt-Ampere).

The first component of the scheme, Inter-state GEC with target capacity of 3,200 (Ckm) transmission lines and 17,000 MVA capacity sub-stations, was completed in March 2020. The second component - Intra-state GEC with a target capacity of 9,700 Ckm transmission lines and 22,600 MVA capacity sub-stations is expected to be completed by March 2023. As on 30.11.2022, 8,697 Ckm of intra-state transmission lines have been constructed and 19,858 MVA intra-state substations have been charged. The goal is to enhance the system in the participating states and evacuate more than 20,000 MW of large-scale renewable energy.

GEC-I will strengthen the evacuation of power from largescale RE projects in eight RE rich states including Gujarat and Tamil Nadu, where OSW projects are coming up in the first phase. A strong ISTS and InSTS grid will also facilitate evacuation of OSW powers.

Table 1: GEC- I Status as on 30 November 2022

State	Lines Target (Ckm)	Line constructed (Ckm)	Substations Target (MVA)	Substations Charged (MVA)
Tamil Nadu	1,068	1,068	2,250	1,910
Rajasthan	1,054	984	1,915	1,915
Andhra Pradesh	1,073	739	2,157	950
Himachal Pradesh	502	470	937	653
Gujarat	1,908	1,429	7,980	6,980
Karnataka	618	609	2,702	2,490

[5] Green Energy Corridor (mnre.gov.in)

State	Lines Target (Ckm)	Line constructed (Ckm)	Substations Target (MVA)	Substations Charged (MVA)
Madhya Pradesh	2,773	2,773	4,748	4,748
Maharashtra	771	625	--	--
Total	9,767	8,697	22,689	19858

2.3 Summary of Green Energy Corridor (GEC-II) schemes and status

The Green Energy Corridor - Intra-State Transmission System Phase-II (GEC-II) programme was authorised by the Indian government on January 6, 2022. GEC-II aims to create intra-state transmission infrastructure required for power evacuation of Renewable Energy (RE) power projects of approx. 20 GW capacity in 7 implementing States - Gujarat, Himachal Pradesh, Karnataka, Kerala, Rajasthan, Tamil Nadu, and Uttar Pradesh. The scheme is for addition of 10,753 circuit kilometres (Ckm) of transmission lines and 27,546 MVA capacity of substations over a period of 5 years, i.e., FY 2021-22 to FY 2025-26. The scheme will be implemented by the respective State Transmission Utilities (STUs)6.

The projects are being set up for evacuation of approx. 20 GW of RE power in the above 7 States. Currently, the states are preparing the packages and are in process of issuing tenders for implementing the projects.

The state-wise brief of transmission projects under the scheme, as appraised by Central Electricity Authority (CEA), are as under:

Table 2: State wise brief of transmission projects under GEC – II

State	Length of transmission lines (Ckm)	Capacity of substations (MVA)	RE addition envisaged (MW)
Gujarat	5,138	5,880	4,000
Himachal Pradesh	62	761	317
Karnataka	938	1,223	2,639
Kerala	224	620	452
Rajasthan	1,170	1,580	4,023
Tamil Nadu	624	2,200	4,000
Uttar Pradesh	2,597	15,280	4,000
Total	10,753	27,546	19,431

GEC-II will strengthen the evacuation of power from largescale RE projects in seven RE rich states including Gujarat and Tamil Nadu, where OSW projects are coming up in the first phase. Transmission strengthening infrastructures under GEC-II will be implemented by 2027 by which time the first OSW evacuation might be taking place, which will also facilitate power evacuation from the OSW project.

[6] Intra State Transmission System Green Energy Corridor Phase- II.Pdf (Mnre.Gov.In) Renewable Energy Cover Final.Cdr (Cea.Nic.In)

2.4 CEA 500 GW RE Development plan and 181.5 GW Transmission Plan

A report titled "Transmission System for Integration of over 500 GW RE Capacity by 2030"[7] was published by CEA in December 2022. The report emphasizes that for enabling growth of Renewable Energy (RE) capacity, areas which have high solar and wind energy potential, needs to be connected to Inter-State Transmission System (ISTS), so that the power generated could be evacuated to the load centres. The transmission system must be planned well in advance due to the gestation period of wind and solar based generation projects being much lesser in comparison to the gestation period of associated transmission system. As a significant step towards successfully achieving the planned RE capacity by 2030, transmission system has been planned for about 537 GW of RE capacity as detailed below:

Details of 537 GW RE capacity by 2030 for which transmission system has been planned.

Table 3: Details of 537 GW RE capacity transmission by 2030

Category	Capacity (MW)
RE Capacity already Commissioned (as on 31.10.2022)	165,943
66.5 GW RE capacity to be integrated to ISTS network (8.861 GW RE capacity already commissioned and included in above)	57,639
Additional RE capacity of 236.58 GW (55.08 GW + 181.5 GW) to be integrated to ISTS network	236,580
Margin already available in ISTS sub-stations which can be used for integration of RE capacity	33,658
Balance RE capacity to be integrated to intra-state system under Green Energy Corridor– I (GEC-I) Scheme	7,000
RE capacity to be integrated to intra-state system under Green Energy Corridor - II (GEC-II) Scheme	19,431
Additional Hydro Capacity likely by 2030	16,673
Total (RE)	536,924

Note: Rows shaded in green refer to RE including OSW related information

The Report "Transmission System for Integration of over 500 GW RE Capacity by 2030" [8] portrays the broad transmission system roadmap for reliable integration of 537 GW RE capacity by the year 2030. The discussions below will highlight transmission planning for first 3 green highlighted categories which includes the transmission planning for evacuation of 10 GW from OSW projects in Tamil Nadu and Gujarat.

[7] Transmission System for Integration of over 500 GW RE Capacity by 2030.pdf (cea.nic.in)

[8] Transmission System for Integration of over 500 GW RE Capacity by 2030.pdf (cea.nic.in)

RE Installed Capacity in the country

India's installed Power Generating Capacity was 409 GW as on 31st October 2022, which comprised of around 166 GW RE capacity as provided in Annexure-I. Transmission system exists for these already commissioned RE capacity.

Transmission system for 66.5 GW ISTS connected RE capacity.

The cumulative solar, wind Bio and small hydro installed capacity target was of 175 GW by the year 2022, out of which 66.5 GW RE capacity was planned to be connected to ISTS network. Transmission system for integration of 66.5 GW RE capacity has already been planned. Part of the transmission system has been commissioned and rest is under various stages of implementation/bidding.

Transmission system for 55.08 GW ISTS connected RE capacity.

Transmission system for 55.08 GW RE capacity has already been planned in Rajasthan (20 GW), Ladakh (13 GW), Gujarat (21.2 GW) and Himachal Pradesh (0.88 GW). Transmission system for evacuation of power from REZ in Rajasthan (20 GW) under Phase III is under various stages of bidding, implementation, and planning. Status and details of the Transmission scheme for 55.08 GW ISTS connected RE capacity is given in Annexure-II

Transmission system for 181.5 GW ISTS connected RE capacity.

Ministry of Power vide letter No. 15-3/2017-Trans (Part 1) dated 7th December 2021, had constituted a 'Committee on Transmission Planning for RE' under the leadership of Chairperson, CEA, for planning of requisite Inter State Transmission System required for having the targeted RE capacity by 2030. MNRE/SECI have identified Renewable Energy Zones (REZs) totalling to 181.5 GW capacity by the year 2030. These REZ's are in eight states as detailed below:

Out of the transmission schemes planned for 181.5 GW RE capacity, transmission schemes for Bikaner-II, Bikaner-III RE Zones in Rajasthan, Koppal-II, Gadag-II RE Zones in Karnataka and Kallam in Maharashtra have already been recommended by NCT. These transmission schemes would be taken up for bidding/ implementation. Transmission schemes for other potential RE Zones would be taken up subsequently. Transmission system planning for these 181.5 GW RE also includes Transmission system for 5 GW Offshore wind farm in Tamil Nadu and Transmission Schemes for 5 GW Offshore Wind farm in Gujarat[9].

Table 4: Details of 181.5 GW RE capacity REZ in eight states by 2030

State	Wind (GW)	Solar (GW)	Total (GW)	Remarks
Rajasthan	15	60	75	45 GW (15 GW Wind & 30 GW solar in GIB Zone)
Andhra Pradesh	18	33	51	

[9] Transmission System for Integration of over 500 GW RE Capacity by 2030.pdf (cea.nic.in)

State	Wind (GW)	Solar (GW)	Total (GW)	Remarks
Karnataka	8	9	17	
Tamil Nadu	5		5	Offshore wind
Telangana	3	10	13	
Madhya Pradesh	2	6	8	
Gujarat	5	--	5	Offshore wind
Maharashtra	2	5.5	7.5	
Total	58	123.5	181.5	

Note: Rows shaded in green refer to OSW related information

Out of 181.5 GW RE capacity, 56 GW RE capacity is likely to be commissioned by March 2025, 62.1 GW RE capacity is likely to be commissioned by December 2027 and 63.4 GW RE capacity is likely to be commissioned by December 2030. Tentative phasing of 181.5 GW RE capacity is given below:

Table 5: Tentative phasing of 181.5 GW RE capacity

	Phase I (By March 2025)		Phase II (by December 2027)		Phase III (by December 2030)		Total	
	Wind (GW)	Solar (GW)	Wind (GW)	Solar (GW)	Wind (GW)	Solar (GW)	Wind (GW)	Solar (GW)
Rajasthan	6	13	5	20	4	27	15	60
Madhya Pradesh	2	0	0	3.1	0	2.9	2	6
Maharashtra	2	3	0	0	0	2.5	2	5.5
Gujarat (offshore wind)			2		3		5	0
Andhra Pradesh	4	8	7	11.5	7	13.5	18	33
Telangana	3	2	0	7.5	0	0.5	3	10
Karnataka	7	6	1	3	0	0	8	9
Tamil Nadu (offshore wind)			2		3		5	0
Total	24	32	17	45.1	17	46.4	58	123.5
Total (S+W)	56		62.1		63.4		181.5	

Note: Rows shaded in green refer to OSW related information

Out of the transmission schemes planned for 181.5 GW RE capacity, transmission schemes for Bikaner-II, Bikaner-III RE Zones in Rajasthan, Koppal-II, Gadag-II RE Zones in Karnataka and Kallam in Maharashtra have already been recommended by NCT. These transmission schemes would be taken up for bidding/ implementation. Transmission schemes for other potential RE Zones would be taken up subsequently.

2.5 Inter-regional corridor capacity plans for 2030

\Inter-regional transmission capacity is 112,250 MW at present. Following additional inter-regional corridors are under various phases of construction and planning for integration of RE capacity by 2030.

- Warora (Pool)- Warangal 765 kV D/c line
- LILO of one circuit of Narendra – Narendra (New) 765 kV D/c line at Xeldem
- Neemuch PS – Chhittorgarh (PG) S/s 400 kV D/C line
- Narendra (New)- Pune 765 kV D/c line
- Jeypore- Jagdalpur 400 kV D/c line 31
- Chittorgarh (Rajasthan) – Neemuch-II (MP) 765 kV D/c line
- Pindwara (Rajasthan) - Ahmedabad (Gujarat) 765 kV D/c line
- Pindwara (Rajasthan) - Prantij (Gujarat) 400 kV D/c line
- Beawar (Rajasthan) – Neemuch-II (MP) 765 kV D/c line
- Kota (Rajasthan) - Shujalpur (MP) 765 kV D/c line
- Barmer-II (Rajasthan) – Jabalpur (MP) 800 kV HVDC line

With the additional inter-regional corridors under implementation/planned, the inter-regional capacity is likely to be 149,850 MW in 2030 as detailed below.

Table 6: Inter-regional corridor capacity by 2030[10]

Inter-region	Capacity (MW)
West-East	22,790
West - North	62,720
West - South	28,120
North-East	22,530
South-East	7,830
East-Northeast	2,860
Northeast- North	3,000
Total	149,850

[10] Transmission System for Integration of over 500 GW RE Capacity by 2030.pdf (cea.nic.in)

With the additional inter-regional corridors under implementation/planned, the inter-regional capacity is likely to be 149,850 MW in 2030 as given in Annexure-III.

2.6 Transmission schemes relevant for OSW evacuation (2030)

Out of the total ISTS transmission schemes planned for 181.5 GW RE capacity, transmission schemes for evacuation 5 GW Off-shore wind in Gujarat and 5 GW Off-shore wind in Tamil Nadu has been planned and discussed below.

ISTS Transmission Schemes for 5 GW Off-shore Wind farm in Gujarat

Offshore Wind (Mahuva / Ubhrat): 5 GW Offshore Wind

a) For 3.7 GW (B3 Pocket: 1 GW, B4 Pocket: 1.11 GW & B5 Pocket: 1.59 GW)

- Establishment of 9x500 MVA, 400/220 kV Mahuva Onshore Pooling Station (Mahuva PS) (with space provision for upgradation to 765 kV level to cater to future Offshore Wind Projects adjacent to B3, B4, B5 pockets in future)
- Offshore Sub-Station (OSS) B3 – Mahuva Onshore PS 220 kV 2xS/c Submarine cable (~45 km)
- Offshore Sub-Station (OSS) B4 – Mahuva Onshore PS 220 kV 3xS/c cables (~44 km)
- Offshore Sub-Station (OSS) B5 – Mahuva Onshore PS 220 kV 4xS/c cables (~45 km)
- Mahuva Onshore PS – Vataman 400 kV T/c line (Out of 2xD/c line, one D/c strung as S/c) (190 km) (Quad Moose) with 63MVAr & 50MVAr, 420kV switchable line reactors on each ckt at Mahuva & Vataman ends respectively
- Installation of 4x1500MVA, 765/400 kV ICTs at Vataman along with 2x125 MVAr (420kV) Bus Reactor
- Suitable Static Compensation / Dynamic Compensation with Mechanical Switched Reactor (MSR).

Note: Vataman S/s has been planned through LILO of Lakadia-Vadodara 765 kV D/c line at Vataman with Khavda Ph-III (7 GW) and Dholera (Ph-I: 2GW) under 55.08 GW ISTS package.

b) For 1.24 GW (B6 Pocket)

- Establishment of 4x500 MVA, 400/220 kV Ubhrat Onshore Pooling Station (Ubhrat PS) (with space provision for upgradation to 765 kV level to cater to future Offshore Wind Projects adjacent to B6 pocket)
- Offshore Sub-Station (OSS) B6 – Ubhrat Onshore PS 220 kV 3xS/c cables (~55 km)
- Ubhrat Onshore PS – Vapi 400 kV D/c line (100km) (Quad Moose) with 50MVAr, 420kV switchable line reactors on each ckt at Ubhrat Onshore PS end
- Suitable Static Compensation / Dynamic Compensation with MSR

Assumption:

1. The no. of 220 kV Submarine Cables has been considered assuming capacity of one three phase cable as 500 MW. However, the requirement of cables (single phase or three phase and its voltage class) would be further firmed up while detailing the scheme.
2. Exact Reactive compensation to be worked out based on data being received from submarine cable manufactures pertaining to MVAr generation from the cables.

Transmission system for offshore wind potential zones in Gujarat is depicted in figure below.

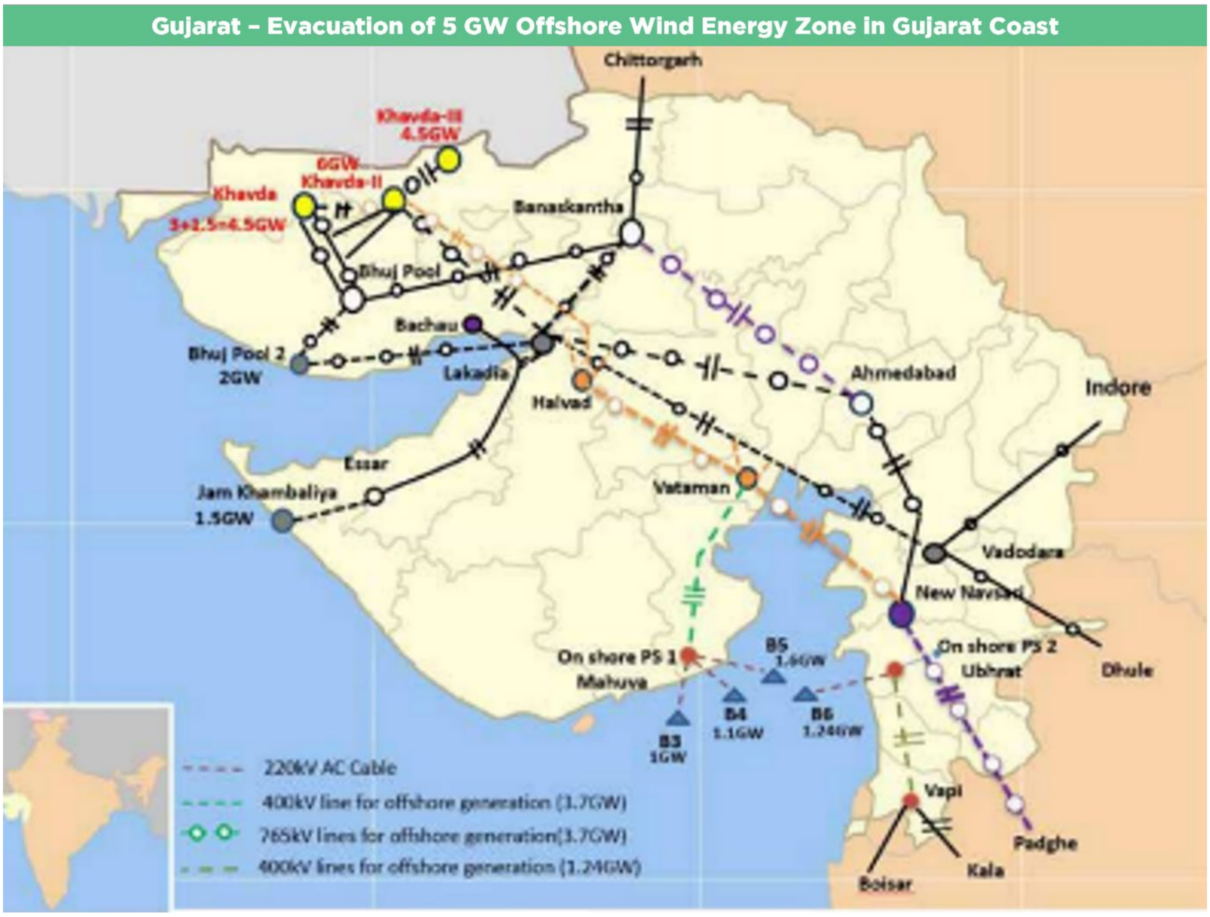


Figure 3: Transmission system for offshore wind potential zones in Gujarat

ISTS Transmission Schemes for 5 GW Off-shore Wind farm in Tamil Nadu

a) Onshore pooling station and Transmission System from Onshore Pooling Station

- Establishment of 12x500 MVA, 400/230 kV Onshore Pooling Station near Avaraikulam, Tirunelveli District in Tamil Nadu
- Avaraikulam Onshore PS – Pugalur (HVDC) 400 kV D/c line (Quad Moose equivalent) with 125 MVAr switchable reactors at both ends (300 km)
- Avaraikulam Onshore PS – Tuticorin PS 400 kV D/c line (Quad Moose equivalent) (100 km)
- Suitable Static Compensation / Dynamic Compensation with MSR

b) Transmission System for integration of Offshore Wind Farms with Onshore PS

- OSS B1 – Avaraikulam Onshore PS 230 kV 2xS/c Submarine cable (30 km)
- OSS B2 – Avaraikulam Onshore PS 230 kV 2xS/c Submarine cable (35 km)
- OSS B3 – Avaraikulam Onshore PS 230 kV 2xS/c Submarine cable (41 km)
- OSS B4 – Avaraikulam Onshore PS 230 kV 2xS/c Submarine cable (43 km)
- OSS G1 – Avaraikulam Onshore PS 230 kV 2xS/c Submarine cable (40 km)
- OSS G2 – Avaraikulam Onshore PS 230 kV S/c Submarine cable (35 km)
- OSS G3 – Avaraikulam Onshore PS 230 kV 2xS/c Submarine cable (36 km)

Assumption:

1. The no. of 220 kV Submarine Cables has been considered assuming capacity of one three phase cable as 500 MW. However, the requirement of cables (single phase or three phase and its voltage class) would be further firmed up while detailing the scheme.
2. Exact Reactive compensation to be worked out based on data being received from submarine cable manufactures pertaining to MVAr generation from the cables.

Transmission system for offshore wind potential zones in Tamil Nadu is depicted in figure below.

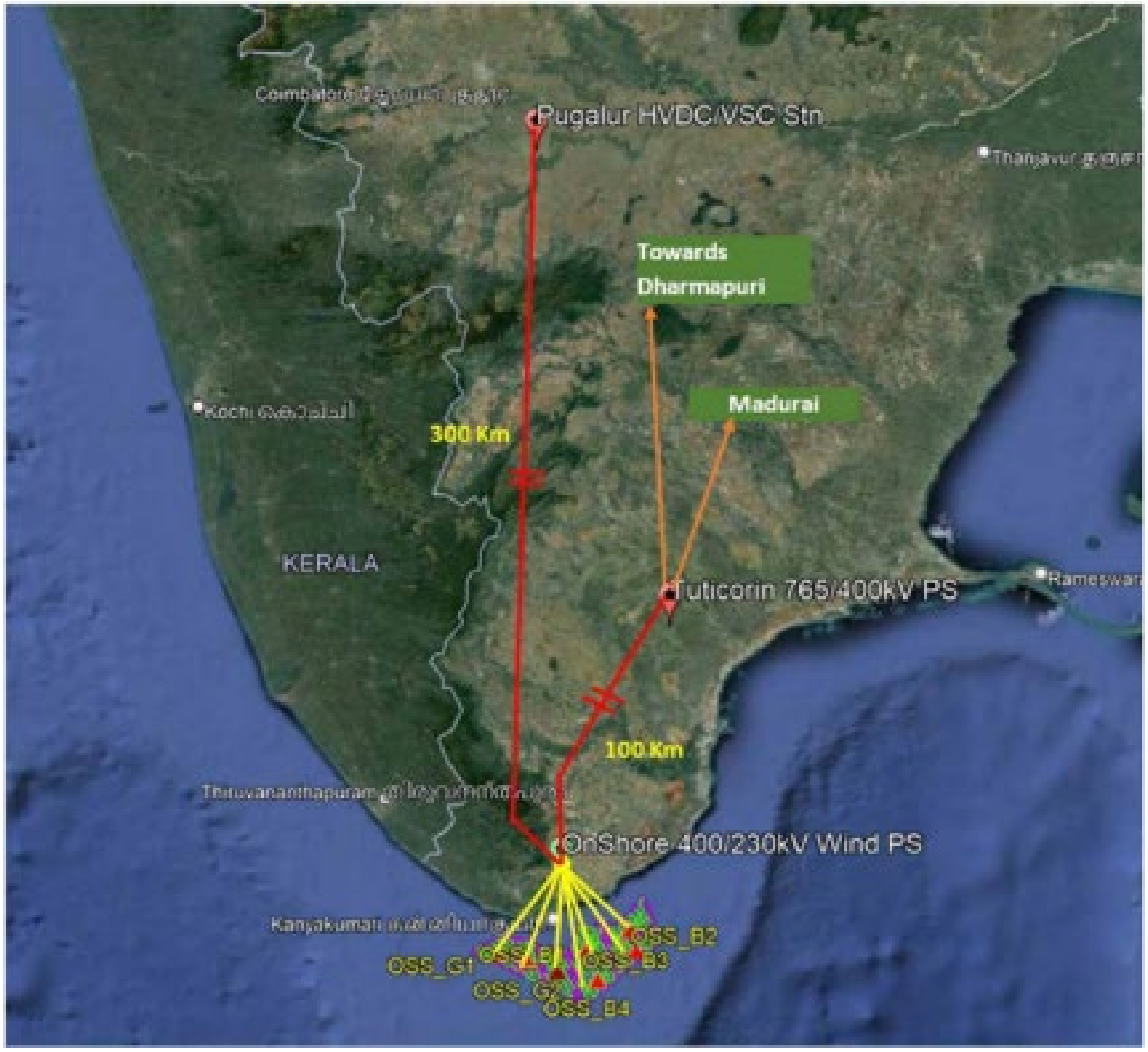


Figure 4: Transmission system for offshore wind potential zones in Tamil Nadu

Key takeaways:

a. The transmission planning considerations are integral to realise the envisioned OSW development in India.

b. 5 GW OSW evacuation planning for Gujarat and Tamil Nadu will be serving the need of upcoming projects, but a roadmap needs to be developed for evacuation of 30 GW OSW capacity.

c. It is necessary to discuss the technology alternatives available at present in commercial scales as well as the upcoming technology.

d. From a planning perspective, coordination, and integration of OSW with onshore facilities is essential for optimising the cost of transmission.

e. There is a need for a long-term planning in case of OSW looking not just at the target year 2030 but also beyond 2030 to ensure the maximum utilisation of OSW as a resource.

2.7 OWF Transmission initiatives in UK & key takeaways for India

Several offshore wind transmission case studies were presented in the ASPIRE report *Offshore wind transmission case studies to share international experience with the Indian offshore wind market, 2022*[11]. Some key learnings are summarised in Table 7.

Table 7: Summary of key case studies included in 'Offshore wind transmission case studies to share international experience with the Indian offshore wind market, 2022'

S. No.	Offshore wind farm	Key learnings for the Indian offshore wind sector
1	Hornsea One (UK)	As the world's largest operational wind farm, with the longest HVAC offshore wind export cables, Hornsea One provides key learnings for India regarding technical limits reached for HVAC transmission. Additionally, Hornsea One demonstrates how mid-point reactive power compensation can be used to facilitate HVAC transmission at distances far from shore and alleviate the need for HVDC conversion in some instances.
2	Dogger Bank A/B/C (UK)	Set to be the world's future largest wind farm, Dogger Bank provides key learnings for India regarding development limits for VSC-HVDC transmission and using turbines up to 14 MW in capacity. Dogger Bank also provides learning opportunities on how VSC-HVDC terminals can be used to provide onshore grid stability services. Findings can be used to inform long-term energy systems and offshore wind integration planning.
3	Sofia (UK)	Sofia provides further key learnings for India for how to deploy a single-connection VSC-HVDC transmission system including +14MW direct drive turbines. Given Sofia is representative of offshore wind farm capacities required for India to meet a 30 GW by 2030 target, it provides an example of a potential transmission system for a wind farm far from shore.
4	Beatrice (UK)	Beatrice provides key learnings for India particularly about the deployment of Offshore Transformer Modules (OTMs) instead of typical offshore substation design, which were used with the objective of reducing offshore substation footprint and costs. The OTM concept may provide a low-cost option for HVAC-connected offshore wind farms in India.
5	Lincs (UK)	Lincs provides a key learning around the importance of long-term transmission planning, which is evidenced through the notable difficulties the site had with routing its export cable. As India develops multiple offshore wind farms over the next decade, this consideration will be important for areas with multiple wind farms connecting to shore in proximity.
6	Thanet (UK)	Thanet provides further useful learnings for India through the sites experience of issues with the export cable and transmission system. Thanet highlights the potential benefits of redundancy in a transmission system to

[11] ASPIRE programme, Offshore wind transmission case studies to share international experience with the Indian offshore wind market, 2022.

S. No.	Offshore wind farm	Key learnings for the Indian offshore wind sector
		de-risk projects and support stable electricity supply in the case of fault incidents.
7	Borssele 1-4 (NL)	The Borssele multi-connection HVAC approach provides learnings for India for configurations to connect multiple wind farms to a central offshore substation, allowing a single connection to shore. These findings will be relevant to India in its long-term system planning for offshore wind and deciding to configure the offshore transmission system to be decentralised, like the UK, or centralised similar to the Germany and The Netherlands.
8	Dolwin 1-3 (DE)	The Dolwin multi-connection HVDC approach converts multiple HVAC wind farms to HVDC and transmits to shore via a single connection. These findings will again be relevant to India in its long-term system planning for offshore wind and deciding to configure the offshore transmission system to be decentralised, similar to the UK, or centralised similar to the Germany and The Netherlands.
9	Ijmuiden Ver (NL)	Ijmuiden Ver provides key learnings for India regarding how to effectively plan for developing Energy islands in Tamil Nadu as well as how to design wind farms to be integrated into high voltage interconnectors - an area India has specific interest in. Ijmuiden Ver also provides learnings with the increased technical capacity of HVDC transmission, with a planned 525kV export system.
10.1	Multi-purpose interconnection	India has a long-term electricity system planning commitment to develop interconnected grids (e.g., through the Green Grids – One Sun One World One Grid Imitative). This case study therefore provides useful insight into how interconnected grids are being developed in Europe, and how offshore wind farms can play a fundamental role in future offshore interconnected systems.
10.2	Low Frequency	LFAC is a potential future alternative to HVAC/HVDC as it can avoid high converter station costs of HVDC, whilst still delivering many of the benefits including being able to serve sites far from shore (80-300km). LCAF could be a possible future alternative to HVDC in India, with appropriate technological developments.

- The United Kingdom (UK) has a well-established offshore wind power sector, and it has implemented several initiatives for the efficient evacuation of power from offshore wind farms. Key initiatives and takeaways for India include:

- Grid Connection: The UK has developed a robust transmission infrastructure to connect offshore wind farms to the national grid. The transmission infrastructure includes subsea cables, offshore substations, and interconnectors.

UK offshore wind transmission planning journey

As the UK has been present for most of the history of the offshore wind industry, UK offshore wind transmission planning reflects the industry's maturation and growth history.
Figure 5 demonstrates this journey, which can be summarised in some industry steps.

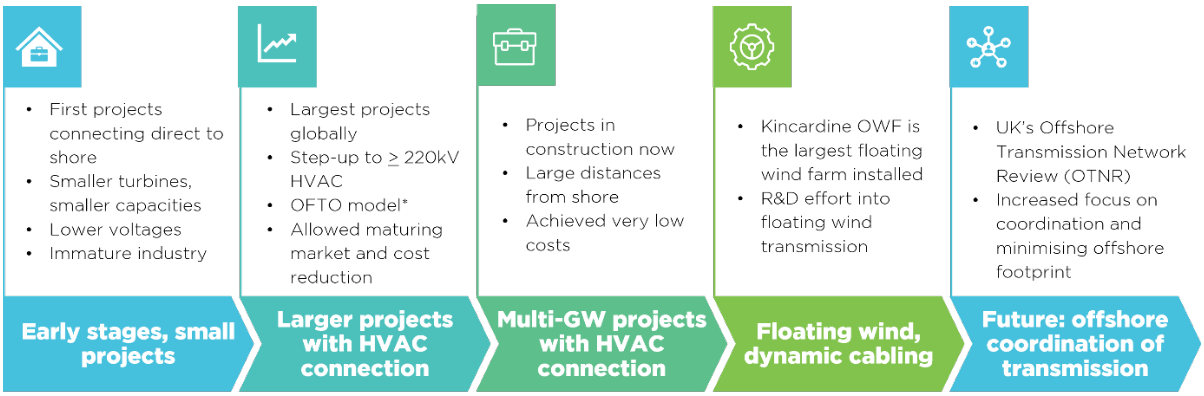


Figure 5: UK offshore wind transmission journey

1) **Early stages, small projects**
   At the industry's immature stage, projects were generally located near-shore, with smaller capacities and turbine sizes by modern standards. In these cases, the wind farms may be connected direct to shore with array voltages.

2) **Larger projects with HVAC connection**
   As the industry has matured, project capacities and turbine sizes increased, giving a greater need for more complex transmission systems. Higher HVAC voltages of ≥220kV have been used, and offshore transmission assets have been transferred to Offshore Transmission Owners (OFTOs) through the OFTO model. Hornsea One's large distance from shore, requiring midpoint compensation, portray the near technical limits of HVAC transmission systems in terms of capacity and distance from shore.

3) **Multi-GW projects with HVDC connection**
   Several large projects due for commissioning from 2024-2026, such as the 3.6 GW site at Dogger Bank, are utilising HVDC transmission, which is of greater efficiency than HVAC at very long distances from shore. This efficiency has enabled the projects to reach very low Contracts for Difference prices from £39-41/MWh[12].

4) **Floating wind and dynamic cabling**
   The UK hosts Kincardine, the largest capacity floating offshore wind farm installed globally, and requiring dynamic cabling. There is an increasing interest in dynamic cabling through research, development, and demonstration initiatives such as the Floating Wind Joint Industry Programme[13] to enable dynamic cables required for floating offshore wind, as well as overcoming challenges to development of floating or subsea substations.

5) **Future: offshore coordination of transmission**
   Whilst the UK developer-led transmission approach, where developers have full responsibility for construction of offshore wind transmission assets, has been very effective for offshore wind development to date, there is consensus that a more strategic and coordinated approach can deliver benefits. The Offshore Transmission Network Review has been commissioned to investigate future options for offshore transmission planning.

Offshore Transmission Network Review

The UK government launched a review of the offshore transmission network in 2020 to ensure that the transmission connections for offshore wind generation are delivered in the most appropriate way,

[12] Low Carbon Contracts Company, CfDs - link
[13] Carbon Trust, Floating Wind JIP - link

considering the increased ambition for offshore wind to achieve net zero, while finding the appropriate balance between environmental, social, and economic costs.

The review investigates the way that the offshore transmission network is designed and delivered, consistent with the ambition to deliver net zero emissions by 2050. The review has determined potential benefits of more centralised network planning including, by 2030:

- Deliver £54bn investment in network infrastructure.
- Create up to 168,000 jobs.
- Save £5.5bn for consumer costs.
- Reduction in environmental impact from cables and offshore infrastructure; and
- Reduction in CO_2 emissions by 2 mega tonnes between 2030-2032[14].

The review brought together key stakeholders involved in the timing, siting, design, and delivery of offshore wind to consider all aspects of the existing regime and how it influences the design and delivery of the infrastructure. The review was done in two main workstreams:

1. The medium-term workstream: With an aim to;

- identify and implement changes to the existing regime to facilitate coordination in the short-medium term.
- assess the feasibility and costs/benefits of centrally delivered, enabling infrastructure to facilitate the connection of increased levels of offshore wind by 2030.
- explore early opportunities for coordination through pathfinder projects, considering regulatory flexibility to allow developers to test innovative approaches;
- focus primarily on projects expected to connect to the onshore network after 2025.

2. The long-term workstream: with an aim to;

- conduct a holistic review of the current offshore transmission regime and design and implement a new enduring regime that enables and incentivises coordination while seeking to minimise environmental, social, and economic costs.
- consider the role of multi-purpose hybrid interconnectors in meeting net zero through combining offshore wind connections with links to neighbouring markets and how the enduring offshore transmission regime can support the delivery of such projects.
- focus on projects expected to connect to the onshore network after 2030.

Key message: This review demonstrates the good practice of mutual collaboration public-private actors in co-designing and co-developing policies.

Relevant links:
Offshore Transmission Network Review[15]
Research and Analysis, Offshore Transmission Network Review terms of reference[16].

Transmission and grid integration R&D programmes

Over £32 million government funding has been awarded to UK projects developing cutting-edge innovative energy storage technologies that can help increase the resilience of the UK's electricity grid while also maximising value for money. Five projects based across the UK will benefit from this funding amount in the second phase of the Longer Duration Energy Storage (LODES) competition, to develop technologies that can store energy as heat, electricity or as a low-carbon energy carrier like hydrogen.

[14] National Grid ESO, The pathway to 2030 – Holistic Network Design - link
[15] https://www.gov.uk/government/groups/offshore-transmission-network-review
[16] https://www.gov.uk/government/publications/offshore-transmission-network-review/offshore-transmission-network-review-terms-of-reference

Ofgem's Strategic Innovation Fund (SIF) responds to the challenge of creating a net zero power system by 2035 and is a major driver of innovation in the sector. A key vision of the SIF is to support Ofgem facilitate the UK's transition to net zero, at lowest cost to the consumer. The SIF has been designed to be agile and responsive and has various project pathways suitable for projects at different innovation phases. It funds feasibility studies for discovery projects, proof of concepts, and large-scale demonstrations. This SIF has supported projects such as the National Grid's Superconductor Application for Dense Energy Transmission where positive results have been found for improving the efficiency of transmission, allowing more of the electricity from renewable generation to reach consumers. SIF recently launched its Round 2 challenge focusing on supporting a just energy transition, preparing for a net zero power system, improving energy system resilience and robustness, and accelerating decarbonisation of major energy demands. Innovation programmes such as the SIF supports technology development and has the potential to inform transmission planning decisions in the long term. Few of the well-known programs are listed below with references for more details.

- Carbon Trust Offshore Wind Accelerator (focus on cables/electrical systems, to bring forward technology, assess challenges, deliver industry standards, and best practice)[17]
- Carbon Trust Floating Wind JIP[18]
- Carbon Trust – The Integrator[19]
- EU – PROMOTION project[20]

Regulatory and Policy Support: The UK government has provided strong regulatory and policy support for the development of the offshore wind sector. This has included incentives for investment in offshore wind projects, and favourable regulatory regime for offshore transmission and grid connections. National Grid Future Energy Scenarios[21] can be referred for more information.

[17] https://www.carbontrust.com/our-work-and-impact/impact-stories/offshore-wind-accelerator-owa

[18] https://www.carbontrust.com/our-work-and-impact/impact-stories/floating-wind-joint-industry-programme-jip

[19] https://www.carbontrust.com/our-work-and-impact/impact-stories/the-integrator
[20] https://www.promotion-offshore.net/
[21] https://www.nationalgrideso.com/document/263861/download

National Grid ESO – Future Energy Scenarios

OSW power evacuation planning are done in UK keeping in mid the Future energy scenarios, which are important in addition to focusing on net zero. Future Energy Scenarios focus on the following components to develop and operate the whole energy system of the future and deliver value to consumers. These components are:

a. The energy consumer - covers the residential, industrial, commercial and transport sectors and considers how decarbonisation affects individual consumers.

b. The energy system – explores how total demand is met using decarbonised energy sources such as electricity, hydrogen, natural gas and bioenergy.

c. The flexibility – ensures energy supply and demand are balanced, and security of supply criteria are met, as the energy system decarbonises.

Today, the electricity system is designed and operated to allow flexible supply to meet whatever demand is required but, in the future, demand must be enabled to flex to supply which will come increasingly from weather-driven renewables. This will involve increased interaction across fuels like natural gas, bio-resources, and hydrogen as well as significantly more non-fossil fuel and demand side flexibility.

A summary of recommended policies from the Future Energy Scenarios are provided in the Table below.

Table 8: Recommended policies from the Future Energy Scenarios[22]

Component	Recommendations
Policy and delivery	A **demand side strategy** that incentivises more flexible electricity consumption, long duration storage and early hydrogen uptake is also required to avoid significant volumes of renewable energy being wasted during periods of oversupply as well as to ensure capacity adequacy.
	Improving energy efficiency is a no-regrets policy solution that can provide immediate benefits in terms of both affordability and energy security while also facilitating more enduring decarbonisation.
	A 'one-size fits all' approach to decarbonisation of residential heat is not optimal due to differences in consumer preferences, availability of resources and proximity to energy infrastructure. Within a national strategy, **delivery of the targeted solutions** and investment required by consumers **should take place at a more regional level** to leverage local knowledge and improve affordability.
Consumer and digitalisation	Suppliers must be further supported to increase the availability of flexible time-of-use-tariffs so that consumers can respond to market signals and benefit from low prices at times of high renewable output.
	Facilitate developments in smart technology and better understanding of regional trends by making data available to innovators while ensuring that appropriate consumer protection is maintained. This is to support innovation in digital solutions that has the potential to automatically optimise energy consumption.
	Targeted campaigns, led by trusted bodies, are required to provide consumers with the information they need to decarbonise and embrace new technology

[22] https://www.nationalgrideso.com/document/263861/download

Component	Recommendations
Markets and flexibility	Operating a future energy system with high levels of renewables and no unabated natural gas generation will require significantly more flexible capacity than we have today. Current market signals mean that flexible assets cannot contribute their full value to the system and may at times exacerbate network constraints - the impact of this will only increase in the future if changes are not made now.
	ESO analysis shows that market reform is needed to provide the dynamic real-time locational signals required to optimise dispatch and siting decisions of flexible capacity on the whole energy system. Improving locational signals has the potential to deliver significant cost savings to consumers without any adverse impact on renewable targets.
	The energy market of the future must harness the vast potential of demand side flexibility to integrate renewables and ensure security of supply at least cost for all. Market changes must facilitate flexible tariffs, support innovation, and reduce barriers to participation for new market entrants from the industrial and commercial sector or in the form of aggregated residential demand.
Infrastructure and whole energy system	Delivery of the British Energy Security Strategy requires urgent anticipatory investment to ensure the energy system is not a blocker to Net Zero. Strategic coordination and whole system thinking, especially across the electricity and hydrogen sectors, is required to achieve decarbonisation targets and avoid unmanageable network constraints and potential curtailment.
	The whole energy system of the future will require strategic storage to balance inter-seasonal demand and supply and increase resilience against external security of supply risks. This will include large-scale geological hydrogen and electricity storage projects which must commence now to support an electricity system without unabated natural gas after 2035.
	To ensure affordable delivery of new infrastructure, competition in delivery must be established for large projects. Competition is also required at a local level to ensure different regions can adopt the low carbon solutions that are most suited to the needs of their consumers

UK offshore wind sector deal

This section highlights on how UK government is planning to support the growth of offshore wind and planning for technology development and setting up local manufacturing to aid the shift to renewable energy. The offshore wind Sector Deal[23], [24], [25] builds on the UK's global leadership position in offshore wind and seeks to maximise the advantages for UK industry from the global shift to clean growth, consistent with the Clean Growth Grand Challenge[26], [27]. It will do this by:

[23] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/790950/BEIS_Offshore_Wind_Single_Pages_web_optimised.pdf
[24] https://www.ofgem.gov.uk/sites/default/files/docs/2020/02/owic_evidence.pdf
[25] https://www.gov.uk/government/publications/offshore-wind-sector-deal

[26] https://www.reuters.com/business/energy/uk-grid-reforms-critical-hitting-offshore-wind-targets-2022-09-16/

[27] https://www.reuters.com/business/energy/europe-thrusts-towards-offshore-wind-grid-testing-regulators-2022-08-09/

1. Providing forward visibility of future Contracts for Difference rounds with support of up to £557m, with the next allocation round planned to open by May 2019, with subsequent auctions around two years thereafter.
2. The sector committing to increase UK content to 60 per cent by 2030, including increases in the capital expenditure phase.
3. Increasing the representation of women in the offshore wind workforce to at least a third by 2030.
4. Setting an ambition of increasing exports fivefold to £2.6bn by 2030. 5. The sector will invest up to £250m in building a stronger UK supply chain, establishing the Offshore Wind Growth Partnership (OWGP) to support productivity and increase competitiveness.

This Deal is built on the foundations of the Industrial Strategy – Ideas, People, Infrastructure, Business Environment and Places. Strategies within this deal include:

Table 9: Foundations of the Industrial Strategies

Foundations	Action by	Strategy
Ideas: To be the world's most innovative economy	Sector Action	o Industry will establish a System Management and Optimisation Task Group to deliver innovative solutions to system integration. o Continue to co-fund investment in UK-based Research, Development and Demonstration activities. o Drive innovation in the UK supply chain to increase competitiveness and development of the UK intellectual property
	Government Action	o Continue to fund collaborative RD&D to increase UK competitiveness and further reduce costs. o Government and research institutions will work with the System Management and Optimisation Task Group on offshore wind system integration
People: To generate good jobs and greater earning power for all	Sector Action	o Develop a skills training needs analysis and an accreditation framework to broaden the UK offshore wind skills base. o Introduce a workforce and skills model to track and report workforce data. o Increase diversity in the workforce with an ambition of 40% women employed in the sector by 2030. Set new target for BAME representation by end of 2019. o The sector will continue to collaborate to ensure the highest health and safety standards during development, construction, operation, and decommissioning. o Build early-stage skills and knowledge accessibility. o Collaborations with universities will be expanded to support research and cultivate a highly skilled Research Development & Demonstration (RD&D) workforce. Review apprenticeship standards and increase apprenticeships with

Foundations	Action by	Strategy
	Government Action	o Government and devolved administrations will participate in a new sector led Investment in Talent Group.
Infrastructure: A major upgrade to the UK's infrastructure	Sector Action	o The sector will deliver cumulative infrastructure investment of over £40bn to 2030 (based on the sector's estimates) to deliver a low-cost, clean energy system. o Collaborate to deliver an efficient, secure, and integrated energy system. o Through the investment certainty provided by the CfD mechanism, the sector will continue to reduce costs to consumers so projects commissioning in 2030 will cost consumers less as we move towards a subsidy free world.
	Government Action	o Government will provide long term certainty to underpin investment. o The government will work collaboratively with the sector and wider stakeholders to address strategic deployment issues including aviation and radar, onshore and offshore transmission, cumulative environmental impacts both in the marine and onshore areas and impacts on other users of sea space such as navigation and fishing. o In support of this commitment The Crown Estate will establish a strategic enabling actions programme with the aim of increasing the available knowledge and evidence to support sustainable and coordinated expansion of offshore wind. o The Crown Estate and Crown Estate Scotland will undertake new seabed leasing in 2019, ensuring a sustainable pipeline of new projects to be developed in the 2020s and 2030s.
Business Environment: The best place to start and grow a business	Sector action	o Build more productive, competitive and export orientated supply chains. o The sector will establish and fund a new Offshore Wind Growth Partnership (OWGP), targeted at raising productivity and increasing competitiveness. Over the next 10 years the sector will be contributing up to £250m into delivering a stronger, more competitive UK supply chain on the way to delivering 30GW of generating capacity around the UK. o The sector will have a target of achieving total lifetime UK content of 60 per cent for projects commissioning from 2030 onwards including increasing levels of UK content in the capital expenditure phase. A roadmap of how this could be achieved will be developed. Measuring and reporting UK content. o Increasing UK exports. o Improving access for SMEs

Foundations	Action by	Strategy
		o Information sharing with supply chain. o Offshore wind commitment on payment practices
	Government action	o Maintain key policies and programmes that support export-led growth. o Maintain key programmes that support inward investment led growth. o Developing frameworks to support future technology
Places	Sector action	o Coordinate to maximise impact. o The sector will continue to invest in projects that will benefit local communities in the regions in which they operate, for example through community benefit funds.
	Government action	o Bolster Regional clusters

These initiatives and takeaways can provide valuable lessons for India as it seeks to develop its own offshore wind power sector. By following the UK's example, India can implement similar initiatives to efficiently evacuate power from offshore wind farms and support the growth of the sector.

Offshore grid coordination

UK has a mature offshore wind sector and there are numerous examples of lack of coordination and these learnings are vital for India. UK has brought required changes for Connections and Infrastructure Options Note (CION) to ensure transmission efficiency. Here are a few pointers.

Key recommendations from the National Grid ESO have been phased over various timescales. Immediate to short term opportunities include[28]:

- Review the Connections and Infrastructure Options Note (CION) to implement improvements that drive and encourage coordination - The CION process evaluates a range of transmission options to lead to the identification and development of the overall efficient, coordinated and economical connection point for offshore connections, onshore connection design and, where applicable, offshore transmission system / interconnector design to develop and maintain an efficient, coordinated and economical system of the electricity transmission network. This review should allow us to facilitate coordination in a clear, transparent, and defined way, allow easier access to connection sites for project developers, and enhance the capacity to connect more customers in the future.

Proposals of medium to long-term opportunities have been developed. However, these opportunities may be adapted based on the overall direction of the Offshore Transmission Network Review. These opportunities are:

- Package or coordinate connection offers - investigate whether it would be possible to package a connection offer with the seabed lease agreement to encourage greater coordination. This would focus connection applications on a specific time window as far as possible and would therefore also potentially facilitate the management of applications as a group. This would help address the issue that the connections process can be long with key milestones for progress often separated by multiple years. It will help with the timing of decision making and the

[28] https://www.nationalgrideso.com/document/183031/download

availability of information throughout the process and help prioritise the projects with higher certainty of progressing.

- Review where the risk sits for financial liabilities for offshore connections and ensure that this is optimal for encouraging coordination - there needs to be clear agreement on how the project liabilities will be managed and ensure that this is done in a way that balances the needs of projects to gain appropriate funding with ensuring that one party does not penalise another and also ensuring that incentives are in place to drive coordination.
- Consider formalising developers' roles in the System Operator-Transmission Owner Code (STC) to improve the efficiency and customer focus of the CION decision making process - enable developers to be formally involved in the CION process especially with the proposed grouped studies and help further with some of the challenges. This would also potentially give developers more direct control over the works that they are reliant on and therefore allow them and others up to coordinate more when the certainty is increased.
- Codification of the CION into the Connection Use of System Code to define timescales and provide clarity and consistency – this would entail a full review of the process with the codification of any revised approach. This would be beneficial in streamlining offers and ensuring consistency for all connections. Codification of the CION would have the benefit of greater transparency for customers, with potentially greater certainty and more information earlier in the process.

Key Takeaways

- A transmission plan for the evacuation of 10 GW of offshore wind (Transmission Schemes for 5 GW Off-shore Wind Farm in Gujarat and Transmission Schemes for 5 GW Off-shore Wind Farm in Tamil Nadu) is developed and made public by CEA in December 2022 based on the planning criteria.
- Relevant ISTS and InSTS system strengthening has been emphasized, which will directly and indirectly help in evacuation of OSW power across the nation.
- The above discussed planning criteria and the transmission planning guidelines will eventually help all the stakeholders for OSW transmission planning based on power system studies, power system model for simulations, time horizon, generation, demand, despatch and short circuit studies.
- The transmission planning considerations are integral to realise the envisioned OSW development in India.
- 5 GW OSW evacuation planning for Gujarat and Tamil Nadu will be serving the need of upcoming projects, but a roadmap needs to be developed for evacuation of 30 GW OSW capacity considering key learnings from UK.
- It is necessary to discuss the technology alternatives available at present in commercial scales as well as the upcoming technology.
- From a planning perspective, coordination and integration of OSW with onshore facilities is essential for optimising the cost of transmission.
- There is a need for a long-term planning in case of OSW looking not just at the target year 2030 but also beyond 2030 so as to ensure the maximum utilisation of OSW as a resource.
- From the international experience it is well understood that long term planning is the key to successful OSW transmission planning.
- The practice of mutual collaboration of public-private actors in co-designing and co-developing policies through stakeholder consultation is key to accelerated adoption of transmission policies and regulations.
- The international experience especially from UK indicates that OSW specific planning for offshore-onshore coordinated transmission planning is an essential element to reduce cost, number of connection and landfall points and the overall impact in marine ecosystem.
- International approaches for long term transmission planning for OSW projects needs to be investigated in order to evolve planning paradigm in Indian context which is discussed in Chapter-3.

3. Planning paradigm for OSW Evacuation

The short term and the long-term transmission planning considerations for offshore wind evacuation need to consider actional items for immediate 5 GW OSW projects in Gujarat and Tamil Nadu, and at the same shall align with the long-term planning for evacuation of 30 GW OSW capacity in these states. This alignment is essential to optimise on the country resources such as land for sub-stations, limited offshore to onshore submarine cable corridors, offshore substation platforms and the environmental footprints for a sustainable development of the sector. The international experiences in the planning of transmission system for OSW projects reveal on adopting an integrated approach and have documented the benefits of integrated planning approach.

- Cost-Savings through Regional & Inter-Regional Planning
- Environmental & Community Benefits
- Employment Benefits
- Using standardized, modular offshore transmission facilities that can be networked into an offshore transmission system and integrated with the onshore grid offers important additional advantages.
- No part of the transmission system is unused later

The section below presents the case studies in UK to highlight the OSW transmission process and criteria followed, mostly dwelling upon the following aspects:

- Network optimization: considering the transmission system in the context of the wider electricity grid to optimize the transmission network and minimize costs.
- Environmental impact: evaluation of the potential environmental impact of the transmission system, including the impact on marine life, habitat, and sensitive coastal areas.
- Technical considerations: consideration of the technical requirements for the transmission system, such as voltage, capacity, and cable routing.
- Cost-effectiveness: assessment of the cost-effectiveness of different transmission options, including the cost of installation, maintenance, and operation.
- Stakeholder engagement: engagement with key stakeholders, such as local communities, regulators, and environmental groups, to understand their concerns and interests.
- Permitting and regulatory compliance: ensuring compliance with relevant regulations and obtaining necessary permits, such as grid connection permits etc.
- Grid stability and reliability: ensuring the transmission system is robust, reliable and will not negatively impact the stability of the wider electricity grid.

3.1 International experience on OSW transmission planning4

3.1.1 UK

The UK Government with a legal commitment of net-zero greenhouse gas emissions by 2050, has an ambition for offshore wind generation growth to 40 GW by 2030 and to 75 GW by 2050. In line with this commitment, a step change is expected to the size and number of offshore wind farms seeking connection to the transmission system. In this regard, the Offshore coordination report[29] on Holistic Approach to Offshore Transmission Planning in Great Britain (GB) was prepared by National Grid ESO, it has carried out an assessment of six regional development zones in GB from the ESO's Future Energy Scenario (FES) Leading the Way (LW) report. The report presents an integrated planning of offshore wind generation as a key recommendation related to the design of integrated offshore networks. A gist of explanation of all the technical analysis is discussed below:

To date, each transmission connected offshore wind project within GB's offshore waters has a separate connection and there is limited opportunity (if any) for shared use of offshore transmission assets. Under current arrangements, each offshore wind farm development will contribute to overall carbon emission reduction targets in accordance with timescales that are defined on a project specific basis. Without a change of approach, the required increase in volume and pace of network development is expected to lead to issues[30] including:

- lack of suitable cable landing points onshore.
- adverse impacts on transmission system stability.
- project delays due to the unavailability of equipment and resources due to stresses on the supply chain, and
- failure to deliver economies that would be expected with a large-scale increase in development volumes.

Each of these issues in the current approach could lead to increases to the overall cost of transmission system extensions and to the risk that connections for offshore wind projects will not be delivered on a timely basis.

In this study, eight (8) conceptual network design building block options for offshore connections were identified of which:

- Four of them in on High Voltage Alternating Current ('HVAC') technologies, and
- Another Four is on High Voltage Direct Current ('HVDC') technologies that have been used in Europe and Asia.

The above network designs through a method of identifying and assessing these designs which is integrated with the onshore processes set out in the Electricity System Operator's ('ESO') Future Energy Scenarios ('FES'), Electricity Ten Year Statement ('ETYS') and Network Options Assessment ('NOA') publications were assessed with the assumptions that:

[29] UK NGESO report
[30] National Grid ESO, *Offshore Coordination Phase 1 Report*, December 2020

- offshore transmission assets can be shared between offshore projects.
- design can be optimised across projects, taking account of the required "end state" (i.e., overall target levels of offshore generation connected), rather than a project by project approach.
- offshore network design to meet current Security and Quality of Supply Standard requirements and consider strategically how the connection can provide support to the wider transmission system. This approach can be used to minimise the consequential impact to the onshore system.
- the overall design may be modularised and implemented in a stepwise manner using standardised components, with that build-up aligning to the capacity required by offshore projects, and
- design efficiencies from a range of technologies available were considered and where possible, used to restrict development of onshore assets to areas where amenity impacts can be better managed.

Based on the above assumptions, the report investigates in detail if there would be benefits from using an 'integrated' approach for offshore transmission development that is more like the approach used onshore. With this purpose the report notes that an integrated offshore network design approach could enable:

- shared use of offshore transmission assets between connections (e.g., wind, interconnectors);
- incremental development of offshore transmission infrastructure that matches the pace required for offshore wind projects, and
- achieving a more holistic network development
- provision of enhanced levels of support to other parts of the transmission system, across a range of areas and services needed for transmission system operation (e.g., voltage control and stability) and power transfer capacity needs now and in the future;
- lower overall transmission losses, and
- greater overall availability of offshore wind capacity provided via flexible more interconnected transmission system connection designs.

The initial findings suggest that the required higher capacity and more rapid pace development required for offshore connections to the GB transmission system could be more efficiently achieved by a combination of integrated offshore network topologies. Other conceptual network design topologies (e.g., HVAC approaches) are expected to offer efficient solutions particularly in areas of less pronounced and slower offshore wind technology growth.
This report concludes that integrated offshore network solutions could deliver benefits in terms of:

- delivery and cost efficiencies that can be achieved by reducing the overall (offshore and onshore) number of assets that is required (compared to current arrangements).
- strategic management of the impacts on coastal communities across multiple projects.

- **UK Offshore Coordination**

A nation-wide study conducted for National Grid UK[31] found that proactively planned offshore and onshore grid investments for approximately 60 GW of OSW generation in the United Kingdom added between 2025 and 2050 would:

- reduce overall transmission costs by 19% (approximately $7.4 billion).
- reduce the miles of transmission cables installed in the ocean floor by 35%.

[31] National Grid ESO, *Offshore Coordination Phase 1 Report*, December 2020

- reduce onshore transmission line miles by 60%; and
- reduce the number of beach crossings by 70%.

Importantly, the study found that delaying the implementation of a planned solution by only five years (by beginning to address 2050 needs starting in 2030 instead of 2025) would reduce the benefits of a planned 2050 solution by about half. The study's results for 2030 and 2050 are illustrated in Figure 5 below.

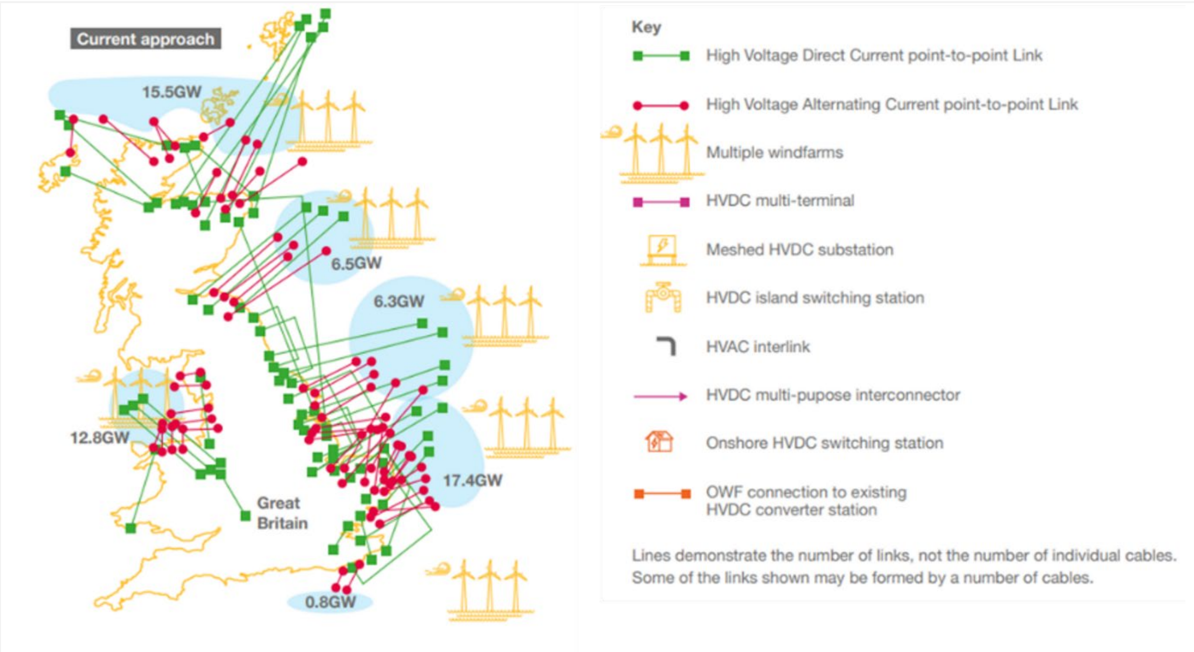


Figure 6: UK current approach for OSW evacuation

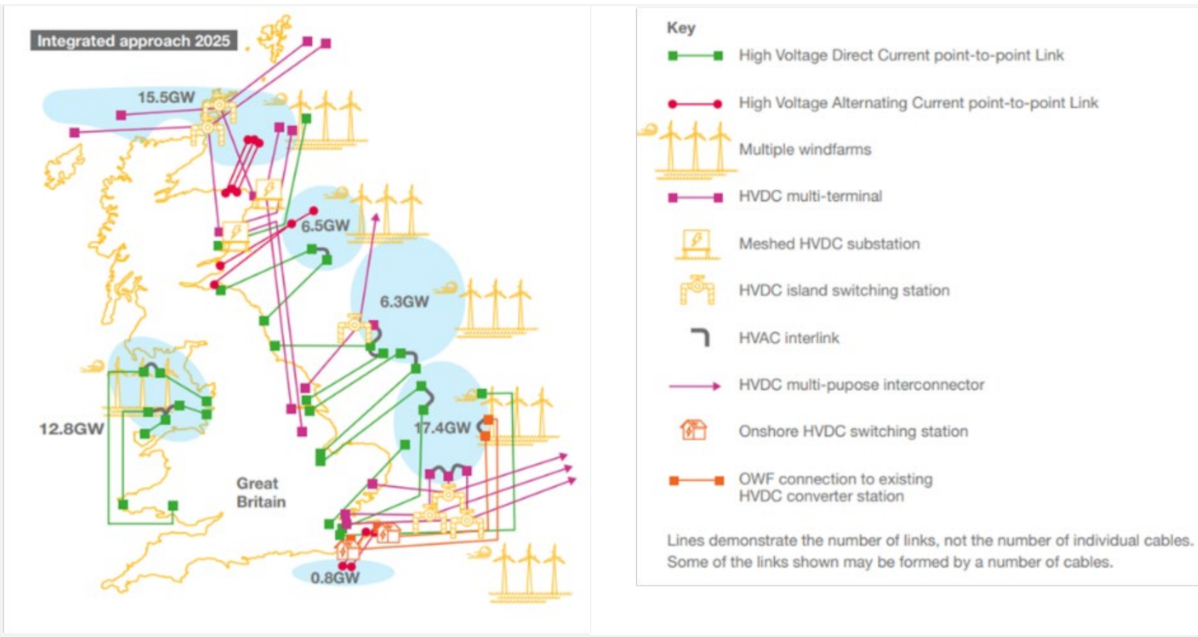


Figure 7: UK planned and integrated approach for OSW evacuation.

Going forward, OSW generation should consequently be procured with offshore facilities that are based on a **standardized, modular design** such that can interconnect with a “meshed” or “networked” offshore grid as part of a holistic grid planning process. Achieving such a **networked offshore transmission** system would further:

- Improve the reliability and value of offshore wind generation deliveries.
- Allow for the utilization of new, higher-capacity transmission cables (each able to deliver 2–2.6 GW of offshore wind generation), which further reduces costs and impacts to communities and the environment.
- Improve the utilization and flexibility of the offshore transmission infrastructure.
- Reinforce, avoid upgrades of, and support the existing regional onshore grids, which will improve grid-wide resilience and reduce future congestion costs; and
- Offer unique, cost-effective opportunities to create valuable new transmission links between regions, including addressing system transmission constraints that reduce system-wide cost and increase interregional grid reliability and resilience.

Numerous regional and national studies confirm that expanding regional and interregional transmission capabilities offer substantial benefits that increase grid resilience, reduce system-wide costs, and mitigate increases in electricity rates as we move to a more decarbonized electric sector by 2030 and If planned proactively and holistically, multi-purpose transmission links between OSW facilities can offer the lowest-cost, lowest-impact, and most feasible solutions for adding such regional and interregional transfer capabilities to the existing grid.

The international studies clearly imply adoption of integrated approach over the decentralised approach for Indian context as:

- Using the best Points of Interconnection (POIs) and transmission corridors for early OSW projects (without considering long-term needs) can severely limit future options and may render the developed transmission system sub-optimized.
- Best transmission solutions for individual projects may foreclose the best options to address long-term needs.
- Technology choices made for individual OSW projects may not allow future interoperability and integration into an offshore network.
- Proactive planning that holistically considers the full set of near-and long-term transmission needs (i.e., generation interconnection, reliability, congestion relief, public policy) would identify the most attractive solutions.

3.2 Planning Criteria and planning considerations for OSW

The planning of the transmission system is undertaken by CEA and CTU along with the stakeholders based on the inputs regarding Open Access / General Network Access / Cross border transactions requested by Designated Inter-state Customers (DICs) and the RE related inputs provided by MNRE. These data are validated by CTU and Load-Generation Balances (LGBs) at All India level for different scenarios through joint consultation in separate regional meetings is prepared. Upon finalisation of transmission schemes and uploading of the final proposal on CTU website, the cost estimation for these transmission schemes is done by National Committee on Transmission (NCT) which includes identification of mode of implementation viz. Tariff Based Competitive Bidding (TBCB) or Regulated Tariff Mechanism (RTM) and the commissioning schedule of the scheme.

Further, CEA has also stipulated certain principles under the *"Manual on Transmission Planning Criteria, 2013"*[32] which are generally followed by the transmission licensees during transmission planning. Recently, CEA has published the '*Draft Manual on Transmission Planning Criteria, 2022*'[33] which are under stakeholder's consultation to incorporate the new developments in the power regulatory landscape. However, for the OSW evacuation, the CTU should also investigate the planning aspects detailed in the Table 10 along with the transmission manual principles.

Table 10: Key Planning aspects for OSW Power Evacuation

Planning Aspects	Remarks
Topography	Site selection is to be based on feasible water depths, proximity to ports/shore, and energy resources including wind. This would provide holistic approach for planning as well as future expansion of the offshore sub-station platform. The sites nearer to shore (say less than 15 km) and with lesser water depths (say less than 20 m) can be considered amenable for planning evacuation directly to the onshore substation obviating the need for offshore pooling substation. However, this development option comes with less possibility of seeking benefits of integrated transmission planning and may need to view judiciously from holistic planning perspective.
Technology	Technology advancements in Turbine size (MW), wind farm simulation techniques, availability of submarine cables, precise generation forecasting, and locating RE management centers (REMCs) at regions and state dispatch centers to manage the large-scale integration of renewable energy into the grid shall drive the planning of OSW evacuation elements.
Cost – capital andoperational cost	CAPEX saving measures for foundations, length of inter-array cables and their installation, choice of turbine size, and the optimum number of turbines to save OPEX shall impact the planning choices.
Array design	The use of radial or looped topology depends upon the number of turbines whether less than 50 or more than 50 respectively considering cost-benefit aspects.

[32] https://cea.nic.in/wp-content/uploads/page/2020/07/tr_plg_criteria_manual_jan13.pdf
[33] https://cea.nic.in/wp-content/uploads/psp___a_ii/2022/06/DRAFT_MTPC_16062022.pdf

Planning Aspects	Remarks
Cable selection and compliance to reliability norms	• Installation expenses and O&M costs while selecting cable diameters if the cable is to be laid over a long distance (say more than 20 km away from shore) • The desired level of cable voltage (say 66 kV and above for Array and 220 kV and above for export cables) for power evacuation from the offshore substation to theonshore substation. • Selecting a suitable cable type from among dry, semi-wet and wet types. • Reliability considerations in provisioning 3 core cable vs. single core cables. The repair and maintenance of sub-marine cable consumes more time and costly affair with limited time window available for the repairs. In case of 3 core cable failure, the entire circuit would not be available for evacuation whereas in case of single core design, as part of reliability an additional single run of the cable would take care of any failure and restore the supply immediately while allowing time for repair and maintenance of failed cable
Selection of HVAC versusHVDC	• Selection depends on the size of the project and the distance from the shore (considering 80 km as the cut-off distance observed in international cases along with quantum of power to be evacuated from OSW projects (considering quantum of 2 GW and above can prove evacuation through VSC based HVDC system would be beneficial) • For small OSW within about 20 km from shore, EHV cables can be developed.
Reactive power compensation requirement	• Reactive power sources, such as shunt reactors, capacitor banks, or even FACTS, may also be linked for safe system operation and to offervariable reactive power generation. • STATCOM can be used based on cost-benefit analysis.
Scalability of OSW SS blocks for bidding/ ownership	• Arrays can be designed in multiple combinations depending on the project site, project capacity, and WTG capacity. • Combinations of various block-wise generation capacities will be advantageous for ensuring grid reliability, optimizing cable length, and accountability for forecasting and scheduling throughout the operational phase.
Ease of erection, installation, and maintenance	The important aspects to be considered while planning the OSW evacuationsystem are: • Site selection for development of OSW pooling substation • Route for submarine power cable from OSW pooling substation up to onshore pooling substation. • Supply of material at the site • Freight costs and transport available to the site location • Availability of adequate space for handling the material
Operational flexibility	Due to variations in the demand patterns, equipment failure incidences, line faults, etc., the power flow in the evacuation system may fluctuate. It is crucial to plan the evacuation infrastructure to ease out monitoring of the power flow continuously in three 8-hour shifts with minimal operational downtime.
Local content requirements andavailability	At present OSW in India is at a nascent stage. Therefore, it is necessary to rely on imported equipment and accessories for the immediate development of high-quality OSW. For an integrated long-term evacuation planning approach, the need to establish an indigenous supply chain is required.

Planning Aspects	Remarks
Spare parts optimization	As OSW is at a nascent stage in India, most of the assets and devices shall be procured from various countries, of various makes and specific standards followed by the respective countries. Therefore, planning evacuation elements for continued inventory management would be essential to maintain the stabilityof the planned grid operation. For an integrated long-term evacuation planning approach, the need to establish indigenization opportunities for spares.

3.3 Key differences in Evacuation planning between Onshore and Offshore Wind

3.3.1 Onshore

Onshore wind technology is matured and well-established in India. The country has developed robust policy and regulatory frameworks for the development of onshore wind power plants, its transmission connectivity arrangements, operational codes, energy accounting and financial settlement practices. The present onshore wind transmission evacuation practices are detailed out in the subsequent subsections which can be immediately applied to an OSW project.

Figure 8 provides a detailed schematic for the evacuation of power from an onshore wind farm. Generally, for the onshore wind, power from the wind turbines is generated at 33 kV which are pooled together to a pooling substation of 33/66-132-220 kV depending on the voltage level of the grid substation. Further, power is evacuated at 66 or 132 or 220 kV to the grid substation.

In the present onshore wind evacuation practices, the wind power developer is responsible for the development and maintenance of a dedicated transmission system up to the interconnection point to be connected to the grid substation. The interconnection point for the onshore wind is generally M4. Further, the entire cost of transmission including the cost of construction of the line, its operation, and maintenance, transmission losses, etc. up to the interconnection point is to be borne by the developer. The sub-meters shall be installed at the pooling substation for the metering, forecasting, and scheduling of power from individual projects. Further, the losses in the common transmission system up to the injection point shall be apportioned to the individual projects for billing.

<u>Present Onshore Wind Evacuation Practice in India</u>:

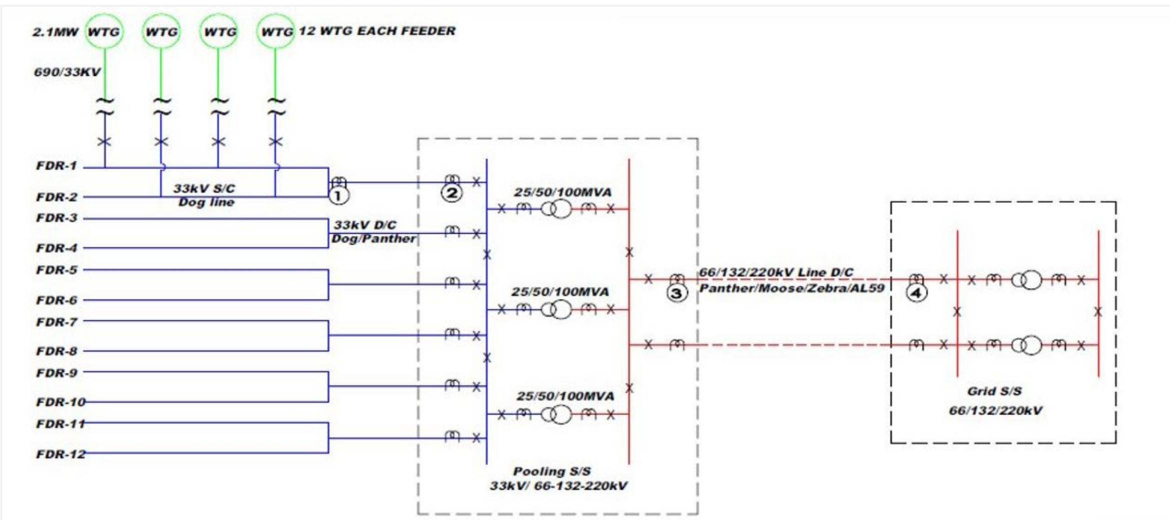


Figure 8: Onshore Wind Evacuation Practices

3.3.2 Offshore

Offshore Wind Evacuation Practice (proposed):

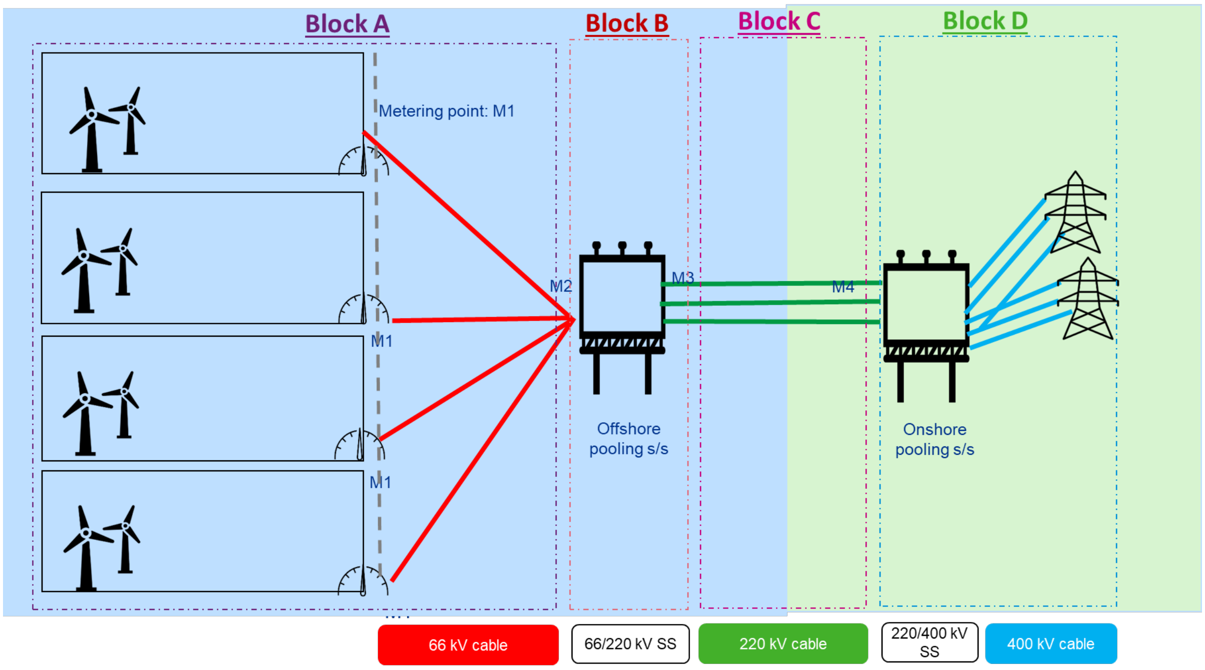


Figure 9: Schematic of OSW evacuation network

Generally, the OSW turbines generations are stepped up to 66 kV voltage and is further export through 66 kV export cables to the OSW pooling substation. With increasing turbine size and higher wind farms capacity, the generations are also stepped at to 110kV or 132kV level to reduce the inter-array cables. Moreover, as a general practice followed for OSW power evacuation, the power from the OSW pooling substation is evacuated at 220 kV or at higher voltage level to the onshore substation through subsea cables. And further transmitted to the grid through overhead/underground cables.

In the proposed OSW evacuation practices under the MNRE Strategy Paper, the CTU is responsible for the planning of transmission infrastructure to evacuate power from the Offshore PSS outgoing up to the grid interconnection point. Further, the developer is responsible for setting up the OSW farms, including the array cables and connection to OSW pooling station. Considering the present arrangement, the point M2 would act as a grid interconnection point unlike the point M4 as in case of the onshore wind.

However, in case of OSW where fair and equitable sharing of cost and risks are important given the marine environment, the grid interconnection point would not be same for every project unlike Onshore wind. It could vary from M2, M3 and M4 based on the transmission business models and accordingly, the scope for the wind power developer and the transmission licensee/CTU would change. Further the entire cost of transmission including the cost of construction of the line, its operation, and maintenance, transmission losses, etc. up to the interconnection point is to be borne by the developer which may make the offshore wind project unviable.

The ASPIRE report on Model Evacuation Framework – Business Models notes that the selection of a specific transmission business model option can be based on cost implications, technology selection, transmission efficiency, environmental impact, and timelines to match with the OSW project. For Indian conditions, the following is recommended:

- The most suitable model is Transmission Service Licensee (TSL) driven both in case of long distance and short distance, as this model offers the clear advantage of a centralized, coordinated approach for the development of OSW transmission system elements like pooling substation, export cables and strengthening of the onshore transmission network. In India, there is adequate policy and regulatory frameworks for planning the pooling stations and common transmission system for the onshore transmission system. With the coordinated approach, selection of the most optimal technology and phase-wise development can be achieved keeping in view the long-term perspective for the targeted OSW capacity addition.
- The TSL driven Business Model Option 3, ensures the effort to cover the maximum of the OSW transmission system elements for the socialization of cost, as against the Developer driven Business Model Option 1, where it will be difficult to socialize it as there is no mechanism to ensure the competitiveness of the price.

3.4 Overview of evacuation mechanism

The long-term evacuation planning necessities to consider right technology while considering the benefits and barriers together. The applicability of transmission technologies available at present such as HVAC and HVDC along with future developments such as 765 kV UHVAC and UHVDC are discussed below:

HVAC

The HVAC is an established transmission technology in India with underground cables operating at 220kV and above. For offshore transmission evacuation the HVAC export cable comes with a 3-core whereas a typical HVDC has a bipolar design with two single-core cables. The AC sub-sea export cables are typically rated between 132kV and 500kV, allowing the export of ranging from 350-400MW per 3-core cable to 1 to 2 GW with 400kV (or 500kV) cables. Further, a 220 kV three-core copper AC export cable has a mass of approximately 90 kg/m and a 320 kV single-core DC copper export cable has a mass of approximately 40kg/m.

The use of HVAC can be proven for near-shore OSW project with a short distance for connection with on-shore transmission grid. This is typical case for connection with the Intra-State transmission network.

HVDC

HVDC schemes based on voltage source converters (VSC) is the key technology for integrated offshore transmission networks that can facilitate the connection of large-scale offshore wind generation.

The Offshore HVDC-connected windfarms were pioneered in Germany, by Tennet and there are currently 9 in operation, 3 in construction, and 2 in planning, with symmetrical monopole topology, long submarine DC cables, significant lengths of DC land cables and at power ratings up to 900MW[34]. Figure 10 shows the simplified electrical system of HVDC-connected windfarms.

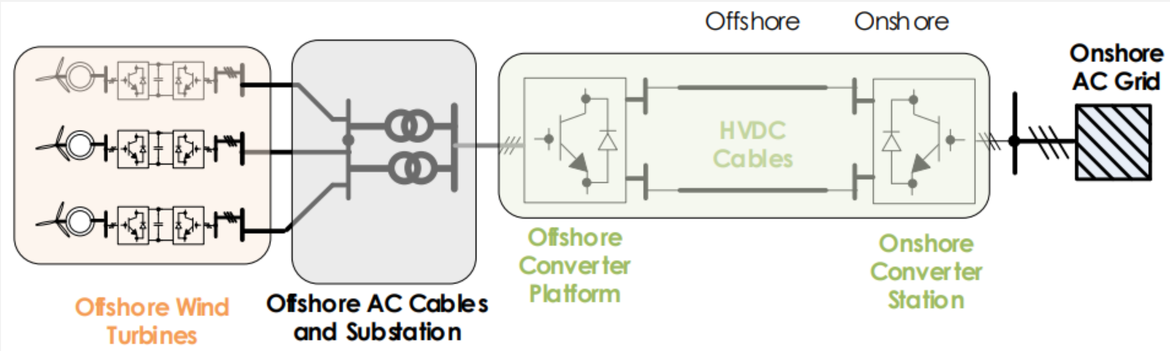


Figure 10: Simplified Electrical System of HVDC-connected Offshore Wind Farms

The key components of HVDC-connected offshore wind farms are:

- Offshore HVAC collection system: comprising array cables rated at AC voltages 66kV, step-up transformers for AC voltages up to 220kV for transmission to for offshore converter, reactive power compensation devices and possibly harmonic filters to maintain power quality of the offshore AC grid.
- Offshore converter platforms: hosting the converter station, which creates the offshore grid AC voltage and transforms the alternating current from the offshore wind generation into direct current transmission; and
- HVDC submarine and land cables: linking the onshore grid to the offshore wind generation; and
- Onshore converter station: to transform the direct current into alternating current for power transmission into the terrestrial grid.

HVDC-connected offshore wind farms have to date used symmetrical monopoles for radial point-to-point connections, which on an individual basis is justified. However, for integrated offshore solutions, bipole configuration gives greater flexibility and higher capacities, which could reduce the extent of cables required and potentially avoid the need for HVDC circuit breakers.

Selection of HVAC versus HVDC

The size of the project and the distance from the shore determine whether AC or DC technology is used. The switching point between HVAC and HVDC varies greatly and depends on the site. The most influential factor is the distance from the seashore and offshore to onshore cable corridor.

When choosing HVAC versus HVDC, the technical sophistication must be carefully weighed against cost. The size and type of cable will be decided by the transmission mode. This decision affects the reactive compensation required for HVAC.

From international case studies and technologies used in Europe for OSW, the following key observations are made as relevant to choosing between HVDC and HVAC in various scenarios (Table 11).

[34] De-risking-Integrated-Offshore-Networks_v2.0_25June2020.pdf (hvdccentre.com)

Table 11: Key criteria for HVAC and HVDC

Criteria	HVAC and HVDC connection
Availability and system losses	HVDC has features like neutral electromagnetic fields, oil-free cables, small converter stations, and power semiconductors to ensure high availability and minimize system losses.
Very long offshore lengths	HVDC is advantageous for connecting large-capacity wind farm zones located far from onshore substations. HVDC is preferred above a certain tipping point due to lower losses and costs of transmission cables. Since active power may be transmitted over the entire capacity of the cable system, HVDC is employed for long-distance transmission (because there is no reactive power flow). The savings from using HVDC cable are not realised until the cable path between the substations is about 80–100 km long, at which point the additional HVDC converter station requirements become cost-effective. However, there are several examples of high-investment projects with VCS-HVDC connections that suffered delays. Generally, the application of VSC in challenging offshore environments is still relatively unproven.
Very long transmission HVAC	HVAC connections are projected to be widely used in the Indian OSW industry since they normally offer a reasonable balance of price, rating, and electrical losses. The electrical system integrates AC power output from individual turbines and steps up the voltage from, for example, 66kV to 220kV for export to the onshore substation.
Small distance < 15 km with no offshore substation	For small OSW at less than a 15 km distance from the shore, medium voltage (MV) within the collection grid can be connected directly, avoiding the need for a costly Offshore S/S. With the introduction of 66kV submarine cables, near-shore (within 10 km) OSW farms of up to 300MW capacity can be built without an offshore substation.

The weight of an HVAC substation ranges from 1,200 to 3,000 tonnes. Typically, one or two substations are needed for a 1GW wind farm depending on the evacuation voltage. The weight of an HVDC substation ranges from 12,000 to 18,000 tonnes. One substation is required for a 1 to 2 GW wind farm. However, additional AC converter stations will be connected to the turbines to convert the 66kV output to 132kV or higher voltage to supply to the HVDC substation. However, an HVAC substation with a 750 MW substation was recently developed for the Borssele wind farm zone. Therefore, it has been deduced that HVDC substations with cost analyses must be examined first for large-scale projects when the distance from the seashore is considerable.

Technical opportunities exist for both AC paralleling of offshore HVDC links and use of bipole HVDC configuration. However, integrated offshore transmission solutions offer enhanced flexibility and reliability for the offshore project, reduced asset footprint offshore, and offer options to present a lesser impact to the onshore systems in areas where new connection capacity is most problematic. The HVDC bipole with return cable solutions appear more cost and technically efficient to HVDC radial monopole solutions, and HVAC offshore solutions.

3.5 Analysis of HVAC and HVDC offshore evacuation scheme approaches

In the Indian context, the applicability of HVAC and/or with combination of HVDC for offshore transmission system while working out long-term transmission planning approaches needs to be considered considering physical distances of OSW projects from the shore and its compatibility with onshore transmission for effective integration along with capex availability for phased implementation. The other important aspects such as OSW projects auction strategy, the technology readiness, indigenisation opportunities gain, capacity building measures and investment channelisation for transmission system will remain key factors for success of selected planning approach.

For considering long term planning approach for 30 GW OSW projects off the Gujarat and Tamil Nadu coast, 09 blocks in Zone B in Gujarat 14 blocks in Tamil Nadu has been considered as shown in the figure below:

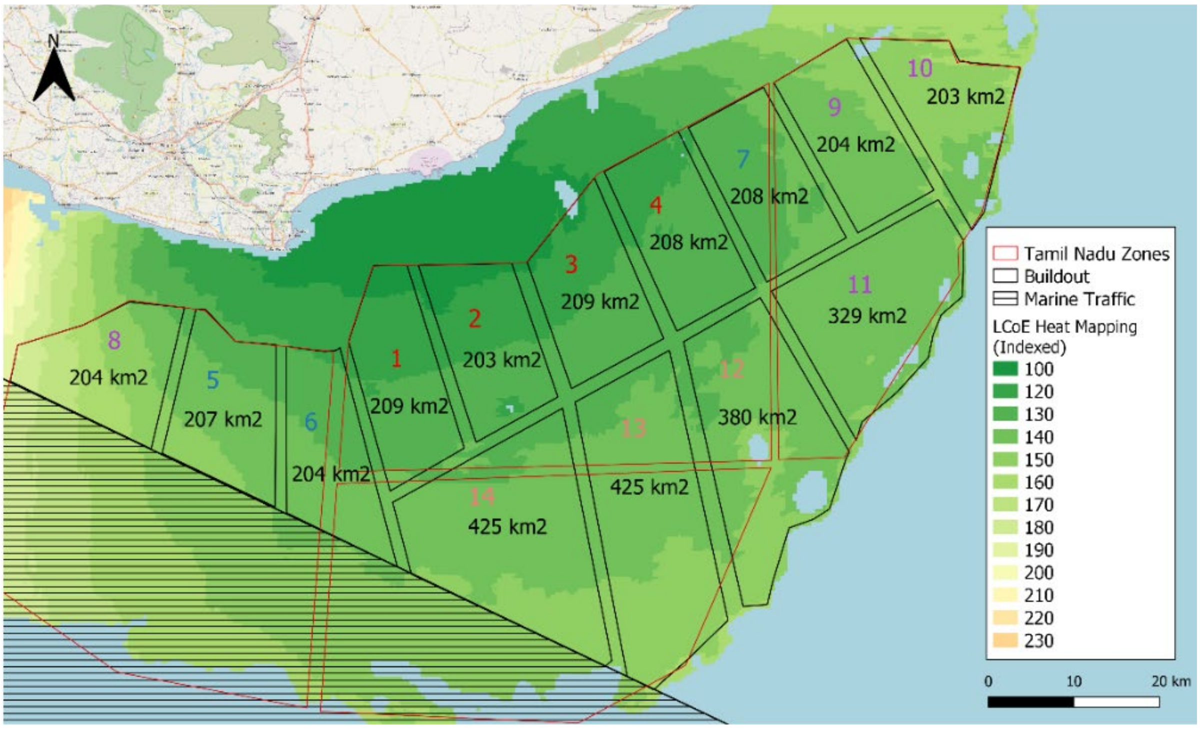


Figure 11: OSW project zones off Tamil Nadu coast

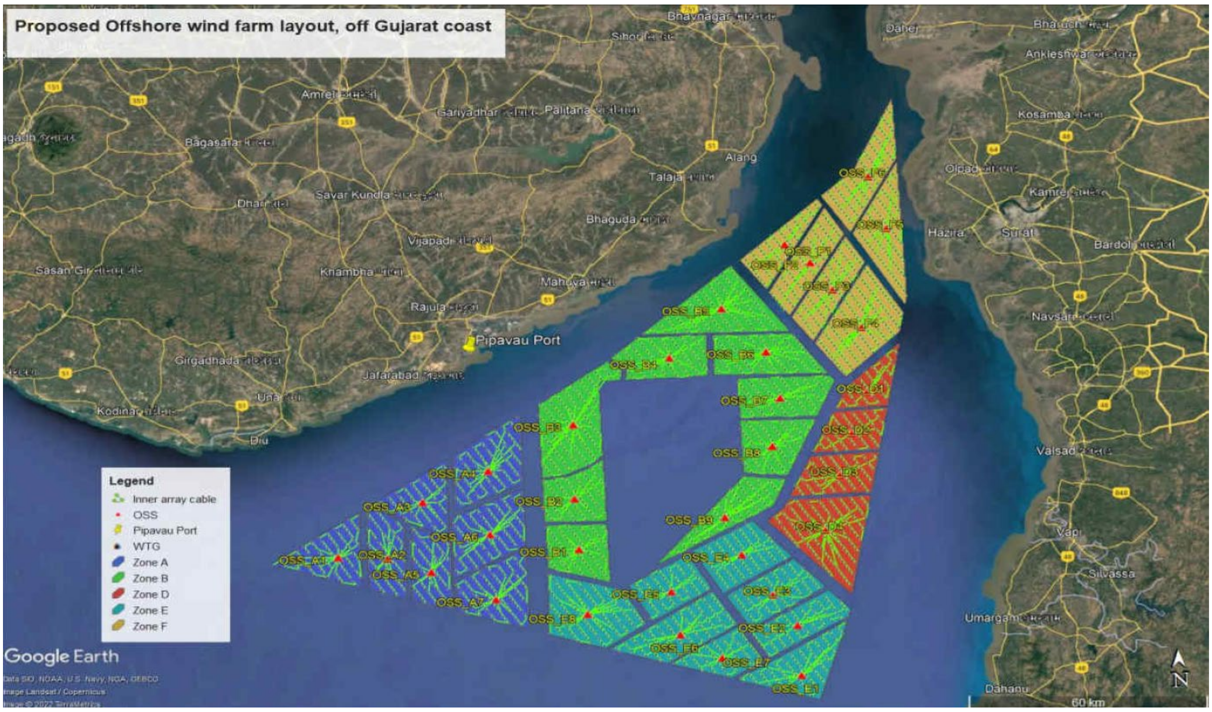


Figure 12: OSW project zones off Gujarat coast

The possible evacuation planning options can be worked out with following alternates and discussed in detail with their merits/demerits for further dwelling into practical options:

3.5.1 66 kV HVAC (Alternate 1.1)

This option is discussed for considering ease of commercially available array cable for immediate projects near shore with possibility of connecting at Intra-State Transmission System. However, considering the typical power evacuation capacity of 125 MVA per circuit of cable, this option leads to a large no. of cable runs and thereby substantial increase in land and sub-sea footprint to consider as a suitable option for long term evacuation. The typical situation that may arise for this option is illustrated in Figure 13 and 14 below for Gujarat and Tamil Nadu OSW zones.

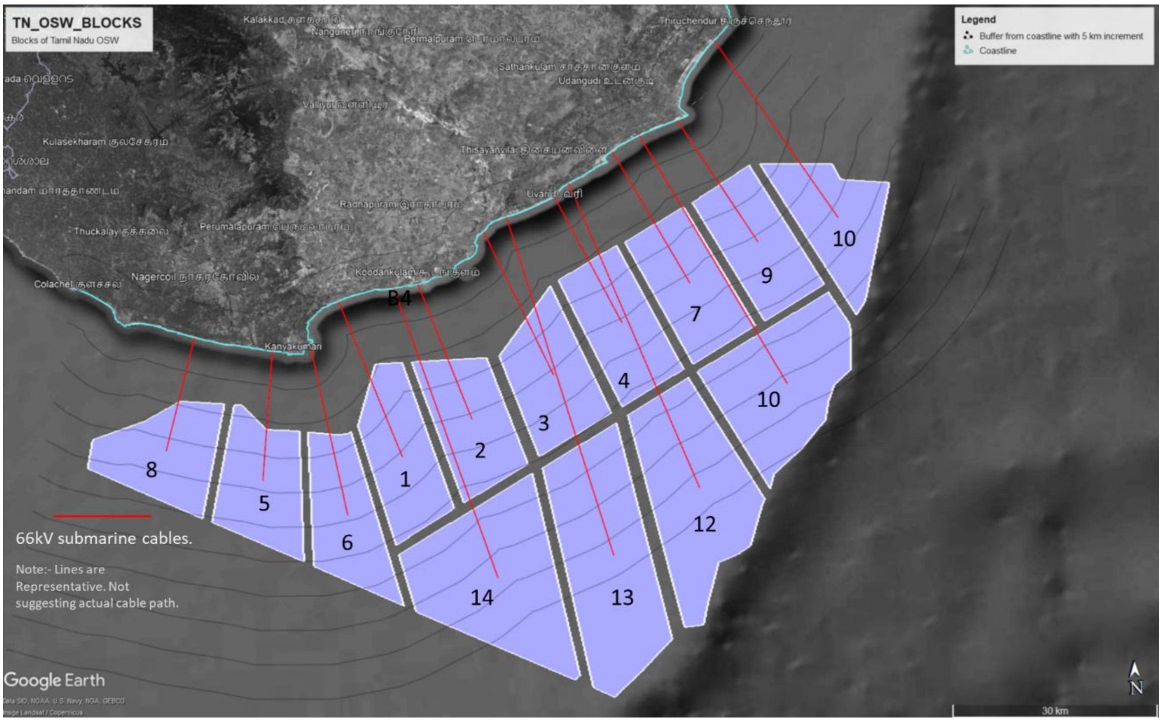


Figure 13: OSW zones in Gujarat and Tamil Nadu with 66 kV AC option

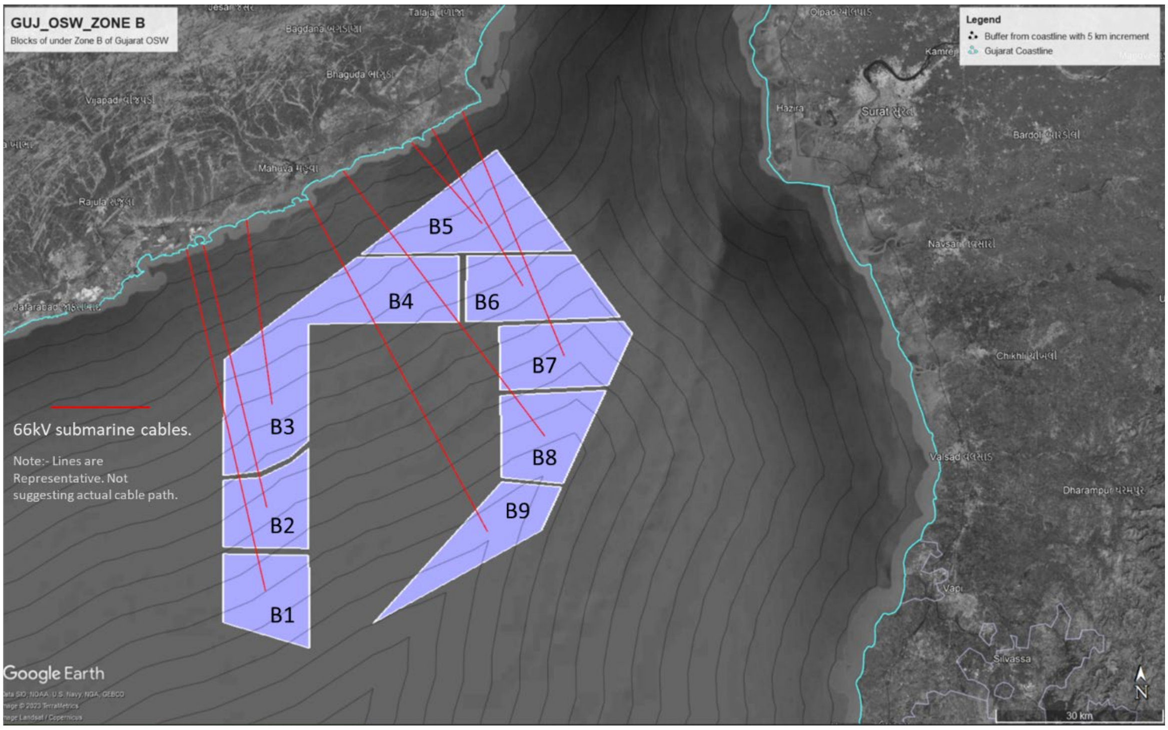


Figure 14: OSW zones in Gujarat and Tamil Nadu with 66 kV AC option

<table>
<tr><th>Option Details</th><th>Gujarat</th><th>Tamil Nadu</th><th>Remarks on applicability for Gujarat / Tamil Nadu</th></tr>
<tr><td>In this option, the 66 kV array cables are proposed for direct connection with the onshore transmission system</td><td rowspan="2">For evacuation of 3GW from B4 and B5 blocks; No. of 66 kV runs: 24 nos.

(24 X 25 kms) = 600 km of cable</td><td rowspan="2">For evacuation of 10 GW from Block 1 to 10; No. of 66 kV runs: 80 nos.

(80 X 25 kms) = 2000 km of cable</td><td rowspan="3">In case of Gujarat, it could be 66 kV options but in case of Tamil Nadu, 66 kV may not be suitable as there is a need for 66/110 kV of 66/230 kV station and hence it would be better to have 110kV as an option in Tamil Nadu if the development of offshore wind capacity is limited to less than 1 GW and it is contracted entirely by STU.</td></tr>
<tr><td>Pros:
No offshore sub-station is required in case the onshore transmission system can offer matching reference voltage for integration.</td></tr>
<tr><td>Cons:
Connection with ISTS having higher reference voltage will require OSS limiting the cost effectiveness offered by this option.
Developer to bear the Cable cost without opportunities for socialisation of cost for transmission system.
Too many runs impacting ecological sensitive areas</td><td>No. of OSS: NIL</td><td>No. of OSS: Need to have 66/110 kV or 66/230 kV onshore substations for connecting to STU network.</td></tr>
<tr><td colspan="4">Overall compatibility for Long-Term Planning of Transmission for OSW projects in India:
Not suitable</td></tr>
</table>

3.5.2 132kV or 110kV HVAC (Alternate 1.2)

This option is discussed for considering projected ease of commercially available array cable for immediate projects near shore with possibility of connecting at Intra-State Transmission System. The typical power evacuation capacity per circuit of cable being 250 MVA, this option still leads to a large no. of cable runs and thereby substantial increase in land and sub-sea footprint to consider as a suitable option for long term evacuation. The typical situation that may arise for this option is illustrated below.

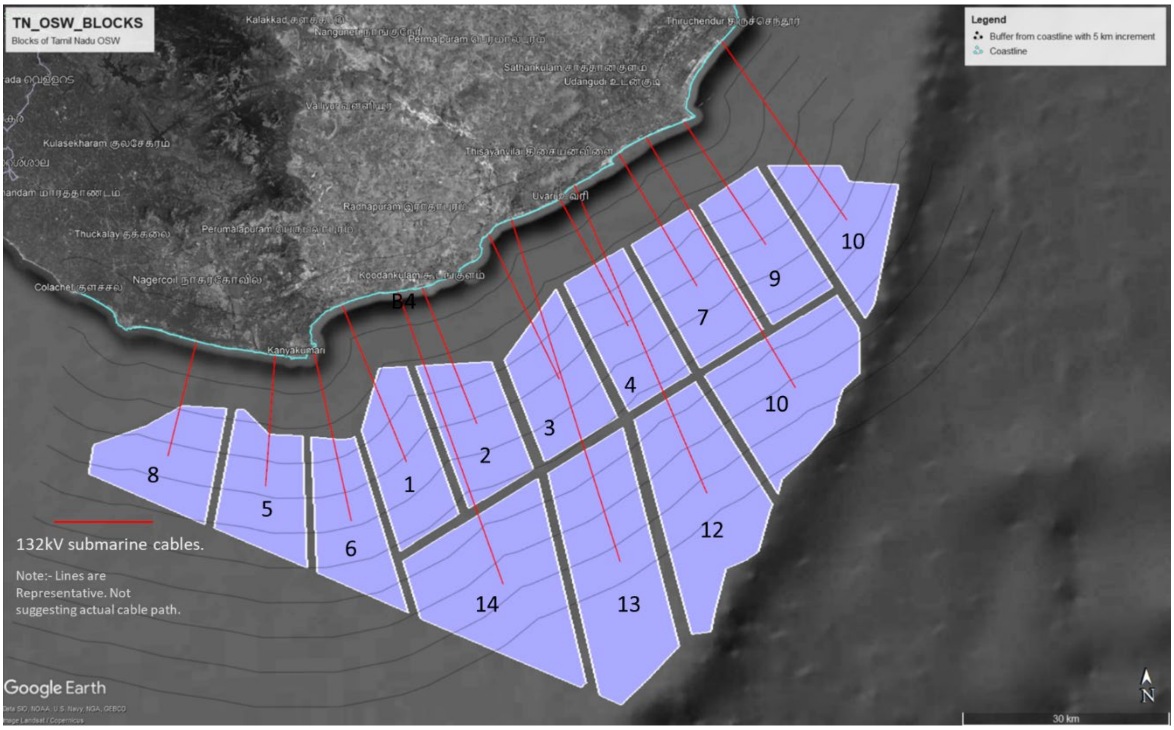


Figure 15: OSW zones in Tamil Nadu with 132 kV or 110kV AC option

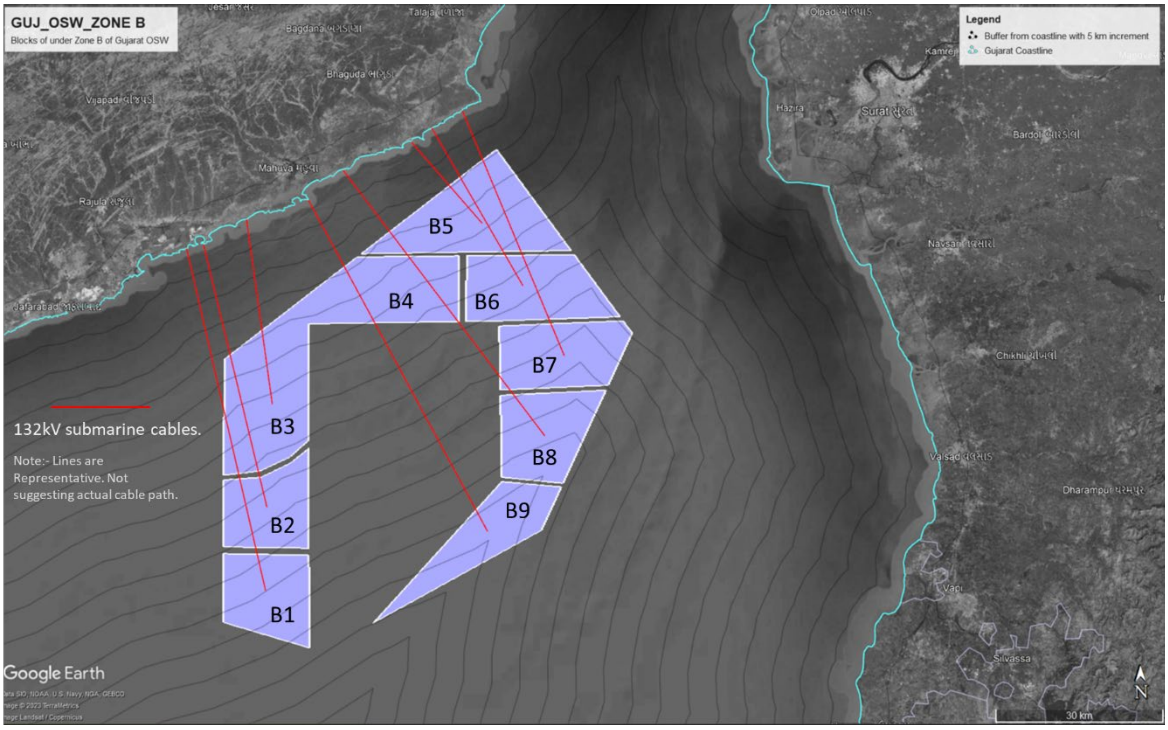


Figure 16: OSW zones in Gujarat and 132 kV or 110kV AC evacuation option

Option Details	Gujarat	Tamil Nadu	Remarks on applicability for Gujarat / Tamil Nadu
In this option, the 132 kV or 110kV array cables are proposed for direct connection with the onshore transmission system	For evacuation of 3GW from B4 and B5 blocks; No. of 132 kV runs: 12 nos. (12 X 25 kms) = 300 km of cable	For evacuation of 10 GW from Block 1 to 10; No. of 132 kV runs: 40 nos. (40 X 25 kms) = 1000 km of cable	In case of Gujarat, it could be a suitable option for the development of offshore wind capacity is limited to less than 1 GW and it is contracted entirely by STU. However, this option will still limit the power evacuation capacity of the future OSW projects by blocking the cable corridor.
Pros: • No offshore sub-station is required in case the onshore transmission system can offer matching reference voltage for integration.			
Cons: • Connection with ISTS having higher reference voltage will require OSS limiting the cost effectiveness offered by this option. • Developer to bear the Cable cost without opportunities for socialisation of cost for transmission system. • Too many runs impacting ecological sensitive areas	No. of OSS: NIL	No. of OSS: NIL	
Overall compatibility for Long-Term Planning of Transmission for OSW projects in India: Not suitable			

3.5.3 220 kV (or 230kV) HVAC (Alternate 1.3)

This option is discussed for considering ease of commercially available submarine export cable for immediate projects with possibility of connecting at Inter-State Transmission System. The typical power evacuation capacity per circuit of export cable being 420 MVA, this option offers significant potential to consider as a suitable option for short term evacuation. The typical situation that may arise for this option is illustrated in Figure 17 and 18 below for Tamil Nadu and Gujarat OSW zones.

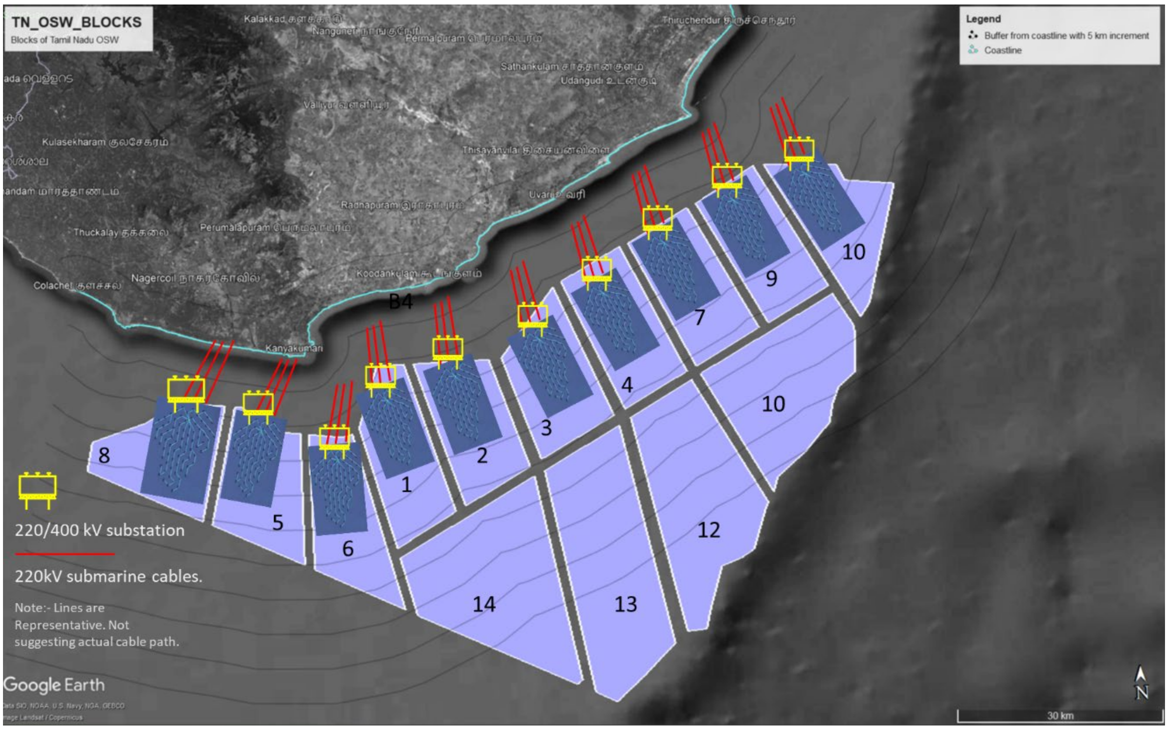


Figure 17: OSW zones in Tamil Nadu with 220 kV HVAC option

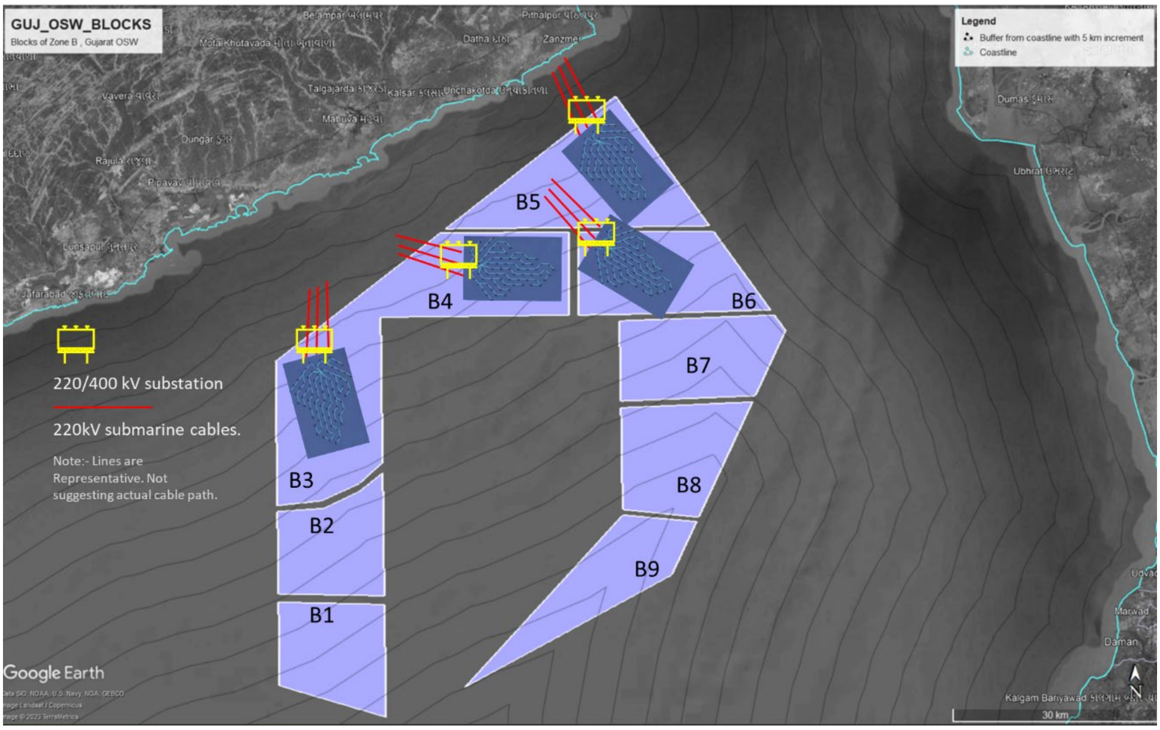


Figure 18: OSW zones in Gujarat with 220 kV HVAC option

Option Details	Gujarat	Tamil Nadu	Remarks on applicability for Gujarat / Tamil Nadu
In this option, the 220 kV submarine export cables are proposed for integration with the onshore transmission system **Pros:** • 1 or 2 nos. OSS per OSW blocks makes this option suitable for a phased development. • Can be directly integrated with ISTS transmission network onshore as well as STU network. • Offers potential for socialisation of transmission system cost. • Lowered risk for developer with Transmission System Licensee (TSL) driven approach for design, development, and O&M of Transmission assets with TSL.	For evacuation of 12 GW from B 1 to B9 blocks; No. of 220 kV runs: 29 nos. (29 X 53 kms) = 1537 km of cable	For evacuation of 10 GW from Block 1 to 10; No. of 230 kV runs: 24 nos. (24 X 25 kms) = 600 km of cable	In case of both Gujarat and Tamil Nadu, it could be a suitable option for the development of offshore wind capacity is limited to less than smaller blocks of 1GW to 2 GW capacity.
Cons: • No. of OSS still may remain high along with many runs impacting ecological sensitive areas	No. of OSS: 15 to 20 (typically one substation for 500 MW to 1GW	No. of OSS: 15 to 18 (typically one substation for 500 MW to 1GW	
Overall compatibility for Long-Term Planning of Transmission for OSW projects in India: Can be considered for short term evacuation			

3.5.4 400 kV HVAC (Alternate 1.4)

This option is discussed for considering projected ease of commercially available submarine export cable for long term projects with possibility of connecting at Inter-State Transmission System. The typical power evacuation capacity per circuit of export cable being 1000 MVA, this option offers significant potential to consider as a suitable option for medium term evacuation. The typical situation that may arise for this option is illustrated in Figure below for Gujarat and Tamil Nadu OSW zones.

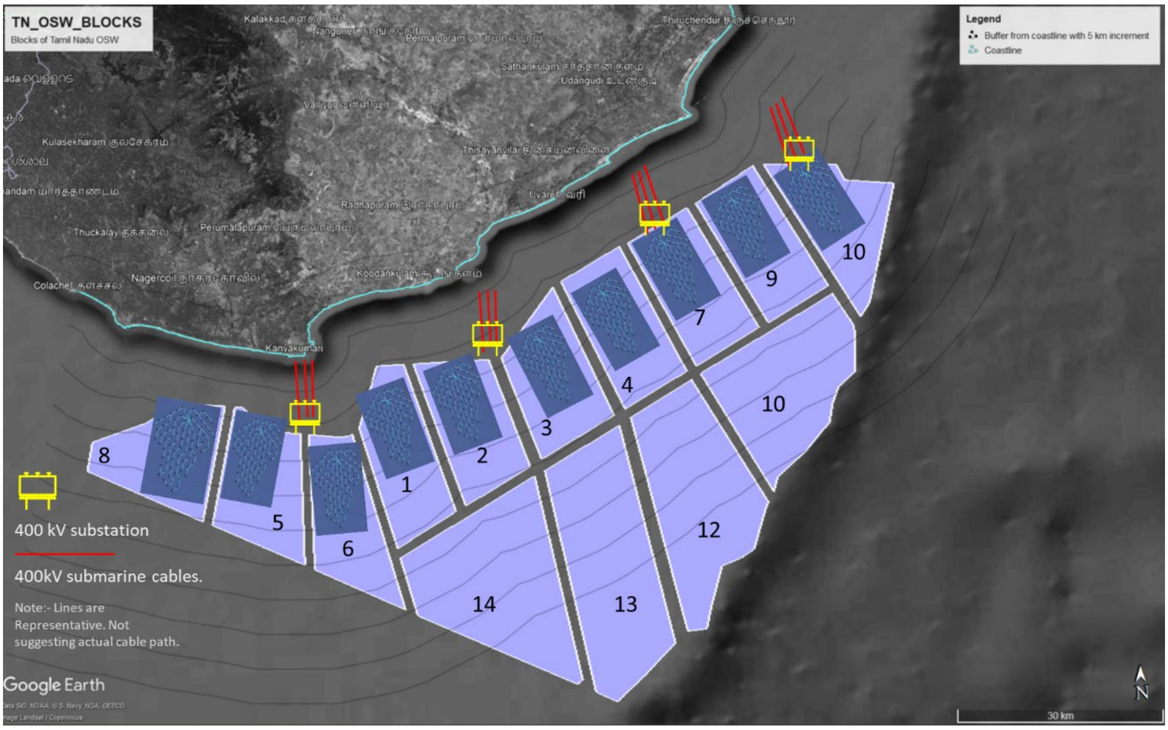


Figure 19: OSW zones in Tamil Nadu with 400 kV HVAC option

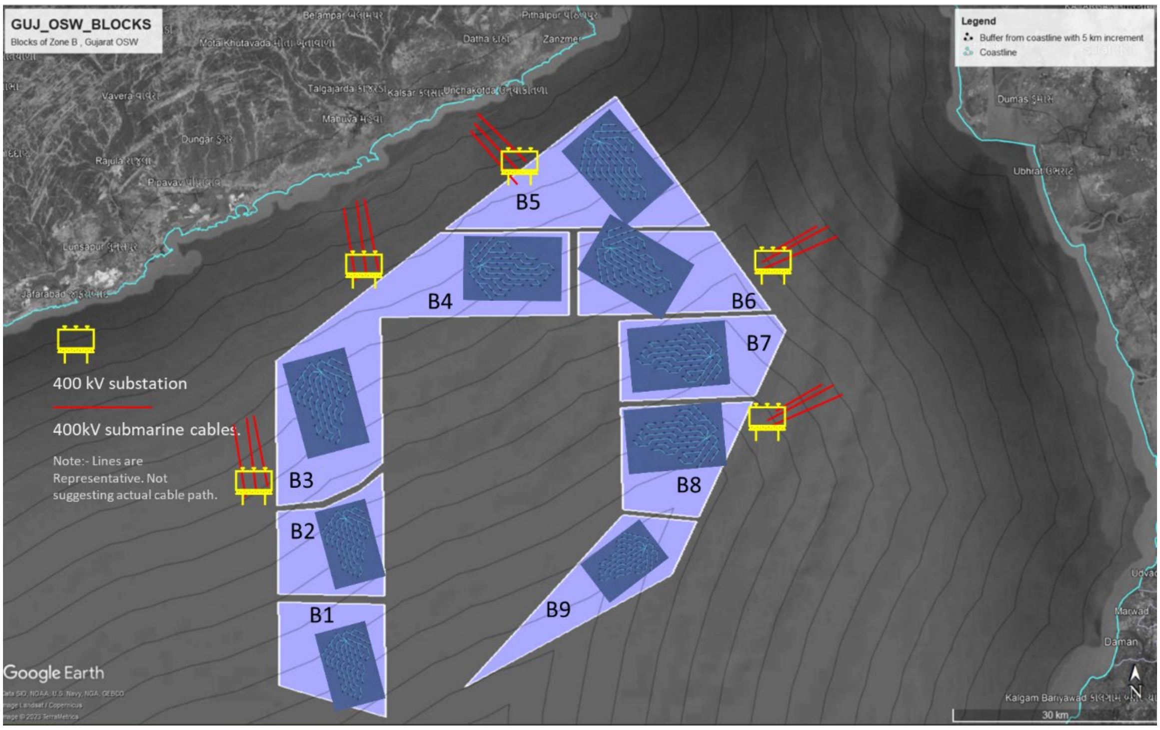


Figure 20: OSW zones in Gujarat with 400 kV HVAC option

Option Details	Gujarat	Tamil Nadu	Remarks on applicability for Gujarat / Tamil Nadu
In this option, the 400 kV submarine export cables are proposed for integration with the onshore transmission system	For evacuation of 12 GW from B 1 to B9 blocks; No. of 400 kV runs: 12 nos. ((12 X 3) X 53 kms) = 1908 km of cable	For evacuation of 10 GW from Block 1 to 10; No. of 400 kV runs: 10 nos. ((10 X 3) X 25 kms) = 750 km of cable	In case of both Gujarat and Tamil Nadu, it could be a suitable option for the development of offshore wind capacity both in medium term as well as long term. However, this system would require higher reactive power compensation devices and may need reactive power sub-stations for cable length more than 15kM. Also, these are single core cables. So, the total cable length will be significantly higher.
Pros: • Lower nos. OSS including sharing among OSW blocks makes this option suitable for a phased development along with grouping options for OSW zones. • Can be directly integrated with ISTS transmission network onshore. • Offers potential for socialisation of transmission system cost. • Lowered risk for developer with Transmission System Licensee (TSL) driven approach for design, development, and O&M of Transmission assets with TSL.			
Cons: • Reactive compensation requirement may make this option costlier than that with 220 kV HVAC	No. of OSS: 4 to 5	No. of OSS: 4 to 5 (typically one substation for 3GW)	
Overall compatibility for Long-Term Planning of Transmission for OSW projects in India: Can be considered for long term evacuation			

3.5.5 HVDC-VSC system up to 500 kV (Alternate 1.5)

This option is discussed for considering projected ease of commercially available submarine HVDC export cable for long term projects with possibility of connecting at Inter-State Transmission System. The typical power evacuation capacity per circuit of HVDC export cable could be up to 2000 MVA, this option offers extremely significant potential to consider as a suitable option for higher offshore wind integration in holistic manner. It would also offer a potential swapping between 400kV HVAC option in the initial period and possible conversion to HVDC system post significant development in offshore capacity. This option is illustrated in Figure 21 and 22 below for Tamil Nadu and Gujarat OSW zones.

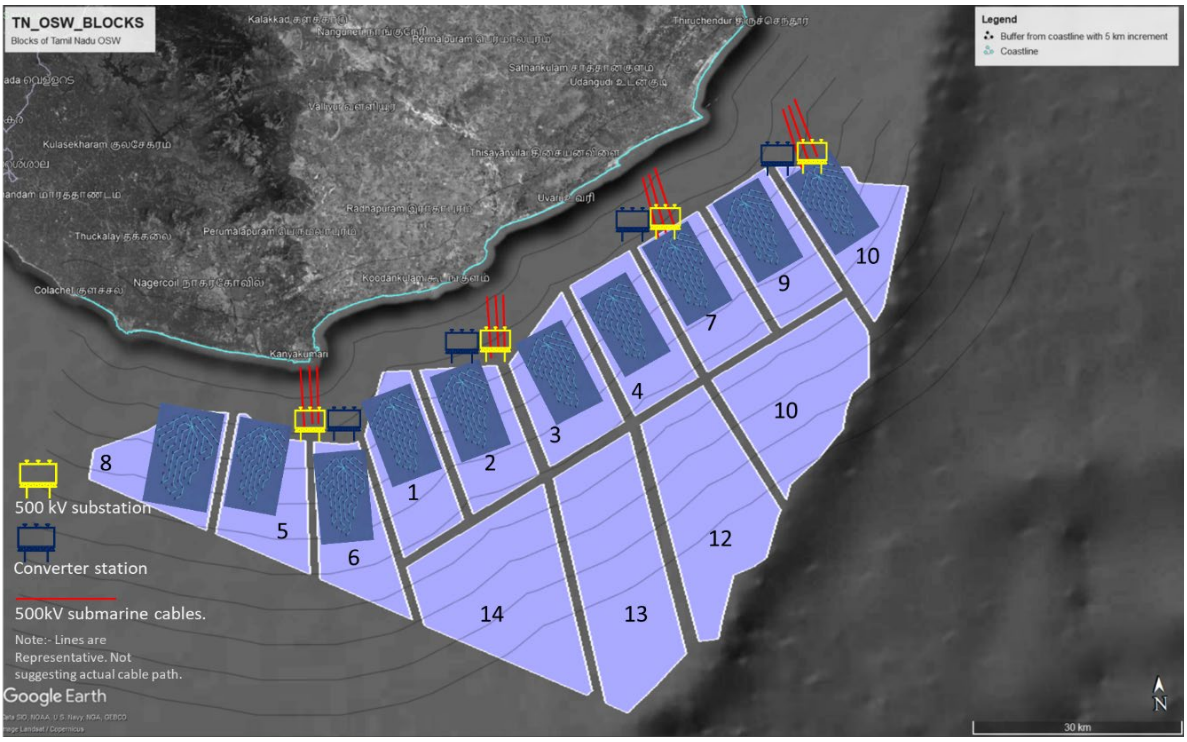


Figure 21: OSW zones in Tamil Nadu with HVDC option

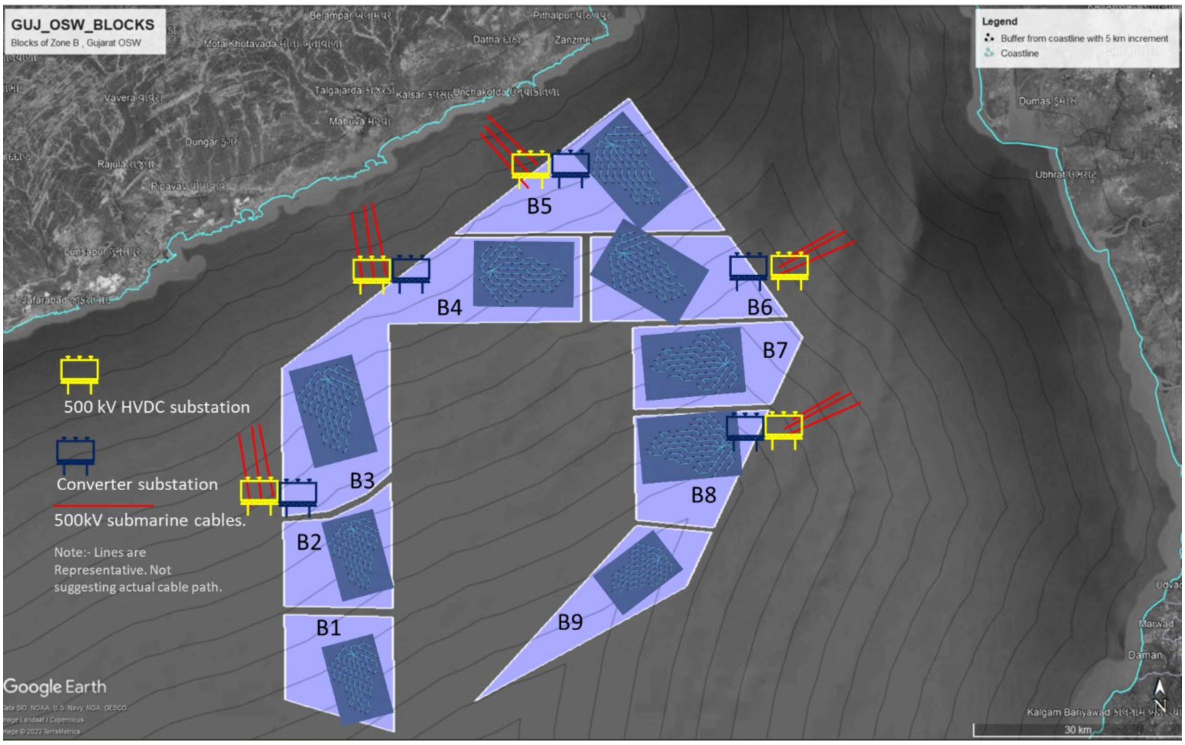


Figure 22: OSW zones in Gujarat with HVDC option

Option Details	Gujarat	Tamil Nadu	Remarks on applicability for Gujarat / Tamil Nadu
In this option, the 500 kV HVDC submarine export cables are proposed for integration with the onshore transmission system	For evacuation of 12 GW from B 1 to B9 blocks; No. of 500 kV HVDC runs: 6 nos. ((6 X 2) X 53 kms) = 636 km of cable	For evacuation of 10 GW from Block 1 to 10; No. of 500 kV HVDC runs: 10 nos. ((5 X 2) X 25 kms) = 250 km of cable	In case of both Gujarat and Tamil Nadu, it could be a suitable option for the development of offshore wind capacity higher than 5 GW.
Pros: • Very lower nos. OSS per OSW blocks makes this option suitable for a phased development along with grouping options for OSW zones. • Can be directly integrated with ISTS transmission network onshore. • Offer lower system losses. • Offers potential for socialisation of transmission system cost. • Lowered risk for developer with Transmission System Licensee (TSL) driven approach for design, development, and O&M of Transmission assets with TSL. • With technological advancement, it would be possible for swapping the 400kV HVAC option to HVDC option with significant development in offshore wind generation			
Cons: • No experience available for commercial deployment of HVDC for OSW evacuation • Technology maturity and supply chain availability risks exist. • Convertor stations required at both ends	No. of OSS: 6	No. of OSS: 5 (typically one substation for 3 to 5 GW)	

Option Details	Gujarat	Tamil Nadu	Remarks on applicability for Gujarat / Tamil Nadu
for evacuation making this option costlier than equivalent HVAC option			
Overall compatibility for Long-Term Planning of Transmission for OSW projects in India: Can be considered for long term evacuation			

3.5.6 Future Technology 765 kV HVAC (Alternate 2.1)

This option is discussed for considering projected ease of commercially available submarine export cable for very long term projects with possibility of connecting at Inter-State Transmission System. The typical power evacuation capacity per circuit of export cable over 3000 MVA, this option offers potential to consider as a suitable option for very high penetration of offshore wind generation. The typical situation that may arise for this option is illustrated in Figure below for Gujarat and Tamil Nadu OSW zones.

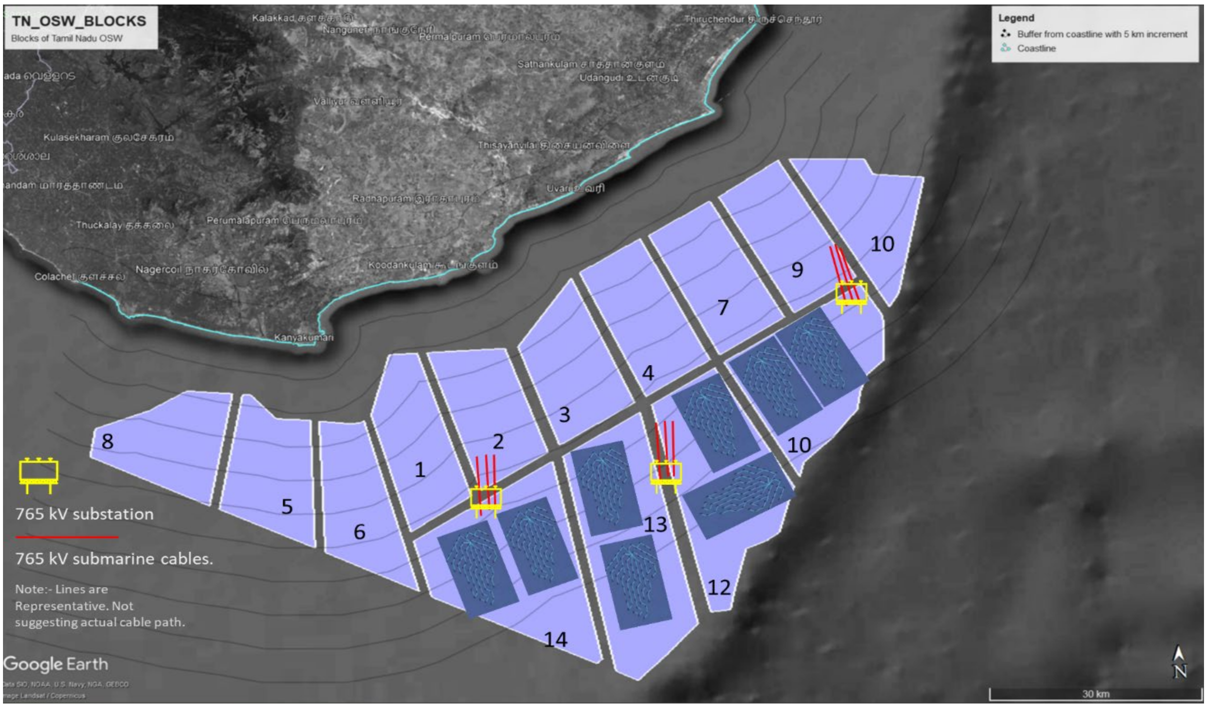


Figure 23: OSW zones in Tamil Nadu with 765 kV HVAC option

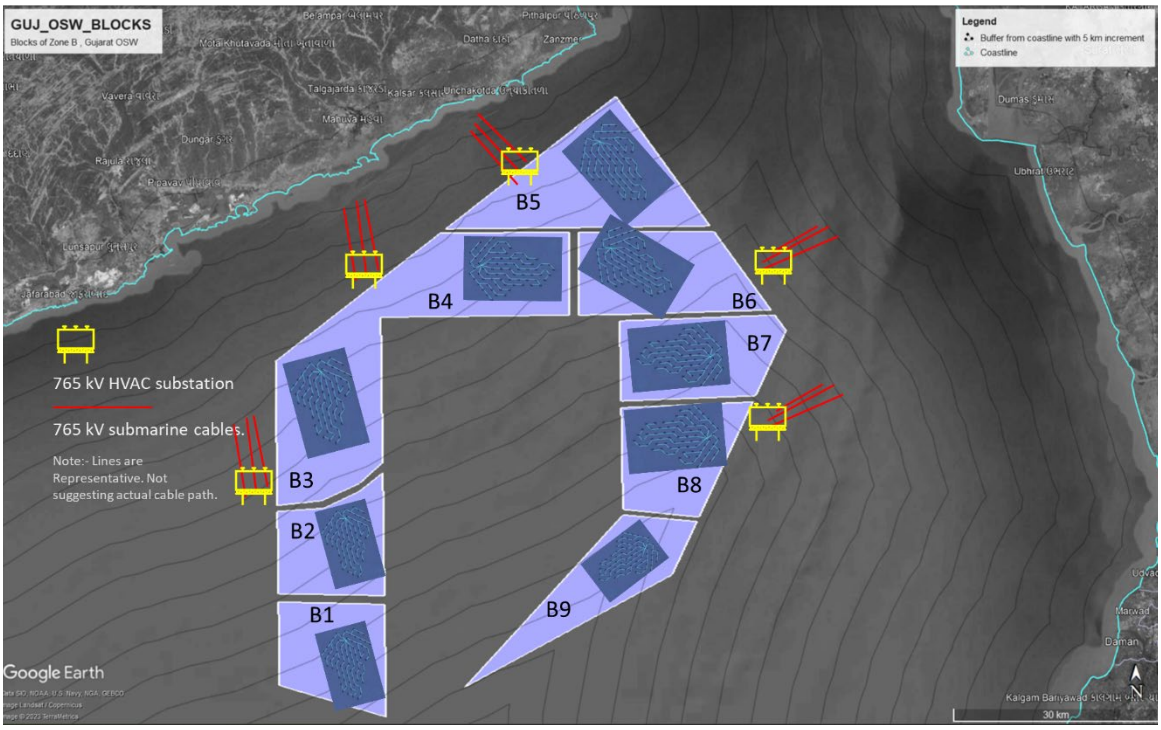


Figure 24: OSW zones in Tamil Nadu with 765 kV HVAC option

Option Details	Gujarat	Tamil Nadu	Remarks on applicability for Gujarat / Tamil Nadu
In this option, the 765 kV submarine export cables are proposed for integration with the onshore transmission system	For evacuation of 12 GW from B 1 to B9 blocks; No. of 765 kV HVAC runs: 5 nos. ((5 X 3) X 53 kms) = 795 km of cable	For evacuation of 8 GW from Block 11 to 14; No. of 500 kV HVDC runs: 4 nos. ((4 X 3) X 45 kms) = 540 km of cable	In case of both Gujarat and Tamil Nadu, it could be a suitable option for the development of offshore wind capacity is higher than 5 GW.
Pros:			

Option Details	Gujarat	Tamil Nadu	Remarks on applicability for Gujarat / Tamil Nadu
• Lower nos. OSS per OSW blocks makes this option suitable for a phased development along with grouping options for OSW zones. • Can be directly integrated with ISTS transmission network onshore. • Offers potential for socialisation of transmission system cost. • Lowered risk for developer with Transmission System Licensee (TSL) driven approach for design, development, and O&M of Transmission assets with TSL.			
Cons: • Very high reactive compensation requirement may make this option costlier than 400 kV HVAC	No. of OSS: 5	No. of OSS: 3 (typically one substation for 3GW)	
Overall compatibility for Long-Term Planning of Transmission for OSW projects in India: Can be considered for very long-term evacuation			

3.5.7 Future Technology UHVDC- system up to 640 kV (Alternate 3.1)

This option is discussed for considering projected future technological options available submarine HVDC export cable for very high capacity projects with possibility of connecting at Inter-State Transmission System. The typical power evacuation capacity per circuit of UHVDC export cable would exceed 3000 MVA, this option offers significant potential to consider as a suitable option for very high offshore capacity going beyond 30GW scenario in an integrated manner. The typical situation that may arise for this option is illustrated in Figure 25 and 26 below for Tamil Nadu and Gujarat OSW zones.

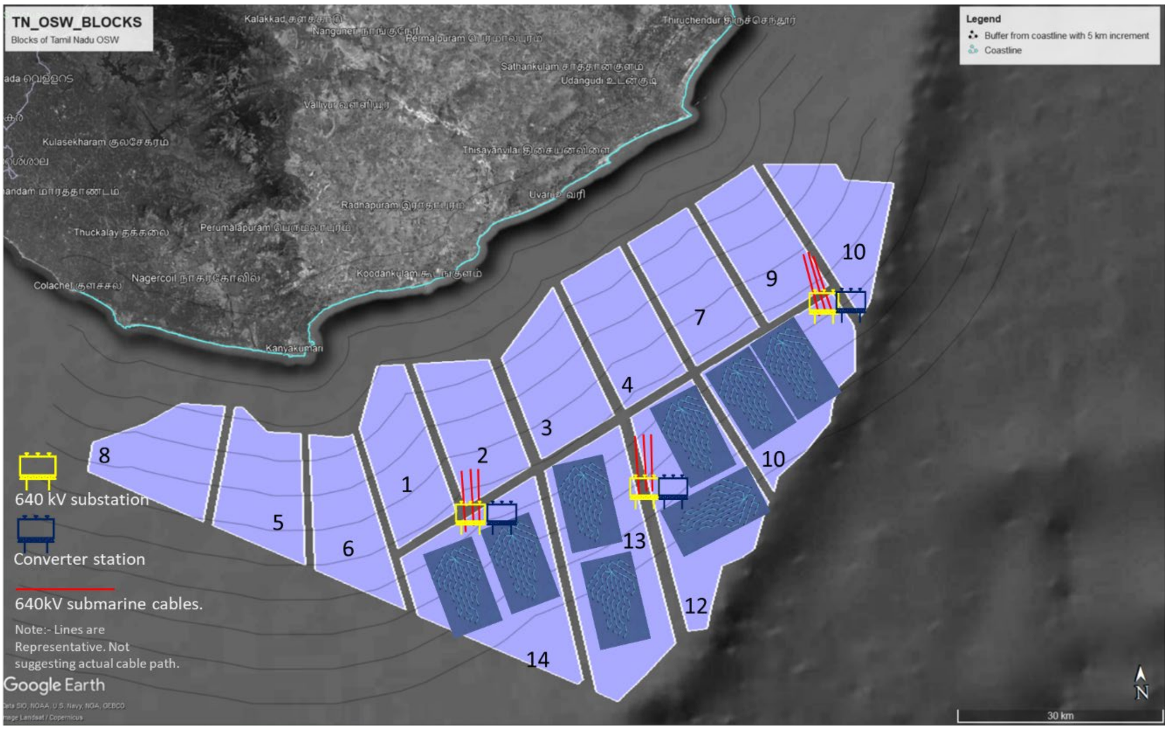


Figure 25: OSW zones in Tamil Nadu with UHVDC option

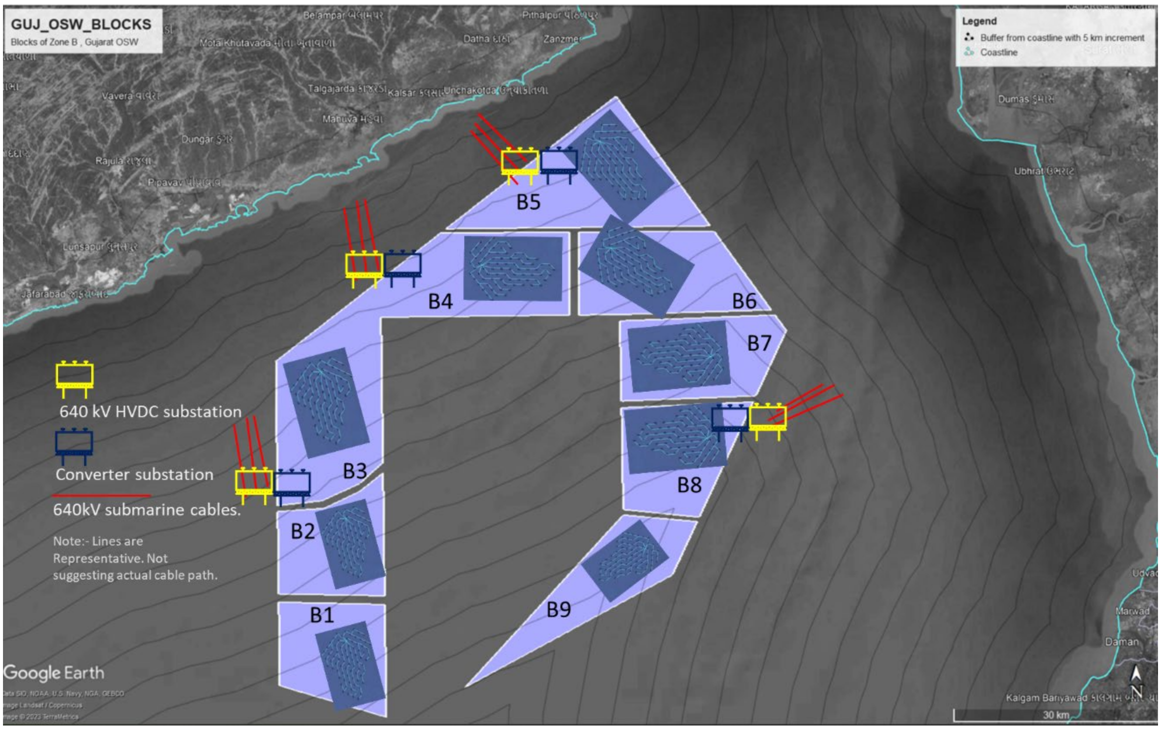


Figure 26: OSW zones in Gujarat with UHVDC option

Option Details	Gujarat	Tamil Nadu	Remarks on applicability for Gujarat / Tamil Nadu
In this option, the UHVDC submarine export cables are proposed for integration with the onshore transmission system **Pros:** • Very lower nos. OSS per OSW blocks makes this option suitable for a phased development along with grouping options for OSW zones. • Can be directly integrated with ISTS transmission network onshore. • Offer lower system losses. • Offers potential for socialisation of transmission system cost. • Lowered risk for developer with Transmission System Licensee (TSL) driven approach for design, development, and O&M of Transmission assets with TSL.	For evacuation of 12 GW from B 1 to B9 blocks; No. of 640 kV UHVDC runs: 4 nos. ((4 X 2) X 53 kms) = 424 km of cable	For evacuation of 8 GW from Block 11 to 14; No. of 500 kV HVDC runs: 3 nos. ((3 X 2) X 45 kms) = 270 km of cable	In case of both Gujarat and Tamil Nadu, it could be a suitable option for far offshore blocks and the development of offshore wind capacity beyond 30GW development perspective.
Cons: • Technology development in UHVDC for OSW evacuation • Technology maturity and supply chain availability risks exist. • Convertor stations required at both ends for evacuation making this option costlier than equivalent HVAC option	No. of OSS: 4	No. of OSS: 2 (typically one substation for 7.5 GW)	
Overall compatibility for Long-Term Planning of Transmission for OSW projects in India: Can be considered for long term evacuation			

3.6 Mapping of Phased approaches for offshore evacuation

Based on the approaches for technology options of HVAC and HVDC scheme discussed in above section, the possible schemes with near shore zone grouping and an integrated scheme combining the near and far shore zones for Gujarat and Tamil Nadu elaborated in Table 12 and Table 13 can further be investigated for Physical, Technology and Development attributes of OSW transmission system development.

Table 12: Evacuation options for 18 GW OSW Capacity – Tamil Nadu (14 blocks)

Evacuation options	Without OSS 66kV (Alt-1.1)	Without OSS 132 KV (Alt-1.2)	220 KV with OSS (Alt-1.3)	400 kV with OSS (Alt-1.4)	HVDC-VSC with OSS (Alt-1.5)	765 kV with OSS (Alt-2.1)	UHVDC (Alt-3.1)
Typical Evacuation Capacity per circuit	125 MVA	250 MVA	420 MVA	>1000 MVA	>2000 MVA	>2500 MVA (As designed)	>3000 MVA
Near shore Zones	1 to 10	1 to 10	1 to 10	1 to 10	1 to 10	11 to 14	11 to 14
Capacity	10 GW	10 GW	10 GW	10 GW	10 GW	8 GW	8 GW
Groupings							
1 GW	10 groups	10 groups	10 groups	X	X	X	X
2 GW	X	X	5 groups	5 groups	5 groups	X	X
3 GW	X	X	3+1 groups	3+1 groups	4 groups	4 groups	4 groups
No. of OSS/transformer - to be confirmed	X	X					
1 GW			10	X	X	X	X
2 GW			X	5	X	X	X
3 GW			X	4 (3 +1)	4 (3 +1)	3	3
Export cable	66 kV (3 core)	132 kV (3 core)	220 kV (3 core)	400 kV (1 core)	300 to 400 kV	765 kV (1 core)	640 kV
- Total run km (no. of run * km per run)	2000 km [80 runs X 25km per run]	1000 km [40 runs X 25 km per run]	600 km [24 runs X 25 km per run]	750 km [(10 X 3) runs X 25 km per run]	250 km [(5 X 2) runs X 25 km per run]	540 km [(4 X 3) runs X 45 km per run]	270 km [(3 X 2) runs X 45 km per run]

Table 13: Evacuation options for 12 GW OSW Capacity – Gujarat (Zone B, Block 1 to 9)

Evacuation Options	Without OSS 66kV	Without OSS 132 KV	220 KV with OSS	400 kV with OSS	HVDC-VSC with OSS	765 kV with OSS	UHVDC
	(Alt-1.1)	(Alt-1.2)	(Alt-1.3)	(Alt-1.4)	(Alt-1.5)	(Alt-2.1)	(Alt-3.1)
Typical Evacuation Capacity per circuit	125 MVA	250 MVA	420 MVA	1000 MVA	2000 MVA	2500 MVA (As per design)	3000 MVA
Applicable to Zones	B4 & B5	B4 & B5	B1 to B9	B1 to B9	B1 to B9	B1 to B9	B1 to B9
Capacity	3 GW	3 GW	12 GW	12 GW	12 GW	12 GW	12 GW
Groupings							
1 GW	3 groups	3 groups	12 groups	X	X	X	X
2 GW	X	X	6 groups	5 groups	6 groups	X	X
3 GW	X	X	4 groups	4 groups	4 groups	4 groups	4 groups
No. of OSS	X	X					
1 GW			12	X	X	X	X
2 GW			X	6	6	X	X
3 GW			X	4	4	4	4
Export cable	66 kV (3 core)	132 kV (3 core)	220 kV (3 core)	400 kV (1 core)	300 to 400 kV	765 kV (1 core)	640 kV
- Total run km (no. of run * km per run)	600 km [24 runs X 25km per run]	300 km [12 runs X 25 km per run]	1515 km [24 runs X 53 km per run]	1908 km [(12 X 3) runs X 53 km per run]	636 km [(6 X 2) runs X 53 km per run]	795 km [(5 X 3) runs X 53 km per run]	424 km [(4 X 2) runs X 53 km per run]

The attributes for evaluation of above options and its suitability are based on the indicators for attribute parameters discussed below:

- **Physical attributes:**

Parameter	Indicator
Topology like near shore zone sites or far zone sites	The possibility of near zone sites can be considered for evacuation from OSW projects in short term, while the integration of near zone sites with the far zone sites can be considered for an integrated approach for OSW projects in long term
Total Cable length and Cable runs requirements	The preference of option with the lower cable length for cost optimisation and lower cable runs for ease of execution and O&M

Parameter	Indicator
No. of OSS required	The preference of option with the lower nos. of OSS to gain cost optimisation and lower the environmental footprints of OSW projects

- **Technical attributes:**

Parameter	Indicator
Reactive Compensation	Reactive compensation requirement to be evaluated for availability, maturity, and cost of technology for each of the option
Transmission Losses	Lower the transmission losses preferred the option
Reliability	The reliability to be evaluated for statutory requirement and cost for each of the option
Convertibility	The preference for option with ease to convert existing option to adapt to future technology.

- **Development attributes:**

Parameter	Indicator
Phased development	The option supporting phased development is preferred considering time availability for establishment of indigenous supply chain and skill set of persons involved in construction and operation of OSW transmission system
Onshore Land usage / Right of Way	The option involving less onshore land usage for Onshore pooling stations/ landfall points and lesser requirement of availing right of way is preferred
Ownership Model	The option amenable to business model with maximum possibility of socialisation of transmission infrastructure cost is preferred.
Environmental footprint and social impact	The option involving less environmental footprint for OSS and submarine cable along with lower social impact possibility is preferred

The Table 14 provides the Configuration Option for an integrated approach for the OSW projects in Tamil Nadu duly mapping of evacuation schemes is arrived at Table12 (refer table nos. for TN). The similar approach can also be worked out for Gujarat.

Table 14: Configuration Options for integrated planning for Tamil Nadu

Configuration options	Brief description of config. option	Physical attributes	Technology attributes	Develop-mental attributes	Environmental footprint	Configuration applicability indicator
Config Option 1 (Alt 1.1 + Alt 2.1)	No OSS but 66kV export cable + 765kV OSS> 50 km 10 groups of 1 GW near shore zones + 4 groups of 3 GW far shore zones	66 kV: 2000 km [80 runs X 25km per run] and 765 kV: 540 km [(4 X 3) runs X 45 km per run] No. of 66 kV OSS: NIL No. of 765 kV OSS: 3	Higher Transmission loss for 66 kV system with Reactive compensation requirement for 765 kV system. This option pose difficulty for technology upgradation at later date.	Too many landfalls and hence substation required for connecting 80 runs of 66 kV system negating the advantage of avoiding OSS. These options pose difficulty for effective O&M and socialisation of cost for transmission system.	Too many cable runs (80 runs) will impact the environment footprint by blocking the cable corridor permanently for effective movement of fishing vessels as well as of aquatic life and society dependent on the fisheries.	Not suggested for the case of TN with 15 GW evacuation scenario considering the increased cost due to higher cable length, higher transmission losses, low scalability and cost socialisation opportunities and irreversible environmental damage and social impact in long term.
Config Option 2 (Alt 1.2 + Alt 2.1)	132 OSS & export cable + 765kV OSS > 50 km 10 groups of 1 GW near shore zones + 4 groups of 3 GW far shore zones	132 kV: 1000 km [40 runs X 25km per run] and 765 kV: 540 km [(4 X 3) runs X 45 km per run] No. of 132 kV OSS: NIL No. of 765 kV OSS: 3	Lower Transmission loss for 132 kV system compared with 66 kV cables with Reactive compensation requirement for 765 kV system. This option pose difficulty for technology upgradation at later date.	Many landfalls and hence substation required for connecting 40 runs of 132 kV system negating the advantage of avoiding OSS. These options pose difficulty for effective O&M and socialisation of cost for transmission system.	Many cable runs (40 runs) will impact the environment footprint by blocking the cable corridor permanently for effective movement of fishing vessels in addition to aquatic life and society dependent on the fisheries.	Not suggested for the case of TN with 15 GW evacuation scenario considering the increased cost due to higher cable length, higher transmission losses, low scalability and cost socialisation opportunities and irreversible environmental damage and social impact in long term.

Configuration options	Brief description of config. option	Physical attributes	Technology attributes	Develop-mental attributes	Environmental footprint	Configuration applicability indicator
Config Option 3 (Alt 1.3 + Alt 2.1)	220 kV OSS & export cable + 765kV OSS > 50 km 10 groups of 1 GW near shore zones or 5 groups of 2 GW near shore zones or 3 groups of 3 GW near shore zones combined with 1 GW near shore zone + 4 groups of 3 GW far shore zones.	220 kV: 600 km [24 runs X 25km per run] and 765 kV: 540 km [(4 X 3) runs X 45 km per run] No. of 220 kV OSS: 10 No. of 765 kV OSS: 3	Lower Transmission loss compared with 66 kV or 132 kV cables with Reactive compensation requirement for 765 kV system. This option offers lower opportunities for technology upgradation at later date.	Many OSS substations required for connecting array cables at the OSS and then export cables to the landfall substations system negating the advantage of avoiding many cable runs. This option offer scalability for phased development This options pose difficulty for effective O&M of OSS, however, provides opportunity for socialisation of cost for transmission system.	Many OSS (10 nos.) will impact the environment footprint by blocking the seabed permanently for effective movement of aquatic life and society dependent on the fisheries.	Can be considered for OSW transmission system in short term due to ease of commercially available technology to gain development advantage. However, the option needs to be evaluated with the increase in cost due to addition of 10 nos. OSS. Also, with this option advantage of modularity for grouping of near shore zones and cost socialisation opportunities can be gained. However, the irreversible environmental damage and social impact in long term due to 10 no. OSS are deterrent for this option.
Config Option 4 (Alt 1.4 + Alt 2.1)	400 kV OSS & export cable + 765kV OSS > 50 km 5 groups of 2 GW near shore zones or 3 groups of 3 GW near shore zones combined	400 kV: 750 km [(10 X 3) runs X 25 km per run] 765 kV: 540 km [(4 X 3) runs X 45 km per run] No. of 440 kV OSS: 5 for group	Very low Transmission loss compared with 220 kV system, however, has higher requirement for Reactive compensation requirement for 400 & 765 kV system. This option offers very high opportunities	Less cable runs 10 nos. and less no. of OSS substation required can bring the cost effectiveness with use of limited cable corridor and seabed footprints	Less cable runs 10 nos. and less OSS substation required can limit the environment footprint and can provide sustainable development option for society dependent on the fisheries.	Can be considered for OSW transmission system in long term due to higher scalability, modularisation, lower losses with a possibility of commercially available technology in future.

Configuration options	Brief description of config. option	Physical attributes	Technology attributes	Develop-mental attributes	Environmental footprint	Configuration applicability indicator
	with 1 GW near shore zone + 4 groups of 3 GW far shore zones.	of 2 GW and 4 for group of 3GW+1GW No. of 765 kV OSS: 3	for technology upgradation at later date considering 400 kV system charged to 220 kV level and then later uprated to 400 kV level. However, commercial availability of technology and establishment of indigenous supply chain development are barriers for this option.	and ease in O&M. This option offer scalability for phased development This provides opportunity for socialisation of cost for transmission system.		With this option advantage of modularity and cost socialisation opportunities can be gained. This option offers best possible way for sustainable development by limiting environmental damage and social impact in long term.
Config Option 5 (Alt 1.3 + Alt 1.5)	>220 kV OSS & export cable + HVDC Stn > 50 km 10 groups of 1 GW near shore zones or 5 groups of 2 GW near shore zones or 3 groups of 3 GW near shore zones combined with 1 GW near shore zone + 5 groups of 2 GW or 4 groups of 3 GW far shore zones	>220 kV: 600 km [24 runs X 25km per run] and 400 kV HVDC: 250 km [(5 X 2) runs X 25 km per run] No. of 220 kV OSS: 10 No. of 400 kV HVDC OSS: 4 (3 GW each)	Very Low Transmission loss compared with combination of 220 kV and 765 kV AC system. Cost of option may be a barrier with addition of converter stations along with HVDC OSS. less Reactive compensation requirement this combination. Except for use in filters This option offers higher opportunities for technology upgradation at later date.	Many OSS substations required for connecting array cables at the OSS and then export cables to the landfall substations system negating the advantage of avoiding many cable runs. This option offers high scalability for phased development. This provides opportunity for socialisation of cost for transmission system.	Many OSS (10 nos. for 220 kV and additions OSS for HVDC & converter platforms) will impact the environment footprint by blocking the seabed permanently for effective movement of aquatic life and society dependent on the fisheries.	Can be considered for OSW transmission system in long term due to higher scalability, modularisation, lower losses with a commercially available technology. With this option advantage of modularity and cost socialisation opportunities can be gained. However, the irreversible environmental damage and social impact in long term due to 10 no. + OSS are deterrent for this option.

Configuration options	Brief description of config. option	Physical attributes	Technology attributes	Develop-mental attributes	Environmental footprint	Configuration applicability indicator
Config Options 6	For the combination options using future Technology of UHVDC- system up to 640 kV, the commercial availability and viability cannot be visualised for a recommendation.					

Key Takeaways

The integrated planning of transmission system is a must for immediate 5 GW OSW projects in Gujarat and Tamil Nadu, which needs to align with the long-term planning for evacuation of 30 GW OSW capacity in these states. This integrated planning approach is proven internationally to bring in cost efficiencies and optimise on the country resources such as land for onshore sub-stations, submarine cable corridors, offshore substation platforms and the environmental footprints for a sustainable development of the sector. The integrated planning approaches further brings visibility of scale of operations to facilitate establishment of indigenous supply chain and increase the employment opportunities and capacity building of the persons in the development cycle.

The evacuation options investigating applicability of HVAC and/or with combination of HVDC for offshore transmission system while working out long-term transmission planning approaches is considered based on zone potential, physical distances of OSW projects from the shore and its compatibility with onshore transmission for effective integration, auction strategy, the technology readiness, indigenisation opportunities gain, capacity building measures and investment channelisation for transmission system. These evacuation options further grouped to devise the Configuration Options and evolve an integrated planning approach while qualitatively validating each of the Configuration Options with the physical, technology, development, and environment parameters.

The Configuration Option 4 comes out with a clear advantage for an integrated approach to implement for its effectiveness to for uprating possibilities i.e. to charge the 400 kV line at lower voltage 220kV during initial phase and later with OSW capacity enhancement, the same transmission corridor capacity could be used to cater for subsequent phases. Only cons would be upfront loading of capital cost for initial phases. With the OSS cost are to be socialised, the integrated approach favours 400 kV OSS system under Configuration Option 4 over 220 kV OSS under Configuration Option 3.

The Configuration Option-5 with HVDC system, can be advantageous considering its modularisation flexibility in OSW capacity augmentation and enhance reliability as against Configuration Option 4, however needs to be dwelled into detail on cost effectiveness for involvement of additional converter stations and environment footprint.

The Configuration Option 1 and 2 involving 66 kV and 132 kV system are not right candidates for integrated planning considering its development will lead a fragmented planning and will cost heavily on environment and social aspects. While the Configuration Option 6 cannot be validated considering its commercial unavailability as on date.

The Configuration Options developed needs further investigations through technical pre-feasibility studies and cost assessment, environment and social impact assessment to undertake relative assessment between Configuration Options 4 and 5.

4. Development and Implementation aspects of OSW Evacuation

4.1 Key Components of OSW Evacuation

The OSW grid system is very similar to the onshore grid systems; however, the nature of components and their ratings are very different, which affects the grid design for OSW evacuation. A typical OSW evacuation network with key components is shown in the Figure 27 below:

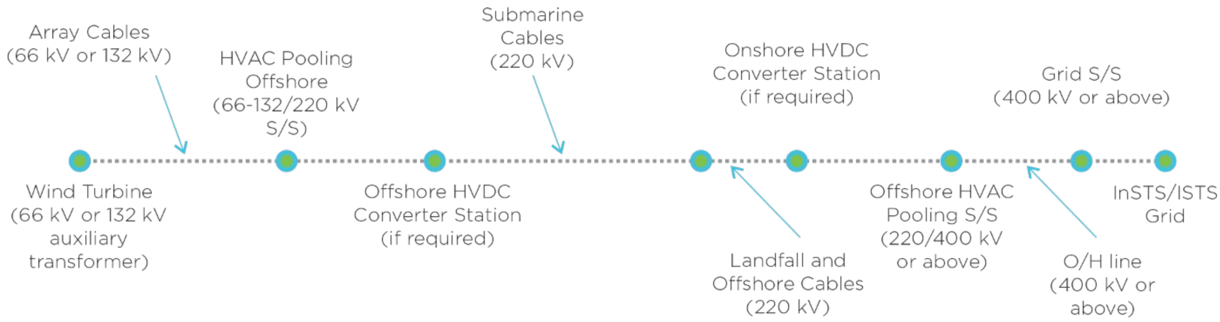


Figure 27: Key Component of OSW Evacuation Network

In an OSW evacuation network, the power is generated by the individual OSW turbines which are pooled together through inter array cables to the HVAC pooling substation. Further, power is evacuated to the onshore landfall through submarine export cables. However, if the distance of wind farm is above 80 km from the coast, then as a general practice, offshore HVDC convertor are used to convert AC power to DC before exporting it to the onshore landfall. From onshore landfall point power is received at the HVAC onshore pooling substation using underground onshore cables, which is further evacuated to the grid substation using overhead cables. A detailed analysis of each of the components are discussed in the subsequent section.

4.2 Offshore Wind Array Cable deployment

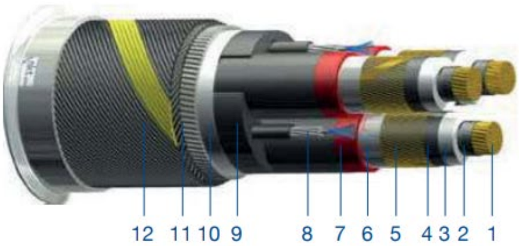
Offshore cables are used to transport electricity from the offshore WTG to either offshore substation, or offshore pooling substation or directly to onshore pooling substation for connecting offshore wind farms to the shore. The installation of offshore cables requires a specialized understanding of marine operations, engineering, and maintenance to ensure the cables are installed and maintained safely. The operations and maintenance of offshore cables involve regular checking of the cables for damage, corrosion, and wear and tear that can occur over time to ensure the cables remain efficient and safe to use. Offshore cable engineering and installation and operations and maintenance support is a growing industry due to the adoption and implementation of OSW as a renewable energy source.

Offshore wind array cables are electrical cable that connects the multiple wind turbines to the offshore substation. All wind turbines are connected to the offshore substation using an array cable. Array Cables costs typically about £35 million for a 1 GW wind farm35. However, the cost may vary depending upon the voltage class considered in array cable design. The cross section and major parts of a submarine cable are depicted in Figure 28 and 29.

[35] Guide to an Offshore Wind Farm by BVGA– ORE (catapult.org.uk)

Figure 28: Cross-Section of a Static Subsea Power Cable (Source-ORECatapult, Nexans)

Standard: IEC 60502 & 60840



Design:
Aufbau:

1 Conductor (Al or Cu)
Leiter (Al oder Cu)

2 Inner semi-conducting layer
Innere Leitschicht

3 XLPE insulation
VPE-Isolierung

4 Outer semi-conducting layer
Äußere Leitschicht

5 Wire screen (Al or Cu)
Drahtschirm (Al oder Cu)

6 Aluminium tape
Aluminiumband

7 PE oversheath with semi-conductive skin layer
PE-Außenmantel mit leitfähiger Skinschicht

6 + 7 Al-PE-laminated sheath
Al-Schichtenmantel

8 Fibre optic cable
Lichtwellenleiterkabel

9 Filler profiles
Profiltrensen

10 Bedding (PP)
Polsterlage (PP)

10 Armouring
Armierung

11 Outer sheath (PP)
Außenmantel (PP)

Figure 29: Three-Core Submarine Cable with Aluminum-Polyethylene-Laminated (APL) Sheath, 66kV, 125 MVA, 1000 mm^2 array cables from NKT.

The cables can evacuate power from the wind turbines to the offshore pooling substation or directly to the onshore grid substation if the distance permits (10 – 15 km) and in case of isolated small offshore wind farms. Standard offshore wind subsea cables are constructed of a stranded, profiled conductor with several armouring, sealing, and cross-linked polyethylene (XLPE) insulation layers. To sustain the laying process and to withstand wave and tidal loads in exposed areas, cable must possess strong chemical and abrasion resistance in addition to tensile strength.

Three different types of insulated power core designs are available as mentioned below:

- Dry, with an extruded lead sheath insulation covering.
- Semi-wet, with a polyethylene sheath covering a steel screen that isn't completely impenetrable.
- Wet, no sheath over a partially impermeable metallic screen

Although wet designs are lighter and more flexible, they are not currently used considering the ease of operation and environmental consideration.

The array cables need special attention in handling and transportation. to maintain the cables at required minimum bend radius during shipping or even at installation to avoid any risk of cable failure. Offshore array cables are generally boxed onto the installation vessel from the factory to eliminate needless handling and storage.

4.2.1 Configuration options and design considerations

Currently 66 kV array cables are mostly in use for WTGs. However, with Higher capacity WTGs are becoming standard for OSW applications then 132 kV array cables may be used in near future, owing to greater cost savings and reduced number of connections and switchgears.

The first generation of OSW farms typically used 33 kV cables, but high voltage cables have been a major focus of technical development because it allows the connection of higher capacity on a single string, thereby reducing the number of cable and the number of switchgear bays required on the substation. In addition to the increased voltage, the deployment of larger turbines above 6 MW has led to an increase in conductor sizing.

The maximum array cable size for early 33 kV wind farms was 630 mm^2, however current projects in the planning and construction phases are heading to 66 kV with cable size of 800 mm^2 or larger of both copper and aluminium.

Following are the main design components of an array cable as illustrated in Figure 29 above.

- Conductor
- Insulator
- Electrical screen
- Optical fibre
- Mechanical and chemical protection

Cable protection devises are used to enhance the safety and reliability of the cable and to ensure protection from anchors and several site-specific issues like avoiding harm to reefs and existing cables. In case of offshore cables, protection is one of the most important factors to consider from implementation point of view. Following are the cable protection equipment used for offshore installations.

- J-tube seals
- Bend restrictors

- Bend stiffeners
- Cable mattresses
- Rock placement/Sandbags

When a cable enters an aperture in a wind turbine, offshore substation, or a set of J-tubes, it is protected from wave and tidal action by cable protection schemes and equipment by offering a clamp that enables the cable to be routed via a hole in the monopile. Some developers offer a J-tube-less alternative for monopile foundations.

J-tube offer a seal at the end to prevent entry of seawater. Several discs are drawn up into the J-tube to form passive seals. After being inserted into the J-tube, active seals need to be inflated, which calls for a remotely operated vehicle (ROV). In some situations, seals are not necessary, however a sealed J-tube may contain a corrosion inhibitor.

Cable stiffeners are other forms of protection. They effectively weigh down the exposed cable if they are made of steel. Typically, the cable stiffeners are placed at the J- tube's exit point into the ocean. It is intended to safeguard the cable through ballast or scour protection, as well as through to any planned cable burial position.

Additionally, cables that are exposed in places where they cannot be buried, such as cables cross, or reefs present. At such points cables are protected by cable matting. Usually, mats are composed of polyurethane or concrete.

4.2.2 International experiences

From international case studies and practices so far following are the learnings that are most significant from Indian OSW market perspective.

- **Cable Failure**

Operators of offshore wind farms routinely report that subsea power cable breakdown is a serious problem. According to studies[36] such failures account for 75–80% of the total cost of offshore wind insurance claims; by contrast, cabling only makes up about 9% of an offshore wind farm's overall cost.

Subsea cable failure is a rather frequent event in the industry, so information exchange and sharing of lessons learned across the larger offshore wind community is highly essential.

It is recommended to create and maintain cable failure database for internal use that will collect data on Indian offshore wind projects and the lifecycle of their power lines from installation to operation.

The recommendations and layout on how to enhance knowledge-sharing in the offshore wind sector to lessen the effect of potential cable failures will be an important step for developers and insurance companies.

- **Subsea Cable Insurance**

The subsea cable insurance market is becoming more competitive, making it tougher to obtain the range of coverage that was once readily available. This is because claims occur frequently for offshore wind and most of the claims are related to faulty cable or installation error. As the business matures, errors in cable construction are diminishing. However, there is still opportunity for error due to complacency, and the talent/experience pool gets smaller as the global market expands. However, manufacturing and design flaws are now more common than mistakes in workmanship.

[36] https://ore.catapult.org.uk/analysisinsight/subsea-cable-trends/,

Expert Marine Warranty Surveyors (MWS) for cables are still in high demand. It is necessary to revise the MWS contracting guidelines and strengthen the insurance market's mandate. This requires a very high level of skill. If the insurance industry doesn't take a strong stance to favourably influence the standards for hiring MWS, there won't be as many MWS businesses or skilled workers soon. New insurance models suitable for Indian offshore wind market might be investigated.

- ### Best Practices on minimising cable failure

Following are best practices adopted in UK and EU to minimise the risk of cable failure.

A. Geophysical surveying for unexploded ordnance and other obstacles

The processes of planning and carrying out cable installation projects require knowledge of the dangers offered by impediments to cable installation. There are many different types of risks and obstructions that can present, including unexploded ordnance (UXO), boulders, in-service and out-of-service cables, pipelines, other seabed infrastructure, wrecks and debris, habitats and environmental constraints, sites of archaeological significance, as well as seabed and sub-seabed engineering considerations and geohazards. Obstructions include everything that could hinder the installation, upkeep, or decommissioning of the cable or the procedures and tools used to do so. Projects may have numerous phases, and at various stages of the project's lifecycle, risks may need to be quantified in various ways.

Shallow geophysical surveys can be done to properly map the seabed and sub-seabed structures and obstacles. Geophysical data can be utilised to assess the danger of installing underwater cables. Potentially impacted parties include those involved in installation, operations, maintenance, and decommissioning. Using geophysical data as part of its risk mitigation strategy considering its own risk appetite and any applicable laws are one of the best practices that can be adopted in case of Indian offshore wind projects.

Following are some of the international standards and guidelines that have been developed for offshore survey operations that are suited to the purposes of obstruction identification.

CIRIA 754, 2015 is considered the de facto standard for the management of UXO risk in marine environments.

There are also a number of useful guidelines that have been developed for offshore survey operations that are suited to the purposes of obstruction identification including:

- SUT OSIG: Guidance Notes for the Planning and Execution of Geophysical and Geotechnical Ground Investigations for Offshore Renewable Energy Developments;
- OGP: Guidelines for the conduct of offshore drilling hazard site surveys.
- DNVGL-RP-0360: Subsea Power Cables in Shallow Water.
- Offshore Wind Programme Board: Overview of geophysical and geotechnical marine surveys for offshore wind transmission cables in the UK;
- Carbon Trust - CTC835 - Cable Burial Risk Assessment Methodology.
- ISO19901-8: 2014 Marine Soil Investigations.
- ISO 19901-10 - International Organisation for Standardisation (ISO) guidelines for Marine Geophysical Investigations in the context of offshore structures for petroleum and natural gas Industries.

B. Cable Burial Risk Assessment (CBRA)

Cable burial risk assessment (CBRA) is another area of international best practices to look forward to.

The new CBRA method and guidelines have been developed by a repeatable approach that determines a target Depth of Lowering that is both practically and economically feasible while offering adequate protection is the main goal of the CBRA methodology[37][38].

Any stakeholder involved in a wind farm, from development through installation to operation to decommissioning, may use the CBRA technique.

The new method and guidelines have been developed by a consortium of UTEC Geomarine, Cathie Associates, and Xodus Ltd for the Carbon Trust for Offshore Wind Accelerator (OWA). The OWA is a collaborative industry project with nine developers, including DONG Energy, E. ON, Mainstream Renewable Power, RWE Innogy, Scottish Power Renewables, SSE Renewables, Statkraft, Equinor, and Vattenfall, who together account for almost three-quarters of the UK's licenced capacity. All the OWA partners agree that maximising the stipulated cable Depth of Lowering can result in significant cost savings.

The CBRA guidelines is meant to provide a standardised, reproducible, and qualitative procedure that all parties engaged in the creation of a wind farm can use.

[37] Cable Burial Risk Assessment (CBRA) guidance (pdf)

[38] Application Guide for the Specification of the Depth of Lowering (pdf)

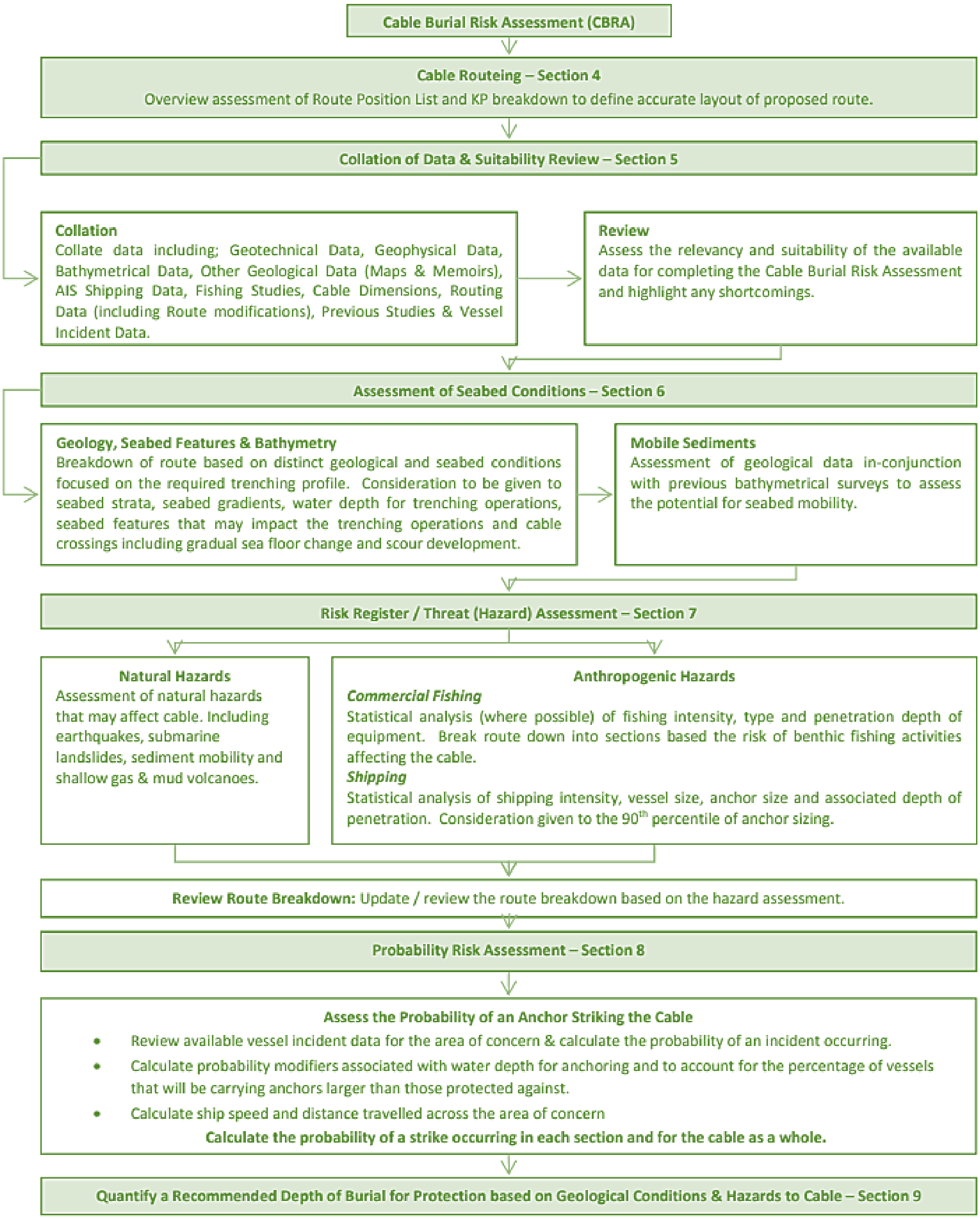


Figure 30: CBRA Flow Chart

4.2.3 Technology roadmap evolution and maturity

The array cable technology of 66 kV is the current standard in the offshore wind energy industry. Many of the leading cable suppliers in the market are supplying 66 kV inter-array cable for offshore wind farm[39].

- By the end of 2030, it is anticipated that more than 63,000 kilometres of offshore wind array cables would have been installed worldwide[40].
- New markets will open starting in 2025, and while the UK will continue to be the biggest European market. OSW initiatives are emerging in Asia, Australia, and USA[41] [42]

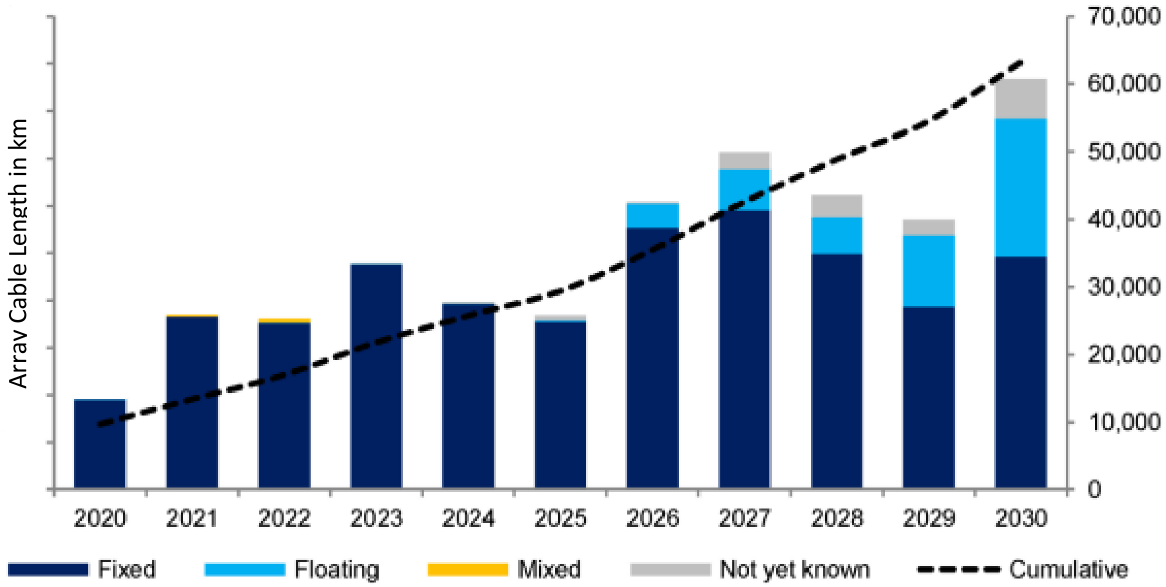


Figure 31: Global Forecast of Array Cable km. (Fixed & Floating) (Source: Renewable UK)

It is quite evident from the above forecast that the array cable market is going to be very demand driven and will open avenues for domestic manufacturing of array cables, accessories, cable protection components and the insurance sector.

- **Future Technologies**

The future operational array voltage level may be 132 kV. There would be a need for switching to 132kV to make future wind farm designs cost effective. 132 kV array cable will reduce the total array cable circuits by at least 40% in comparison to 66kV. This would also be better suited over the present 66 kV standard to support WTG with capacity greater than 14MW.

A thorough and in-depth engineering research together with life cycle cost-benefit analyses concluded that the 132 kV operating voltage is the most cost-effective voltage for a case study[43]. For instance, cost reductions of between £32M and £50M are anticipated for a 1200MW offshore wind farm using a single offshore substation as compared to the corresponding 66kV system.

[39] J. L. Rebecca Williams, Feng Zhao, "GLOBAL OFFSHORE WIND REPORT 2022," *Glob. Wind Energy Counc.*, 2022
[40] RenewableUK ruk_cables_2021.pdf (renewableuk.com)
[41] Cables for the world's first 66 kV offshore wind farm: Blyth
[42] 66kV Inter-array Cable Archives - Thorne & Derrick
[43] Unlocking the next generation of offshore wind: step change to 132kV array systems (windows.net)

The adoption of 132 kV array cables for wind farms depends on major proactive work being done right away by developers and the supply chain. To ensure the significant cost savings that 132 kV will bring are realised as quickly as possible, the industry may focus on 132 kV technology development.

The technology roadmap of 132 kV offshore wind array cables for both wet and dry cables are depicted in Figure 32 and 33. But offshore wind being a demand driven market, the 132kV technology would be adopted with large size wind turbines.

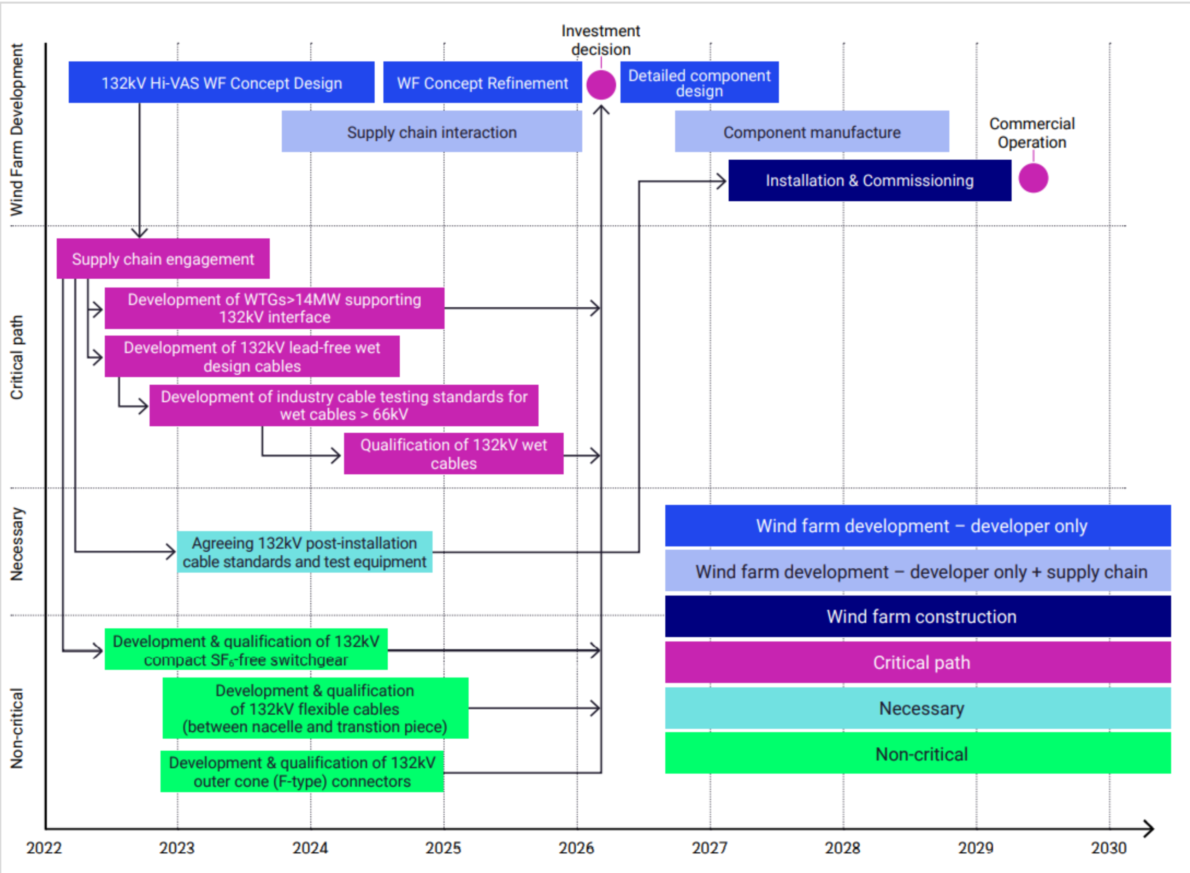


Figure 32: Proposed 132kV Array Technology Roadmap – Wet Cables.

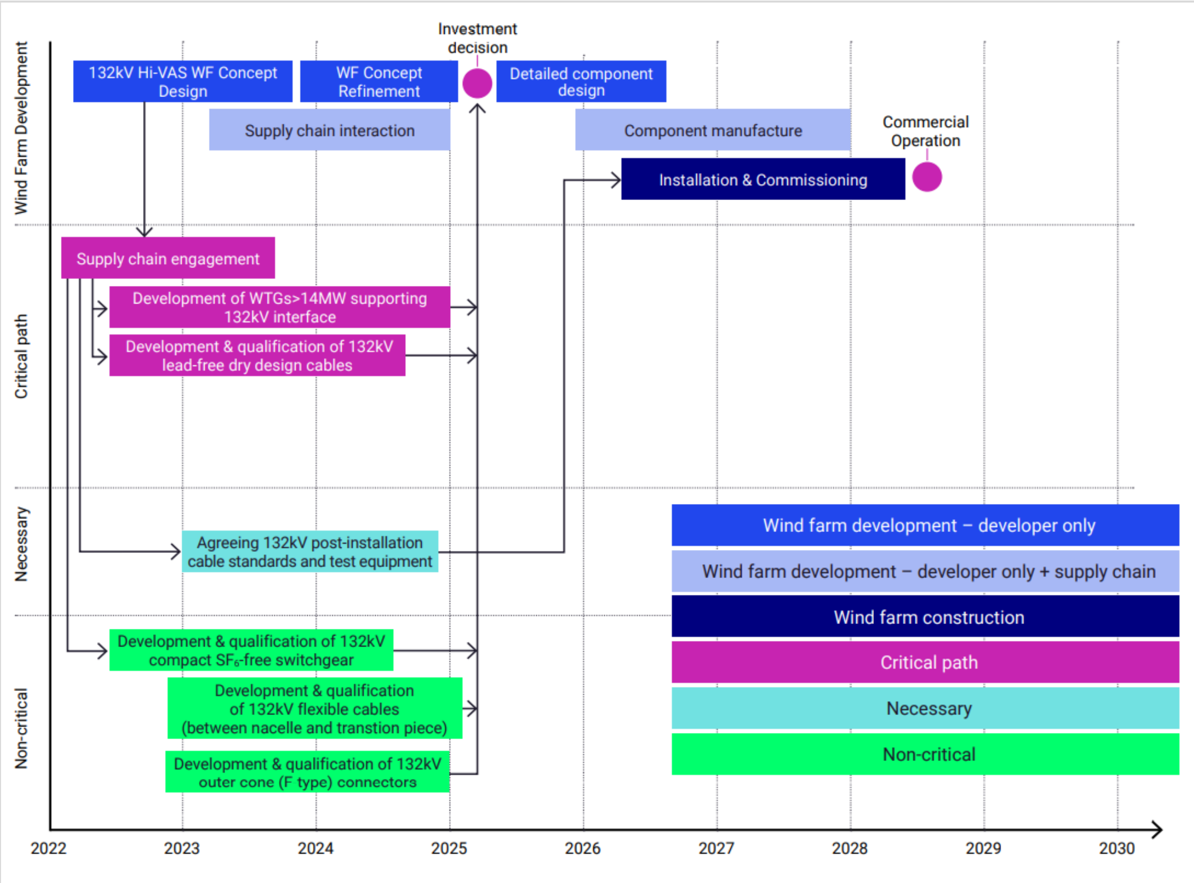


Figure 33: Proposed 132kV Array Technology Roadmap – Dry Cables

- **Key suppliers and technology providers – Global & India**

Following is the list of array cable manufactures, cable protection device providers and cable engineering and installation as well as cable operations and maintenance service providers. There are no Indian OSW array cable manufacturers at present. So, the most favourable solution is to tap into the UK and EU market.

Table 15: List of Array Cable and accessories manufacturers

Component	Supplier	Website/URL
Offshore Wind – Subsea array cable manufacturers		
OSW Array cable manufacturers	JDR Cable Systems, UK	https://www.jdrcables.com/
	Prysmian Group	https://www.prysmiangroup.com/en
	Hellenic Cables S.A. (Greece)	https://www.cablel.com/716/en/hellenic-cables-sa/
	NKT	https://www.nkt.com/
	TKF (Twentsche Kabelfabriek)	https://www.tkf.nl/en

Component	Supplier	Website/URL
	NSW	https://www.nsw.com/en/
	Aker Solutions (Norway)	https://www.akersolutions.com/
	Furukawa Electric Co. (Japan)	https://www.furukawa.co.jp/en/
	Zhongtian Technology Submarine Cable Co., Ltd [ZTT] (China)	https://www.zttcable.com/
	NEXANS	https://www.nexans.com/en/
Subsea cable protection device providers		
OSW Cable protection device manufacturers	Blue Ocean	https://www.blueoceanprojects.com/
	Seaproof	http://www.seaproof.com/
	Subsea Protection Systems	https://www.subseaprotectionsystems.co.uk/
	Tekmar	https://tekmar.co.uk/
	Terram	https://terram.com/
	Trelleborg	https://www.trelleborg.com/en
	Vos Prodect	https://www.vos-prodect.com/
	Synthetex	https://synthetex.com/
Cable engineering and installation as well as cable operations and maintenance		
cable engineering and installation as well as cable operations and maintenance service providers	BPP Cable Solutions	https://www.bpp-renewables.com/
	Acta Marine	https://www.actamarine.com/
	DEME	https://www.deme-group.com/
	4Subsea	https://www.4subsea.com/
	Technip Energy	https://www.technipenergies.com/en
	Wind and water work	https://www.windandwaterworks.nl/
	Fugro	https://www.fugro.com/

4.3 Offshore Substation Platform

Offshore substations (OSS) are an essential component of offshore wind farms that collect and export the power generated by turbines through specialized submarine cables to reduce electrical losses before export of power to shore. Primary objective of offshore substations is to reduce the energy losses before export of power to onshore pooling substation. This is done by increasing the voltage to a desired value for example either to 220 kV or 400kV, and in some cases converting from alternating current (AC) to direct current (DC) The substation also contains equipment to manage the reactive power consumption of the electrical system including the capacitive effects of the export cables.

The overall OSS not only comprised of the electrical substation itself but also all components for accessing and performing maintenance as well as temporary accommodation facilities. The components above the substructure of OSS is termed as 'topside' that covers an area of around 800 to 900 m^2 for HVAC, around 7000 m^2 for HVDC system which can reach several stories in size. The total weight of the OSS topside can vary between 1000 to 3000 tons in the case of HVAC while that of HVDC substation will vary between 12000 to 18000 tones. A typical substation platform is about 25m above the sea level and can support the input of about 500 MW to 600 MW. Thus a 1 GW wind farm would require two or three HVAC OSS. Whereas 1 GW wind farm can be evacuated with only one HVDC offshore substation, where the individual turbines are connected to the single HVDC substation by several transformers and that would convert the 66kV-output from the turbines to 132 kV or higher to feed the HVDC substation. With introduction of 66 kV subsea cables, isolated near shore wind farms up to 300 MW can be built without an OSS. The offshore substation can have interconnected each other and optimum export submarine cable can be used to interconnect the OSS and PS. By reducing the number of circuits, the number of switchgears in substation will also be reduced and fewer transformers. This will offer comparatively a smaller number of substation and reduced platform and foundation cost.

4.3.1 Configuration options and design considerations

OSS are often delivered as a single element of a contract to connect the wind farm generating assets to the onshore transmission grid. Though it is encompassed the following segments.

- Electrical Systems
- Facilities or Auxiliary Systems
- Substation Foundation or substructure

An offshore substation platform shall be designed to (1) ensure the safety of personnel required to operate and maintain the substation and (2) protect the assets and the overall integrity of the platform in the event of a catastrophic failure of plant or equipment.

- **Electrical Systems**

The electrical system integrates AC power generated by different wind turbines and transform voltage from, for example 66 kV to 220 kV (Gujarat) or 230 kV (Tamil Nadu) if the system is HVAC or to 400kV if the wind farm size is larger, else converts to DC for transmission in case of HVDC. Higher capital cost and concerns about the reliability of offshore HVDC convertor stations have led some developers to implement technology solutions to allow AC transmission to be used over longer distances. Some OSS have used additional equipment for the reactive power compensation, located on offshore platforms.

The key components of the electrical system include:

- HV switchgear sets to isolate and protect each array and export connection to the substation.

- Transformers (if HVAC) to transform to higher voltage for onward transmission. A typical offshore substation will have two or more transformers to improve availability. Transformers are oil cooled, requiring the use of fire and blast protection.
- Converters (if HVDC) to convert AC to DC for onward transmission.
- Passive and active reactive power compensation, typically large coils and power electronics, to improve stability of the local grid system.
- Earthing systems including lightning protection connecting electrical components and the substation structure
- Cable trays, tracks, clamps, and supports to protect electrical items.

OSS situated at a distance less than 80 km from the onshore pooling substation (PS) may use the HVAC topology while OSS located at a distance from 80 to 100 km from the pooling substation may follow the HVDC. Since the maximum distance for the proposed OSS in Gujarat is approximately 55 km (OSS of Zone B6 – Ubhrat PS) and that of Tamil Nadu is approximately 43 km (OSS of Zone B4 – Avaraikulam PS), the HVAC system may be used. However, the factors deciding the choice between HVAC and HVDC system are complex.

<u>HVAC Systems</u>

An HVAC OSS receives the electrical energy from the individual wind generator, at say 66 kV AC, thereafter, converts to 220 kV AC for Gujarat and 230 kV for Tamil Nadu or to 400kV and transmit to onshore PS through the export cables. The HVAC transmission systems which include OSS, PS and submarine export cable normally have lower lifetime cost (when also taking into account electrical losses) than the equivalent HVDC systems. HVAC electrical systems designed based on the standard technology and systems, which may be customised for use in a marine environment.

The number of OSS may vary depending upon the configurations used. In case of Gujarat, considering a capacity of 500 - 600 MW for a single OSS (in case of 220kV system and over 1GW in case of 400kV system), there will be 7 OSS which may relate to PS located at Mahuva and 2 or 3 OSS which may be connected to PS located at Ubhrat. For Tamil Nadu, the OSS may be interconnected each other and will be connected to PS. In case of Gujarat four different export cable will be used to interconnect OSS with two PS located at Mahuva and Ubhrat. For Tamil Nadu, it is planned by CEA to have 13 OSS which will be connected to PS located at Avaraikulam. Transformers in the onshore substation may increase the voltage further to 400kV for connection to the onshore transmission grid.

<u>HVDC Systems</u>

An HVDC system receives electrical energy generated from the wind turbine, at say 66 kV and convert the same to higher voltage for example 220 kV or higher by means of transformers. Further convert to DC using the AC-DC converters and transmits the electrical power to the onshore substation through the export cables at say 375 kV DC. The DC – AC converter in the onshore PS will converter the received DC electrical energy to AC at 400 kV or even above for connection to the onshore transmission grid. The HVDC transmission systems which includes OSS, onshore PS and submarine export cable normally have lower lifetime cost (when also taking into account electrical losses) than the equivalent HVAC systems for wind farms where the distance between the OSS and onshore PS is greater than about 80-100km. HVDC system is designed and customised usually for the transmission of high power, for more than 1 GW over long distance. Relatively HVDC is a new technology and systems which may not be viable for short distance power transmission. Also, HVDC systems currently only operate point-to-point and require the use of a matched pair of converters at each substation (one onshore and one offshore).

- ### Facilities or Auxiliary Systems.

Facilities and auxiliary systems are added to the OSS to support operation and maintenance of substation that enable the wider wind farm activities. The important components are explained below.

- Monitoring and controlling systems: Advanced monitoring and controlling systems are incorporated to ensure the fast detection of faults, security, and safety.
- Fire and blast protection systems: The transformers contain oil and coolants which is inflammable in nature. Thus fire and blast protection system is required to avoid the fire risk. In some of the transformer module of HVAC for example in Siemens Offshore Transformer Module, uses Esters as the transformer coolant which is non-combustible and biodegradable fluid that has reduced the need for active firefighting system.
- Standby generator (normally for HVDC substations): A secondary source of supply is required to power lighting and other emergency loads at the time of disconnection of supply from onshore PS for which a standby generator is used. This will also require to provide power to restart and establish reconnection with the onshore PS.
- Crane: An on-board crane will be available to lift the loads from the service vessels typically capacity of around three tonnes.
- Control room & refuge: A advanced control room with sufficient facility will be required to refuge for visiting crews. Also, clean and black water systems, fuel tanks, low-voltage power supplies, navigational aids, air conditioning equipment and safety system are required.

- ### Substation Foundation or substructure

The mechanical structure to the substation provides support and protection to the electrical and other systems. The substation is usually installed on Jacket foundations or on monopoles, though, the structure is complex, with many safety considerations. For small substations, the foundation may be constructed in the similar way to a turbine foundation, but with a different loading pattern. For a large substation, distributed piles or a jacket is preferable. Access through vessels is provided and helideck is also specified to enable helicopter landing. The use of helicopters for crew transfer is an integral part of maintenance and service operations for some but may only be used for emergency access or egress by others.

New concept developed to install the OSS on a floating platform where the sea depth is comparatively high. The concept of the floating platform is designed in such a way that it can be applied in water depths in excess of 150 metres and with minimal vertical motion in sea conditions. Some essential principles for the design of the floating transformer platform can be listed as follows

- the concept must conform to the set requirements for wind energy at sea
- it must not be too heavy in steel weight and must not be complex in terms of fabrication, safety, and reliability must also be guaranteed,
- it must be possible to guarantee a very high availability.
- the platform must have a lifespan of at least 30 years.
- In addition, the social costs of supplying sustainable electricity must remain affordable, and the solution itself should therefore not be too expensive in terms of costs

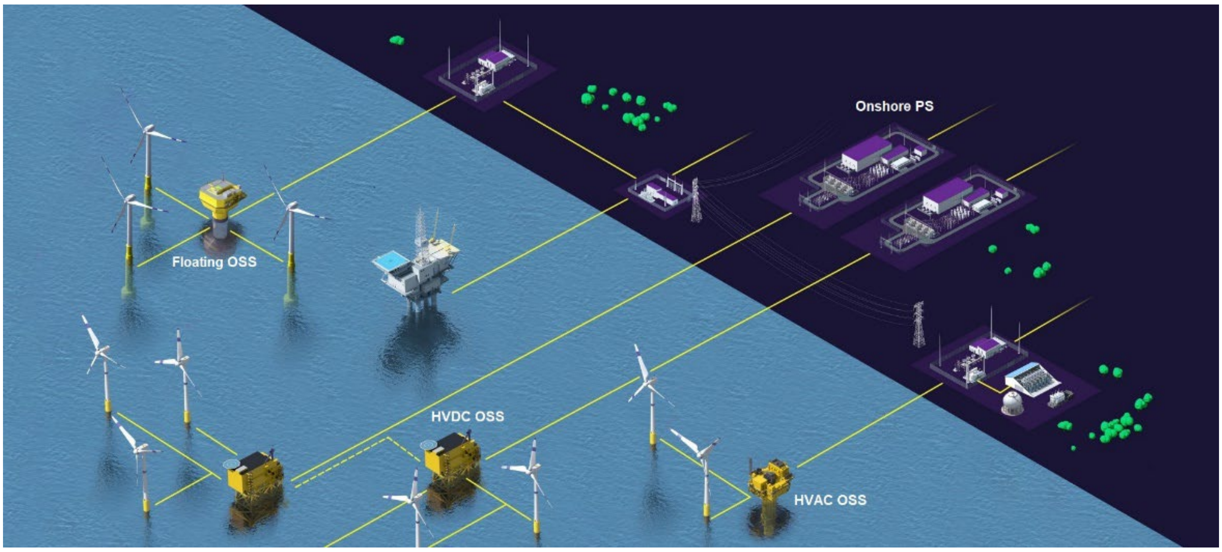


Figure 34: Interconnection of OSS with Onshore PS (Source: Siemens)

4.3.2 Technology roadmap evolution and maturity

The evolution and advancement of the offshore wind industry require the development of new technologies and contractual concepts suitable for the future wind farm. As discussed in the previous sections, the present substations are configured in either HVAC or HVDC depending upon the size of wind farms or/and distance from the shore that consist of a topside or a deck installed over a monopile or steel jacket structures.

Regarding the capacity of the substation, the project in Hornsea 2, English North Sea, UK, set a new record with a 1320 MW capacity and a weight of 8000 tonnes of topside installed on a jacket foundation[44] being operational from the month of August 2022. The substation is situated 89 km away from the shore where the water depth is 36 m.

Floating offshore substations

As the water depth increase, the fixed topside offshore substation may not be suitable, and the floating offshore substations can be used. Floating offshore substations offer the possibility to install wind farms in deeper offshore areas with high wind potential. In September 2022, Saipem and Siemens Energy have signed an MoU to develop a cutting-edge technology solution in the offshore wind energy sector by which they will jointly frame the concept design for a HVAC floating offshore substation with a capacity of 500 MW[45]. But, developing offshore floating wind for the energy transition have challenges related to the cost and technology.

Subsea substation

Significant improvements are observed when the substation is moved from its traditional placement – above the sea surface to the seabed which can be termed as a Subsea substation. This will be helpful in unlocking the potential of offshore floating wind. The advantage of Subsea substations are a) reduced cost of substation up to 30%, b) reduced the CO_2 emissions, c) improved energy efficiency, and d) increased personal safety as there are no manned operations. The subsea substation is the combination of standardised modules which will be added in parallel to achieve several gigawatts. The

[44] Hornsea 2 | ISC Consulting Engineers A/S
[45] Newsletter - Saipem and Siemens Energy sign a MoU to jointly develop a concept for floating electrical substation | Saipem

solid structure which is resilient in any weather conditions will enable use even 1500 m beneath the sea surface with a life span of 30 years without a need for maintenance. In November 2022, Aker Solutions in collaboration with ABB and Benestad developed a subsea substation as a part of the Ocean Grid program supported by the Norwegian Research Council and Innovation Norway. The subsea substation is expected to be available for the market in 2024[46].

4.3.3 International Learnings

Following are a few international learnings that can be useful for OSW development in India from power transmission perspective.

High Voltage Alternating Current (HVAC) and High Voltage Direct Current (HVDC) Transmission

The UK has implemented HVAC and HVDC technology to efficiently transmit power over short and long distances. This technology has been used to connect offshore wind farms to the national grid. Initiatives has been taken for reducing the cost and complexity of grid connections. Previously the emphasis has been on installing offshore wind and reducing costs – now there will be increased emphasis on increasing efficiency of multi-GW scale OSW, reducing numbers of offshore connections, and planning for 50GW rather than a few initial GW.

A cost benefit analysis of a more coordinated offshore network, compared to the current individual, radial approach was undertaken as part of the Offshore Coordination Review. Indicators assessed in the analysis can be broadly classified into three:

- Monetised elements - capital expenditure, operating expenditure, costs of different types of transmission assets
- Quantified elements - carbon intensity variation
- Qualified elements – considerations around impact on local communities from a social and environmental perspectives

The key learning here is to plan for multi GW scale from transmission planning perspective. i.e., 18 GW for Tamil Nadu and 12 GW for Gujarat. This approach may allow in reducing the offshore connections.

Following is a summary of the holistic network design in UK as given in Offshore Coordination phase I report[47].

[46] Newsletter - Subsea Substation – Unlocking the potential of floating offshore wind | Aker Solutions
[47] https://www.nationalgrideso.com/document/183031/download

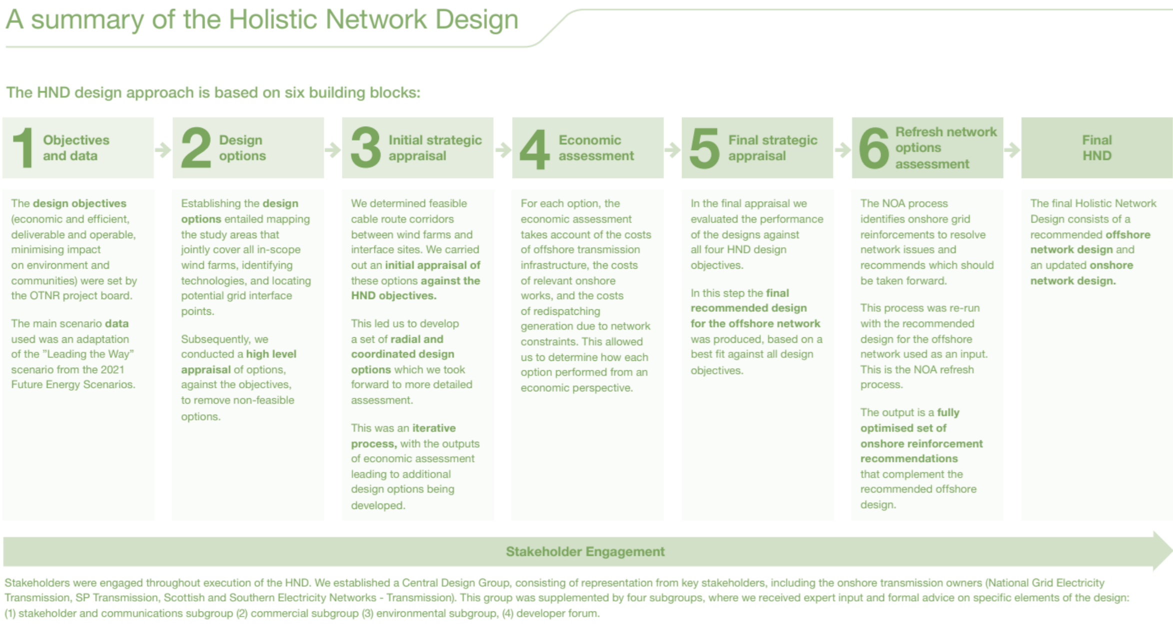


Figure 35: Summary of holistic network design

4.3.3 Key suppliers and technology providers – Global & India

The OSS is considered as a single unit that comprise vast amount of equipment and interfaces. The supply can be divided into the three categories as we discussed in the previous sections out of which the support structures, topside are the important elements. Support structures like jackets and monopoles are similar to the foundation of wind turbines and can be provided by the same companies who provides the foundation of wind turbines. Topsides are commonly produced by large yards like Bladt, Bilnger. Therefore, the construction of topsides will be a market opportunity for all major Indian companies which already involved in the oil and gas industry. Along with Jackets, the main players in the yards like Larsen & Toubro (L&T), Essar Projects or Dolphin Enterprises could enter and expand into this sector by implementing collaboration with international suppliers or manufactures with an early 0-5 GW phase. Still, only limited number of suppliers are available in the offshore wind sector. The key players with majority of share in the international markets are ABB, Siemens, Alstom, and CG Power. The detailed list of components and respective suppliers are listed below. The available Indian suppliers and international suppliers are tubulised separately.

Table 16: Indian and International Suppliers

Component	Supplier	Website/URL
Electrical Systems		
Electrical components	ABB	https://new.abb.com/windpower
	CG (Pauwels)	https://pauwels.com/systems-solutions/
	GE	https://www.ge.com/renewableenergy/wind-energy/offshore-wind
	Schneider Group	https://www.se.com/ww/en/work/solutions/for-business/electric-utilities/power-generation/wind-power.jsp
	Siemens Power Transmission and Distribution.	https://www.siemensgamesa.com/en-int/products-and-services/offshore

Component	Supplier	Website/URL
Systems integrators	Engie Fabricom	https://www.engie.com/en/flying-offshore-wind-sector
	Iberdrola	https://www.iberdrola.com/about-us/what-we-do/offshore-wind-energy
	Ørsted	https://orsted.com/en/our-business/offshore-wind
	Petrofac and Semco	https://www.petrofac.com/markets/new-energies/offshore-wind/
Structural designers	Arup	https://www.arup.com/markets/energy/offshore-wind
	Atkins	https://www.atkinsglobal.com/
	ISC and Ramboll	https://ramboll.com/services-and-sectors/energy/wind-energy/offshore-substations
Power Transforner	above plus Tironi	https://www.tironi.com/
Facilities or Auxiliary Systems		
Communications and networking	Atos	https://atos.net/en/solutions/critical-communications-systems-ccs/wind-farm
	Cisco	https://www.cisco.com/c/en/us/solutions/collateral/enterprise/design-zone-industry-solutions/digital-substation-automation-so.html
	Cobham Wireless	https://cobham-satcom.com/offshore
	Semco Maritime Motorola	https://www.semcomaritime.com/
Crane	Granada and Kenz Figee	https://kenzfigee.com/
	Caterpillar	https://www.cat.com/en_US/by-industry/marine/offshore.html
	Veco	https://www.veco.net/en/
	Midas and Mitsubishi	https://meppi.com/
Fire and blast protection	Mech-Tools (steel) and Solent Composite Systems (composites)	http://mechtools.co.in/
Heating, ventilation, and air conditioning	Heinen & Hopman	https://www.heinenhopman.com/
Facilities or Auxiliary Systems		
Structure	Bladt Industries	https://www.bladt.dk/
	Harland and Wolff	https://www.harland-wolff.com/
	Heerema.	https://www.heerema.com/offshore-wind/offshore-substation-installation

4.4 Submarine Export Cable

In an offshore wind farm, the export cable connects the offshore and onshore substations. These are the most critical component for power evacuation from the offshore wind farm to the onshore grid substation. They are used to transfer power from offshore wind farms to connect to an onshore grid network, typically via intermediate AC pooling substations or DC converters. The export cable market at present is well established in Europe with most of the manufacturing base and has seen significant growth in last 10 years. By the end of 2030, it is anticipated that about 40,000 km of export cables would have been installed worldwide, up from just over 7,500 km at the end of 2021[48].

Export cable can be HVAC or HVDC cables. A normal HVAC export cable has three cores. HVDC features two single-core cables having a bipolar design, but HVDC cables are lighter than AC cables for a given capacity, which has an impact on installation costs and simplicity of installation. For example, a pair of single cores 320 kV cables can transmit up to 1,200 MW per HVDC system, and over time, this maximum power will increase. Three-core copper AC export cable with a 220 kV rating can transmit up to 400 MW and weighs about 90 kg/m. A 320 kV single-core DC copper export cable weighs about 40 kg/m.

Also, longer distance HVAC cables experience significant losses because of reactive power flow. HVDC is employed for long distance transmission (because there is no reactive power flow). The savings from using HVDC cable are not realised until the cable path between the substations is more than 50 km, because HVDC converter stations are expensive. Project-specific factors can complicate final concept selection. The deployment of export cable in Europe is given in Figure 36.

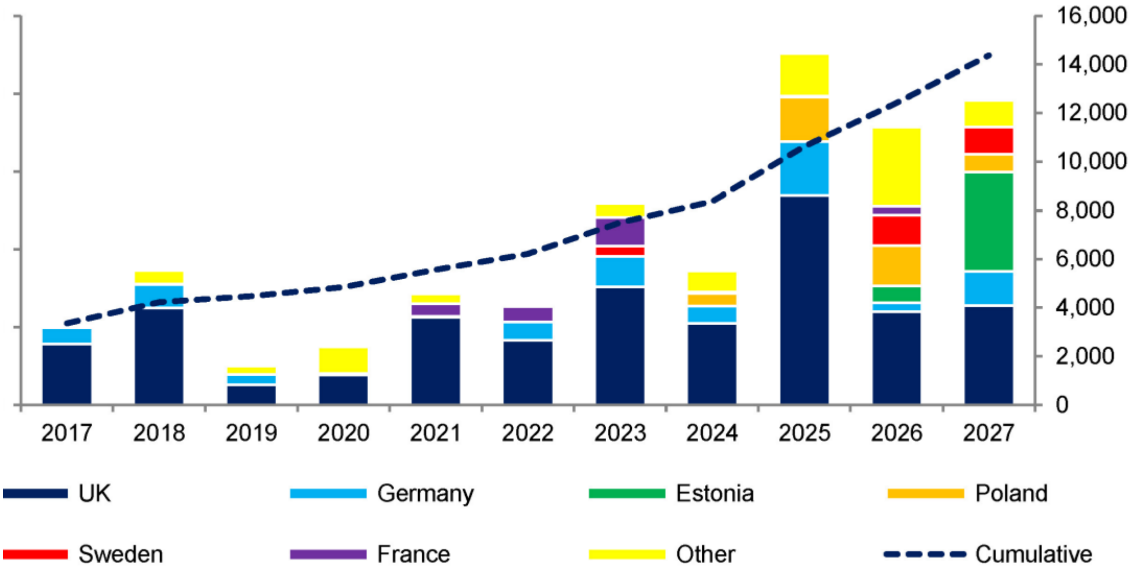


Figure 36: Export Cable Deployment and Forecast in km for Europe

[48] ruk_cables_2021.pdf (renewableuk.com)

The voltage level of export cable selected strikes a compromise between the price per km of cable, the number of circuits required for grid connection, and the required number of substations. An increase in export cable voltage has been linked to the tendency towards wind farms farther away from the coast, and 220 kV is becoming more and more the norm. Small wind farms near the shore may employ medium-voltage cables for export. For Indian context, this roadmap discussion will be useful to identify the best possible option for evacuation of more than 30 GW of OSW power from Tamil Nadu and Gujarat.

4.4.1 Configuration options and design considerations

The Export cable are made up of the following design elements.

1. Cable Core
2. Cable outer
3. Cable accessories
4. Cable joints

The elements of a 3 core export cable are illustrated as below.

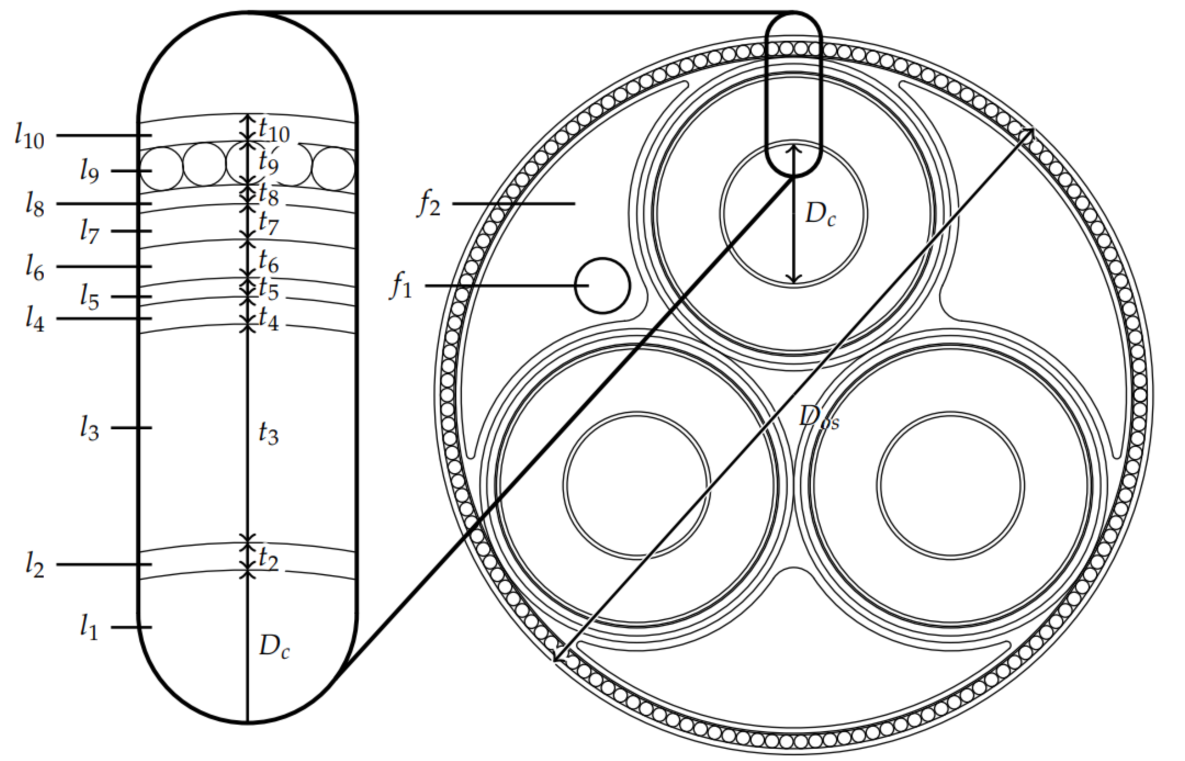


Figure 37: General structure of a three-core cross-linked polyethene (XLPE) separate lead (SL)-type submarine export cable

General structure of a three-core cross-linked polyethene (XLPE) separate lead (SL)-type submarine cable. diameters are D, and thickness is t. layers are l as labelled bellow[49].

[49] https://doi.org/10.3390/app9040800

l_1 = Conductor l_2 = Conductor screen l_3 = Insulation (XLPE) l_4 = Insulation screen l_5 = Swelling tape l_6 = Metallic sheath/screen l_7 = Anti-corrosion sheath and the common covering l_8 = Bedding l_9 =Armour
l_{10} = Outer serving f_1 = optical fibre f_2 = fillers
The elements of a single core export cable are illustrated as below.

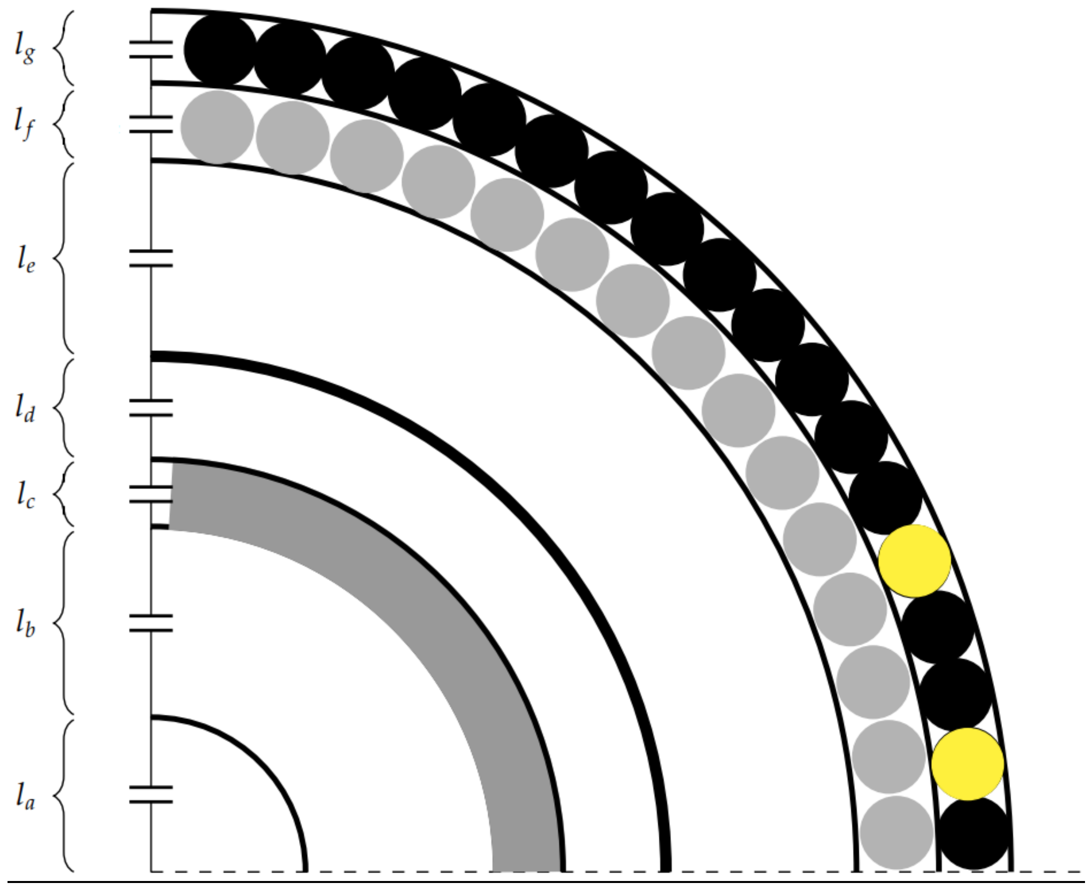


Figure 38: Quarter cross-sectional area of a single-core XLPE SL-type equivalent submarine export cable

Quarter cross-sectional area of a single-core XLPE SL-type equivalent submarine cable. layers are l as labelled bellow[50].

l_a = Conductor *and* Conductor screen l_b = Insulation (XLPE) and Insulation screen l_c = Swelling tape

l_d = Metallic sheath/screen l_e = Anti-corrosion sheath and Bedding l_f =Armour l_g = Outer serving

[50] https://doi.org/10.3390/app9040800

1. Cable Core:

Cable core constitutes the following elements in general. Typically, a conductor, screen, XLPE insulation, and protective sheath make up the core.

- Conductor (Al or Cu)
- Conductor Screen
- Insulation (XLPE)
- Insulation Screen
- Sheath

Conductor (Al or Cu) and Conductor Screen

The conductor could be made of aluminium or copper strands. Both have low resistance, superb conductivity, are ductile, and are comparatively corrosion resistant. Compared to aluminium, copper has a conductivity that is 60% higher, but it is also more expensive and subject to price fluctuations. On the other hand, aluminium is lightweight, handling requires less effort. The cable's conductor cross section needs to be sufficient to meet the system requirements for power transmission capacity. Using conductors of larger diameter can reduce energy losses, but the capital cost will be higher.

The cross-sectional area of a 66 kV subsea cable core ranges from 150 mm2 (14 mm diameter) to 800 mm2 (13 mm of insulation). The cross-sectional area of a 220 kV subsea cable core ranges from 800 mm2 (32 mm diameter) to 1600 mm2 (23 mm of insulation). The cross-sectional area of a 320 kV DC cable core ranges from 1,000 mm2 (40 mm diameter) to 2500 mm2 (25 mm of insulation).

A semiconducting film is used as a conductor screen, which surrounds the conductor to maintain a consistent electric field and reduce electrostatic stress on the cables.

Insulation (XLPE) and Insulation Screen

The insulation material used for offshore export cable is XLPE, or cross-linked polyethylene. XLPE cables are often chosen over paper-insulated cables for offshore wind. XLPE cables are less expensive and lighter.
Another screen that is like the conductor screen is placed around the insulation.

Sheath:

Lead has traditionally been the sheath material, but now a days alternatives are also available which are more sustainable.

2. Cable Outer

Cable outer is typically the outer covering that surrounds the core and are materials that protect the cable and houses the fibreoptic cable. Cable outer has the following components.

- Polypropylene filling
- Armour
- Fibreoptic Cable

Polypropylene filling

A three-core cable is filled with polypropylene based non-conductive filler material. Its goal is to keep the cable's form and surrounding tape secure.

Armour

The armouring consists of the armour, and the bedding and serving layer. The cable is covered with a layer of polypropylene string to act as a bed for the armour wires. The armouring typically encloses the cable in helical metal wires, frequently steel. To further increase adhesion and prevent corrosion, bitumen may be applied over the armouring. Above the armoured cable, a layer of polypropylene string is put to protect it from abrasion and to lessen cable friction while it is being laid. The cable is marked with a black and yellow pattern on a polypropylene serving to make it more noticeable during laying. Typically, steel wire armour is used on three-core subsea cables. Cables with a single core have nonmagnetic armour. Single-core cables can be laid apart or together next to one another. Less armour loss occurs when laying close but there is a risk of mutual heating. Separation stops mutual heating but results in greater armour loss. The induced current in the armour can be as high as in the conductor.

Fibreoptic Cable

The cable includes a fibre optic wire which is used for communications and distributed temperature sensing. The fibreoptic cable is multimodal, which means that it can transmit a variety of types of data at various frequencies including cable temperature, voice, turbine, switchgear, and security data. Normally it contains 48 strands.

3. Cable Accessories

Both during and after installation, cable accessories are used to provide mechanical support and electrical termination for cables. Cable accessories includes Pulling heads, Kellums Grips, termination hang offs, Interface plug, Hang-off clamp, Offshore junction cabinets, Coupling connectors, Cable connector, T-connector, Cable cleats, Cable trays and Cable Protection System (CPS). A list of manufacturers for cable accessories is provided in section 4.4.4

4. Cable Joints

There are two different kinds of joints: The factory flexible joints and Field rigid joints.

The factory flexible joints join various cable core segments together to form a single continuous length during the lay-up process. It is to ensure that the joint must have the same electrical, thermal and mechanical properties as the rest of the cable in order to provide a connection that does not impede installation or raise the possibility of cable failure.

The field rigid junction is a manufactured product supplied by the cable manufacturer and it is provided with the cable in the event of a failure during operation or provided as a planned joint to connect parts of the export cable. Due to the significant differences in cable design between wind farms, field rigid joints have often been bespoke solutions. There is a growing demand from offshore transmission owners and developers to create joints that work with a variety of designs.

Depending on the cable type and voltage class, cables go through a number of tests before being dispatched. These are:

- Cable (and accessories) pre-qualification tests
- Cable (and accessories) type tests
- Cable routine electrical tests on each manufacturing length before jointing and armouring.
- Sample tests
- Routine factory splice tests, and
- Tests on complete cable lengths including factory installed joints (if any).

4.4.2 International experiences

Subsea cable installation is a long undertaking that can take up to 7 years in total. Proper planning is needed to ensure the project succeeds. Following are key learnings from the projects in UK and Europe.

- **Consents and planning**

A developer needs to consider all planning and consenting requirements as a whole; it is not possible to treat consenting and planning of subsea cables as an isolated element. A range of organisations, including local planning organisations, environmental agencies, water authorities, etc, will be involved in the consenting phase.

The following table provides a breakdown of a cable installation timeline, together with the lead stakeholders involved in each stage for OSW projects in UK.

Timeline	Stage of the project	Description	Lead stakeholders		
	Secure the site	Obtain development rights	Crown Estate	Developer	
-48 months	Initial feasibility	Initial engineering/pre-FEED	Developer		
-36 months	Consenting	Start consent process	Planning Inspectorate	Developer	
-36 months		Initial surveys	Survey contractor		
-12 months		Obtain planning consent	Planning Inspectorate	Developer	
-9 months	Tendering	Writing of specification	Developer		
-6 months		Cable installation tendering period	Developer	Contractors	
-3 months		Installation tender evaluation	Developer		
-1 months		Preferred bidder selected	Developer		
0	Securing investment	Financial Investment Decision	Developer	Investors	
+1month	Tendering	Contracts awarded	Developer		
+2 months	Route survey	In depth route engineering/detailed FEED	Developer	Contractors	
+2 months		Further seabed surveys (if required)	Developer	Contractors	
+18 months	Installation and commissioning	Cable installation, burial and jointing	Contractor		
+18 months		Post-installation survey	Contractor		
+20 months		Cable termination	Contractor		
+21 months		Cable testing and energisation	Developer	Contractor	
+36 months	Fully operational	Handover from Developer to OFTO	Ofgem[4]	Developer	OFTO

Figure 39: Overview of the offshore transmission cable installation process in the UK[51]

[51]https://ore.catapult.org.uk/app/uploads/2018/02/Overview-of-the-offshore-transmission-cable-installation-process-in-the-UK.pdf

- ### Surveys for route planning and cable protection

Surveys are crucial to early planning decisions, especially regarding cable routing, installation methodology and tools, capabilities of the installation vessel and the time required for operations. Information obtained from survey outputs help to reduce uncertainty and risks.

Due to the risk of a project not proceeding beyond the FID-stage, developers often seek to manage risk by minimising investment in the early project development phase. This limited funding affects investment in the initial surveys. However, inadequate surveys can lead to the wrong tool being deployed, or failure to bury at the target depth.

<u>Outline of marine surveys undertaken for export cable installation</u>

Surveys provide detailed analysis of seabed conditions and help with finding foreign objects on the seabed and the potential risks such as unexploded ordinance. Additionally, they must also inform the environmental impact assessment. There are normally three steps to a site investigation. These steps are depicted in the flowchart below.

Desktop Study

- To identify areas of interest and what is required for detailed investigation

Geophysical Survey

- To obtain data about the surface of the seabed
- Non-intrusive and consists mostly of bathymetric surveys, side-scan sonar and the use of a sub-bottom profiler to characterise the seabed, the mobility, and the shallow geology
- Enables the provision of information along the entire cable route

Geotechnical Survey

- Consists of discrete seabed tests undertaken at intervals along the route to validate the geophysical data
- Helps to identify seabed type, seabed strength and layer thickness

Figure 40: Steps to a site investigation for OSW projects

Key message:

Involve all stakeholders as early as possible in planning the marine surveys, as the results can impact upon consenting, environmental monitoring, and engineering design. It would be useful, if possible, to involve relevant stakeholders, such as cable installation contractors, when planning the marine surveys, to ensure that the information produced is suitable for planning and costing the installation works.

• Installation methods and execution

Cable installation activities commence with a pre-lay grapnel run to clear debris from the cable route or an alternative route to check for debris. The export cable will be collected from the load-out port or the cable manufacturer. Following transit to the work site, a 'shore pull' will take the cable to the onshore transition joint pit, where it will eventually be jointed to the onshore cable. Typically, this stage involves floating the cable to the shore, using flotation devices and/or rollers at intervals along the cable length.

Following the shore pull the cable will be laid along the predetermined route, which may include pipeline and cable crossings. Typically, water depth will increase along the route and whilst the cable catenary becomes easier to manage, tension in the cable becomes more important. Weather conditions in deeper water, further offshore, are often significantly less favourable than those found near shore and may require a vessel with a keel.

Upon approaching the substation location, the cable will be either temporarily set down and wet-stored, in anticipation of substation installation, or directly installed into the substation by the cable lay vessel. Prior to the start of the pull-in operation, the cable needs to be cut to the right length on board the installation vessel.

• Post installation

It is important that developers ensure that contractors have installed cable systems appropriately per the project specification. Post-installation tests that are recommended include electrical testing, depth of burial assessment, post-burial risk assessment, including any remedial works that may be required. These tests are necessary to evidence that the developer's obligations have been met and risks associated with the fulfilment of the offshore transmission operator licence can be mitigated[52].

• International projects and technology provider

ABB (Sweden)[53], Prysmian Power Link (Italy)[54], Nexans (Norway)[55] and NKT (Denmark)[56] are the prominent HVAC and HVDC export cable manufacturers. Also, the recent innovations in high voltage submarine export cable technology are driven by demand from UK and European offshore wind market. the Following export cable technologies are currently offered and are being used for offshore wind power evacuation.

- 320 kV HVDC submarine export cable (MI & XLPE)
- 400 kV HVDC submarine export cable (MI & XLPE)
- 500 kV HVDC submarine export cable (MI & XLPE)
- 625 kV HVDC submarine export cable (MI & XLPE)
- 220 kV HVAC submarine export cable (XLPE)
- 420 kV HVAC submarine export cable (XLPE)
- A detailed list of projects with subsea export cable (HVAC) is as presented below.

Table 17: A detailed list of projects with subsea export cable (HVAC) is as presented below

Name	Elements Type	Technology Type	Voltage Level (kV)	Expected / Commissioning Year	Country
Kriegers Flak CGS, TYNDP ID: 36.141	Subsea Cable	HVAC	150	31/12/2018	Denmark

[52] Overview of the offshore transmission cable installation process in the UK
[53] wind_submarine-power-cables--cables-for-offshore-wind-farms_2gm5010-gb.pdf (abb.com)
[54] High Voltage Grid Access | Prysmian Group
[55] Nexans - The King of long distance
[56] High Voltage Cable Solutions | NKT

Name	Elements Type	Technology Type	Voltage Level (kV)	Expected / Commissioning Year	Country
Modular Offshore Grid	Subsea Cable	HVAC	220	2020	Belgium
MOG II: connection of up to 2 GW additional offshore wind Belgium	Subsea Cable	HVAC	220	2030	Belgium
Offshore Connection Cluster 1	Subsea Cable	HVAC	220	2019	Germany
AC Offshore Connection Cluster 1, 2,4	Subsea Cable	HVAC	220	2022	Germany
Offshore Connection Cluster 6	Subsea Cable	HVAC	220	2029	Germany
Southern Aegean Interconnector (Levitha – Syrna)	Subsea Cable	HVAC	220	2025	Greece
Southern Aegean Interconnector (KINAROS – LEVITHA)	Subsea Cable	HVAC	220	2024	Greece
Southern Aegean Interconnector (Kandeliousa – Syrna)	Subsea Cable	HVAC	220	2025	Greece
Southern Aegean Interconnector (Kandeliousa – Pergousa)	Subsea Cable	HVAC	220	2025	Greece

Table 18: A detailed list of projects with subsea export cable (HVDC) is as presented below

Name	Elements Type	Technology Type	Voltage Level	Expected Commissioning Year	Country
HVDC Gatica-Cubnezais	Subsea Cable	HVDC	320	01/ 01/ 2025	Spain
IFA2	Subsea Cable	HVDC	320	1/ 1/ 2020	France

Name	Elements Type	Technology Type	Voltage Level	Expected Commissioning Year	Country
First HVDC Module IT-ME	Subsea Cable	HVDC	500	2019	Italy
Second HVDC Module IT-ME	Subsea Cable	HVDC	500	2026	Italy
Elmed Project	Subsea Cable	HVDC	400	2025	Italy
Norway - Germany HVDC	Subsea Cable	HVDC	500	01/ 01/ 2020	Norway
COBRA Cable	Subsea Cable	HVDC	400	2019	Denmark
NEMO	Subsea Cable	HVDC	400	1/ 1/ 2019	Belgium
Western HVDC Link	Subsea Cable	HVDC	500	2017	United Kingdom
France Ireland Interconnector	Subsea Cable	HVDC	320	2026	France
Norway - Great Britain	Subsea Cable	HVDC	500	2021	United Kingdom
Nautilus: 2nd interco UK - BE	Subsea Cable	HVDC	400	2028	Belgium
France-Alderney-Britain	Subsea Cable	HVDC	320	1/ 1/ 2022	France
Great Belt II	Subsea Cable	HVDC	400	2030	Denmark
Hansa PowerBridge I	Subsea Cable	HVDC	300	2026	Germany
DKE-DE (Kontek 2)	Subsea Cable	HVDC	400	> 2030	Denmark
NorthConnect	Subsea Cable	HVDC	500	2022	Great Britain
BorWin3	Subsea Cable	HVDC	320	2019	Germany
Cluster DolWin 5 (NOR 1-1)	Subsea Cable	HVDC	320	2024	Germany
Cluster DolWin6	Subsea Cable	HVDC	320	2023	Germany
DolWin3	Subsea Cable	HVDC	320	2018	Germany
SylWin2	Subsea Cable	HVDC	320	2025	Germany

Name	Elements Type	Technology Type	Voltage Level	Expected Commissioning Year	Country
Cluster BorWin 5 (NOR-7-1)	Subsea Cable	HVDC	320	2025	Germany
DolWin 4 (NOR-3-2)	Subsea Cable	HVDC	320	2028	Germany
BorWin 6 (NOR-7-2)	Subsea Cable	HVDC	320	2030	Germany
Interco Iceland-UK	Subsea Cable	HVDC	500	2030	Iceland
EuroAsia Interconnector	Subsea Cable	HVDC	500	2020	Cyprus
EuroAsia Interconnector	Subsea Cable	HVDC	500	2021	Cyprus
EuroAsia Interconnector	Subsea Cable	HVDC	500	2020	Cyprus
DKE-PL-1	Subsea Cable	HVDC	400	>2030	Denmark
Fenno-Skan 1 renewal	Subsea Cable	HVDC	300	2029	Finland
AQUIND Interconnector	Subsea Cable	HVDC	320	2022	France
DC Offshore Connection Cluster 1, 2, 4	Subsea Cable	HVDC	320	2027	Germany
Hansa PowerBridge II	Subsea Cable	HVDC	300	2030	Sweden
TuNur DC	Subsea Cable	HVDC	500	2025	Tunisia
LEG1	Subsea Cable	HVDC	400	2021	Libya
Greenlink	Subsea Cable	HVDC	320	2023	Ireland
Southern Aegean Interconnector	Subsea Cable	HVDC	320	2024	Greece
Southern Aegean Interconnector	Subsea Cable	HVDC	320	2026	Greece
Maali	Subsea Cable	HVDC	320	2025	United Kingdom
SACOI3	Subsea Cable	HVDC	200	2023	Italy
NeuConnect Interconnector	Subsea Cable	HVDC	500	2022	United Kingdom
New HVDC line between Villanova and	Subsea Cable	HVDC	500	2027	Italy

Name	Elements Type	Technology Type	Voltage Level	Expected Commissioning Year	Country
Fano existing 400 kV substations					
Eastern HVDC Link	Subsea Cable	HVDC	500	2024	United Kingdom

4.5.3 Technology roadmap evolution and maturity

HVAC and HVDC submarine export cables are used for evacuation of power from OSW projects. The losses in HVAC export cable and also reactive power compensation are a drawback, but the technology for operation and maintenance is mature and support low construction costs. On the other hand, in case of HVDC long-distance & bulk power transmission is easy with minimal losses.

- **HVAC XLPE (Cross-linked Polyethylene) Submarine Cables**

HVAC cable can be categorized into 2 types based on the number of conductors (cores) present together to form the cable.

1. Three Core HVAC cable and
2. Single Core HVAC cable.

The extruded XLPE insulated offshore export cables have been used 132 kV to275 kV, and with recent advancements upto 400 kV and more. Submarine cables with three cores typically include steel wire armour. Single-core export cables contain non-magnetic armour. Single-core cables can be installed either apart or together. Lower losses result from close laying. Separation eliminates mutual heating but means higher losses in the armour. The induced current in the armour can be high, up to the same value as in the conductor.

At least 40 years are the expected lifespan of XLPE wires. HVAC XLPE export cables can withstand temperatures as high as 90 °C and a max of 250 °C for short circuits. Long outages following damage or failure, transient behaviour, and the reactive power generated by cables are some of the difficulties that must be overcome while installing HVAC XLPE cables. Each individual risk to network operation must be thoroughly examined.

<u>Three Core HVAC Export cable - 220 kV</u>

220 kV HVAC submarine export cables are a norm today for evacuation of power from offshore wind farms. A 220 kV HVAC export cable can evacuate maximum power of 440 MVA and can be configured for voltage level of 275 kV depending on the current carrying capacity of the conductor, the insulation technology, and its dielectric properties.

Following are the typical parameters of a 3 core HVAC XLPE Export cable with lead sheath with nominal voltage of 220 kV (Um = 245 kV)[57]

[57] xlpe-submarine-cable-systems-2gm5007.pdf (abb.com)

Table 19: Parameters of 3 core 220 kV HVAC XLPE export cable

Cross section of conductor	Dia of Conductor	Insulation thickness	Lead sheath thickness	Outer diameter of cable	Cable weight (Aluminium)	Cable weight (Copper)	Capa-citance	Charging current per phase at 50 Hz	Induc tance
mm2	mm	mm	mm	mm	kg/m	kg/m	µF/km	A/km	mH/km
500	26.2	24	2.9	219	71.8	81.3	0.14	5.7	0.43
630	29.8	24	3.0	224	74.9	86.7	0.16	6.4	0.41
800	33.7	24	3.1	234	80.2	95.3	0.17	6.9	0.40
1000	37.9	24	3.1	241	85.1	104	0.19	7.4	0.38

<u>Single Core HVAC Export cable - 220 kV</u>

Three independent single-core underwater cables, each carrying just one insulated conductor and one phase of the three-phase electric current, are used in AC systems to evacuate larger amounts of power. As a backup in case one of the three main cables needs to be repaired or replaced, a fourth identical wire is frequently inserted in parallel with the other three.

The decision to use single core 220 kV export cable is often taken on the basis of reliability of system and cost benefit calculation based on the number of cable runs required per circuit. Single core 220 kV export cable are easier to install and handle. Single core cables are preferred considering reliability as any failure of one cable will not result in entire circuit would be outaged rather with provision of additional run for every double circuit can ensure low interruption time.

Following are the typical parameters of a single core HVAC XLPE Export cable with lead sheath with nominal voltage of 220 kV (Um = 245 kV) [58]

Table 20: Parameters of single core 220 kV HVAC XLPE export cable

Cross section of conductor	Dia of Conductor	Insulation thickness	Lead sheath thickness	Outer diameter of cable	Cable weight (Aluminium)	Cable weight (Copper)	Capa-citance	Charging current per phase at 50 Hz	Inducta nce
mm2	mm	mm	mm	mm	kg/m	kg/m	µF/km	A/km	mH/km
500	26.2	24	2.9	111.0	19.1	29.3	0.14	5.8	1.42
630	29.8	23	3.0	112.8	20.0	31.2	0.16	6.4	1.40
800	33.7	23	3.1	117.5	21.9	34.5	0.17	6.9	1.37
1000	37.9	23	3.1	121.9	23.5	37.7	0.19	7.4	1.35
1200	41.2	23	3.1	125.2	24.8	40.4	0.20	7.8	1.33
1400	44.4	23	3.1	128.6	26.1	43.2	0.21	8.2	1.32
1600	47.4	23	3.1	131.8	27.5	46.0	0.22	8.6	1.31

<u>3 core and Single Core HVAC Export cable - 400 kV</u>

Single core export cables of rating 400 kV and higher are recent advancements in submarine export cable technology with XLPE insulation. 420 kV XLPE AC cable can evacuate up to typically 1 GW for a single core link and typically 700MW for a three-core link. Following is an example of three-core submarine cable with lead sheath from the manufacturer NKT[59].

Following are the typical parameters of a single core HVAC XLPE Export cable with lead sheath with nominal voltage of 400 kV (Um = 420 kV) [60]

[58] xlpe-submarine-cable-systems-2gm5007.pdf (abb.com)
[59] A_2X_F_K2YRAA_3_up_to_420_kV_V2.indd (widen.net)
[60] xlpe-submarine-cable-systems-2gm5007.pdf (abb.com)

Table 21: parameters of a single core 400 kV HVAC XLPE Export cable with lead sheath

Cross section of conductor	Dia of Conductor	Insulation thickness	Lead sheath thickness	Outer diameter of cable	Cable weight (Aluminium)	Cable weight (Copper)	Capa-citance	Charging current per phase at 50 Hz	Inductance
mm2	mm	mm	mm	mm	kg/m	kg/m	µF/km	A/km	mH/km
630	29.8	32.0	3.1	132.8	26.1	38.8	0.13	9.6	1.40
800	33.7	30.0	3.1	133.1	26.5	40.2	0.15	10.7	1.37
1000	37.9	29	3.1	135.3	27.5	42.6	0.16	11.7	1.35
1200	41.2	27	3.1	134.6	27.7	44.0	0.18	12.9	1.33
1400	44.4	27	3.1	138.0	29.0	46.9	0.19	13.5	1.32
1600	47.4	27	3.1	141.0	30.4	49.7	0.19	14.1	1.31

(A)2X(F)K2YRAA up to 420 kV

Three-core submarine cable with lead sheath

Dreileiterseekabel mit Bleimantel

NKT

Standard: IEC 60840 & 62067

Design:
Aufbau:

1 Conductor (Al or Cu)
Leiter (Al oder Cu)

2 Inner semi-conducting layer
Innere Leitschicht

3 XLPE insulation
VPE-Isolierung

4 Outer semi-conducting layer
Äußere Leitschicht

5 Swellable tape
Quellvlies

6 Lead sheath
Bleimantel

7 PE oversheath
PE-Außenmantel

8 Fibre optic cable
Lichtwellenleiterkabel

9 Filler profiles
Profiltrensen

10 Bedding (PP)
Polsterlage (PP)

11 Armouring
Armierung

12 Outer serving (PP)
Außenschutz (PP)

Application:
Anwendung:

The cables are suitable for installation in the ground and in water.
They may be laid directly in the ground, in ducts or in cable troughs.

Die Kabel sind geeignet für die feste Verlegung in Erde und in Wasser.
Sie können direkt in den Boden, in Schutzrohre oder in Kabelkanäle gelegt werden.

Properties:
Eigenschaften:

Conductor Leiter	Circular, solid or stranded (Al or Cu) Rund, eindrähtig oder mehrdrähtig (Al oder Cu)
Lead Sheath Bleimantel	Radial water barrier Radiale Wassersperre
FO cable LWL-Kabel	Integrated fibre optic cable for communication and temperature monitoring Integriertes Lichtwellenleiterkabel für Kommunikation und Temperaturüberwachung
Armouring Armierung	Capable of high tensile forces, adjusted to project specific requirements, available in aluminium, steel or mixed with plastic wires Aufnahme hoher Zugkräfte, angepasst an projektspezifische Anforderungen, möglich in Aluminium, Stahl oder gemischt mit Kunststoffdrähten

Figure 41: 420 kV HVAC three-core submarine cable with lead sheath from the manufacturer NKT

Current ratings for single core submarine export cables with rated voltage of 100 kV to 420 kV is provided in Annexure-IV. and current rating for 3 core submarine export cable with steel wire armour for rated voltage of 100 kV to 300 kV is provided in Annexure-V.

- ## HVDC submarine export cable

The type of cable for offshore wind farm will mostly depend on how far away from the shore it is. While the larger wind farms farther offshore prefer using HVDC cables, many of the near shore wind farms prefer AC export lines. HVDC is economically favourable since line losses from capacitance are substantially higher for underwater transmission lines.

XLPE and MI At present there are two HVDC insulation technology available commercially. Over the traditional Mass Impregnated cable technology, XLPE-insulated cables provide several advantages. They can operate at a higher working temperature and are typically mechanically more robust than MI. This enables them to transfer more power while carrying more current for a given conductor cross-section. On the other hand, compared to XLPE, MI cable is a more mature technology for HVDC export cables.

The use of extruded insulation submarine cables for HVDC applications have been in demand in offshore wind power evacuation due to favourable installation, operating, and testing criteria. XLPE is the new material advancement and is being used to insulate extruded cables instead of oil or MI. In comparison to other technologies, the thermal qualities of XLPE enable a continuous maximum conductor temperature of 90 °C and a maximum short circuit temperature of 250 °C.

The highest verified voltage rating is currently provided by MI, although XLPE cable, a developing technology, offers generally less expensive production, jointing, and installation expenses.

The capability of XLPE products up to roughly 500kV is now being extended by several manufacturers to compete with MI. Both copper and aluminium conductors can be used to create both types of cable.

Evolution of HVDC XLPE export cable

Along with converter technology, XLPE DC cable systems have offered a significant platform for high voltage direct current (HVDC) power transmission since its inception in 1998. The creation and commercialization of XLPE HVDC cable systems began at an 80 kV level and quickly increased to 150 kV, 200 kV, and 320 kV. These systems share a common technological foundation. According to feasibility studies, an improvement of the XLPE insulation material was necessary to achieve greater voltages. A complete HVDC cable system with a 525 kV voltage was launched in 2014 to provide this new technology to the market. The 640 kV extruded DC cable system from NKT is the most recent addition to this product line, and it uses the same materials and accessory options as the 525 kV system. The HVDC transmission technology field gains a new high with the introduction of this new cable system. The illustration below shows that extruded cable technology has developed rapidly and become an attractive solution for the OSW developers.

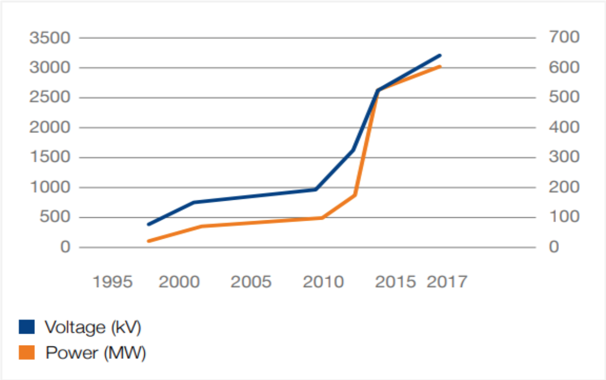


Figure 42: Evolution of Extruded HVDC cable voltage and power transmission capacity

<u>Extruded HVDC Export cable – Up to 525 kV</u>

Cross-linked polyethylene (XLPE) is the insulation material used for Extruded HVDC 525 kV export cables, suitable for HVDC power transmission up to 2600 MW. Low conductivity of this sturdy insulation material solution eliminates the possibility of thermal runaway and electrical failure. Following is an example of Extruded HVDC 525 kV submarine export cable with lead sheath from the manufacturer NKT[61]

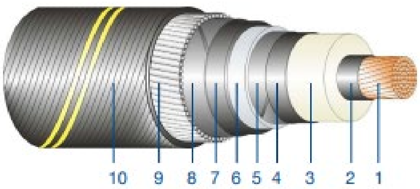
[61] Extruded DC cables leaflets 525kV V3.indd (widen.net)

Extruded DC up to 525 kV

Single-core submarine cable with lead sheath

Einleiterseekabel mit Bleimantel

Standard: Cigré TB 496, TB 623



Design:
Aufbau:

1 Conductor (Al or Cu)
Leiter (Al oder Cu)

2 Inner semi-conducting layer
Innere Leitschicht

3 DC-XLPE insulation
XLPE-Isolierung

4 Outer semi-conducting layer
Äußere Leitschicht

5 Swellable tape
Quellvlies

6 Lead sheath
Bleimantel

7 PE inner sheath
PE-Innenmantel

8 Bedding (PP)
Polsterlage (PP)

9 Armouring
Armierung

10 Outer serving (PP)
Außenschutz (PP)

Application:
Anwendung:

The cables are suitable for installation in submarine environments.

Die Kabel sind für die Verlegung auch in grossen Seetiefen geeignet.
Sie können weiterhin in Schutzrohren oder direkt im Erdboden verlegt werden.

Properties:
Eigenschaften:

Conductor Leiter	Solid, compacted or keystone Solid, verdichtet, Profildraht
Lead Sheath Bleimantel	Radial water barrier Radiale Wassersperre
Armouring Armierung	Capable of high tensile forces, adjusted to project specific requirements, available with steel wires. Single or double wire layers for larger depth, or protection Aufnahme hoher Zugkräfte nach projektspezifischen Anforderungen, möglich in Stahl. Einfach- oder Doppelarmierung für große Tiefen oder hohen Schutzbedarf

Figure 43: Extruded HVDC XLPE 525 kV submarine export cable with lead sheath

Extruded HVDC Export cable – 640 kV

Cross-linked polyethylene (XLPE) is the insulation material used for Extruded HVDC 640 kV export cables. A 640 kV XLPE DC cable system may transmit power as high as 3 GW. The 640 kV HVDC termination is filled with non-flammable SF6 dielectric gas. Both copper and Aluminium can be used as conductor. Following is a diagram showing transmitted power as a function of conductor area for copper and aluminium.[62]

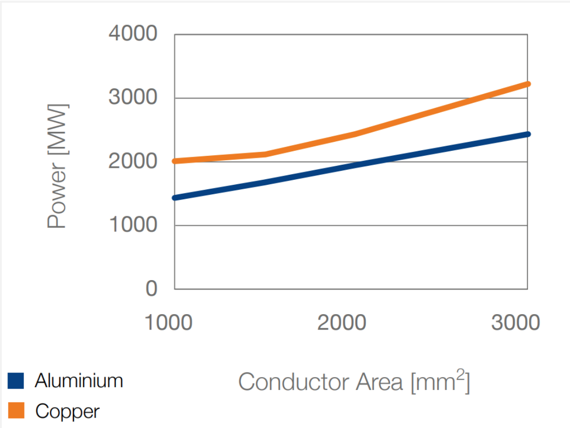


Figure 44: 640 kV XLPE DC cable system – Power as a function of conductor area.

Evolution of MI HVDC export cable

In mass impregnated paper insulated cables, the conductor is surrounded by layers of Kraft paper that have been heated, vacuumed, and then impregnated with high viscosity oil. Since the 1950s, this cable technology has been used for HVDC applications, making it quite mature.

A variation of this technology uses Paper Polypropylene Laminate (PPL) as the insulating medium, which, due to its enhanced temperature performance and higher dielectric strength, enables the realisation of larger voltages and currents and, consequently, higher power transfers.

Design voltage has a significant role in the development and adoption of technologies. The thickness of the insulating material used, manufacturing costs, and the complexity of the electrical and mechanical stresses must be considered while choosing export cable for higher voltages.

The initial IFA interconnector had a voltage of 270kV (MI), however subsequent UK HVDC interconnector projects increased that voltage to 450kV (MI) for BritNed, 600kV (MI PPL) for Western Link, 515kV (MI) for NSN, and 400kV (XLPE) for NEMO Link. All European producers offer various XLPE and MI products, albeit at various stages of technological development and maturity.

Mass Impregnated HVDC Export cable – Up to 525 kV

MI paper or PPL is the insulation material used for MI HVDC 525 kV export cables, suitable for HVDC power transmission up to 2500 MW. Following is an example of MI HVDC 525 kV submarine export cable with lead sheath from the manufacturer NKT[63]

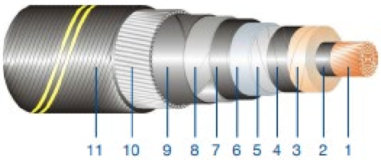
[62] 640kV-XLPEHV_HV_DS_EN.pdf (widen.net)
[63] MI cable up to 525 kV submarine_V3.indd (widen.net)

MI DC up to 525 kV DC

Mass impregnated submarine cable

Masse-imprägniertes Seekabel

Standard: Cigré Electra no. 189



Design:
Aufbau:

1 Conductor (Al or Cu)
Leiter (Al oder Cu)

2 Conductor screen
Innere Leitschicht

3 Mass impregnated kraft paper insulation
Masse-imprägnierte Papierisolierung

4 Insulation screen
Äußere Leitschicht

5 Metal paper laminat
Höchstädterpapier

6 Lead sheath
Bleimantel

7 PE inner sheath
PE-Innenmantel

8 Reinforcement
Stahlbandarmierung

9 Bedding
Polsterlage

10 Armouring
Armierung

11 Outer serving (PP)
Außenschutz (PP)

Application:
Anwendung:

The cables are suitable for submarine or underground installations.
Die Kabel sind für feste Verlegung im Boden sowie im Wasser geeignet.

Properties:
Eigenschaften:

Conductor Leiter	Compressed round wires or keystone conductor Verdichtet mehrdrähtig oder Profildraht
Lead Sheath Bleimantel	Radial water barrier Radiale Wassersperre
Armouring Armierung	Capable of high tensile forces, adjusted to project specific requirements, available with single or double wire layers Aufnahme hoher Zugkräfte nach projektspezifischen Anforderungen. Einfach- oder Doppelarmierung für große Tiefen oder hohen Schutzbedarf

Figure 45: MI HVDC 525 kV submarine export cable with lead sheath from the manufacturer NKT

4.5.4 Key suppliers and technology providers – Global & India

Following are the list of export cable manufactures, cable protection device providers and cable engineering and installation as well as cable operations and maintenance service providers. There are no Indian OSW array cable manufacturers at present.

Component	Supplier	Website/URL
Offshore Wind – Subsea Export cable manufacturers		
OSW Array cable manufacturers	LS Cable	http://www.lscns.com/
	Prysmian Group	https://www.prysmiangroup.com/en
	Hellenic Cables S.A. (Greece)	https://www.cablel.com/716/en/hellenic-cables-sa/
	NKT	https://www.nkt.com/
	ABB (Sweden)	https://global.abb/group/en
	JPower/Sumitomo	https://sumitomoelectric.com/
	Zhongtian Technology Submarine Cable Co., Ltd [ZTT] (China)	https://www.zttcable.com/
	NEXANS	https://www.nexans.com/en/
Export cable Accessory supplier		
Interface plugs	Pfisterer	https://www.pfisterer.com/de/
	Ridderflex	https://www.ridderflex.com/home_en
	TE Connectivity	https://www.te.com/usa-en/home.html
Hang-off clamps		
	Vos Prodect	https://www.vos-prodect.com/
	WT Henley	https://www.wt-henley.com/
Cable jointing and testing	In house by cable manufacturers and independents as:	
	Maillefer	https://www.maillefer.net/en/
	PCSL	https://powercsl.com/products-services/other-products-services/cable-testing-consultancy-services/
	WT Henley	https://www.wt-henley.com/
Fibre optic manufacturer	Hexatronic	https://www.hexatronic.com/en
	Huber + Suhner.	https://www.hubersuhner.com/en
Fibre optic jointers and systems	Aceda	https://www.aceda.co.uk/
	CCL UK	https://www.colcomms.com/
Subsea cable protection device providers		
OSW Cable protection device manufacturers	Blue Ocean	https://www.blueoceanprojects.com/
	Seaproof	http://www.seaproof.com/
	Subsea Protection Systems	https://www.subseaprotectionsystems.co.uk/
	Tekmar	https://tekmar.co.uk/
	Terram	https://terram.com/

Component	Supplier	Website/URL
	Trelleborg	https://www.trelleborg.com/en
	Vos Prodect	https://www.vos-prodect.com/
	Synthetex	https://synthetex.com/
Cable engineering and installation as well as cable operations and maintenance		
cable engineering and installation as well as cable operations and maintenance service providers	BPP Cable Solutions	https://www.bpp-renewables.com/
	Acta Marine	https://www.actamarine.com/
	DEME	https://www.deme-group.com/
	4Subsea	https://www.4subsea.com/
	Technip Energy	https://www.technipenergies.com/en
	Wind and water work	https://www.windandwaterworks.nl/
	Fugro	https://www.fugro.com/

- **Reactive Compensation Equipment**

As the capacity of wind farm increases, the length and cross-section of the transmission cable used are getting larger and larger. Both High-voltage AC cable and high-voltage direct current (DC) cable are commonly used in offshore wind power transmission schemes. HVAC transmission lines has simple structure and low cost for long distance transmission by which submarine cables are widely used to evacuate the generated electricity from offshore wind farms to onshore pooling substations. But the HVAC submarine cables possess 20 times more capacitance than that of overhead lines with same length and same voltage[64]. So, these cables will be affected by the charging current and contribute the reactive power to AC transmission system which will increase complexity in the power flow and network loss and lead to rise in terminal voltage. The transmission capacity of HVDC cables is larger compared to the HVAC cables and the loss is low. But it possesses high construction and operation costs due to the requirement of power electronics converters at sending and receiving end. These hurdles are leads to adopt methods which make the HVAC cables feasible than the HVDC transmission lines. The reactive power compensation equipment is used to achieve the following.

- To increase the transmission capacity of the AC cables.
- To reduce losses
- To ensure stable system voltage

  - Configuration options and design considerations

The reactive power compensation techniques are adopted to solve the generation of reactive power due to the large capacitance of HVAC cables. But there exists limitations of engineering conditions and reactive power compensation for subsea cables cannot be applied along the line[65].

- Submarine Cable without Reactive Power Compensation

Due to capacitive nature of submarine cables, charging currents will be generated in the cable. In no load conditions, the charging current distribution on the cable exhibits a linear relationship with the distance of transmission. If the submarine cable is under fully loaded or half loaded, it is observed that, the current at the receiving end of the line is larger than the current at the sending end due to the large

[64] Research on Optimal Allocation of Reactive Power Compensation in Offshore Wind Power Transmission System via AC Cable Based on Controllable Reactor - IOPscience
[65] Gatta, F.; Geri, A.; Lauria, S.; Maccioni, M. Steady-state operating conditions of very long EHVAC cable lines: Two case studies. *Electr. Power Syst. Res.* 2012, *83*, 160–169, doi: 10.1016/j.epsr.2011.11.002

charging current generated in the cable without the reactive power compensation. The relation between current and the cable distance is depicted in Figure 46.

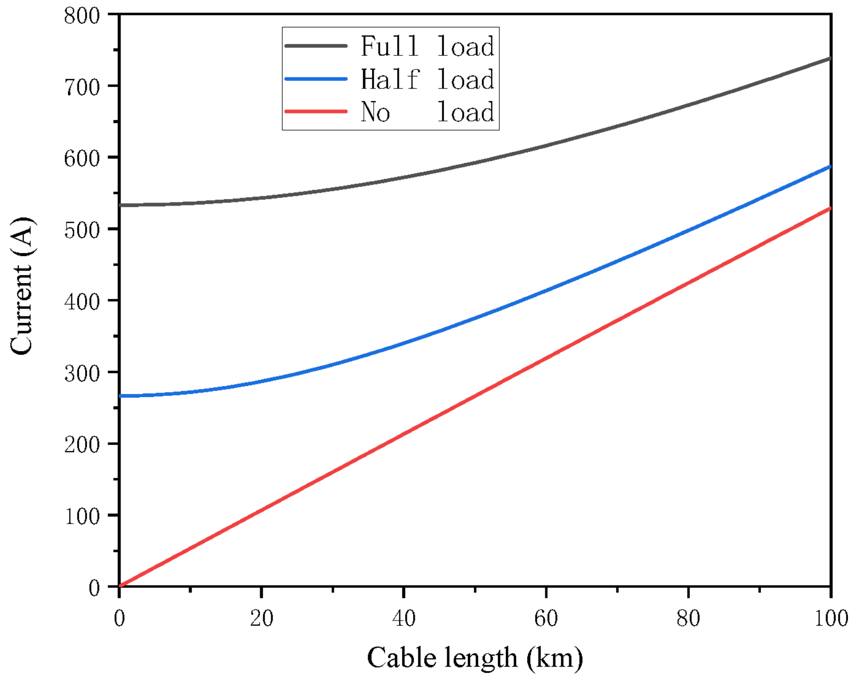


Figure 46: Current Distribution of Submarine Cables Under Different Load Conditions Without Reactive Power Compensation

For a transmission line with distance of 100 km, current at the line terminal increased to 138% and 220% of the current at the sending end respectively under full load and half load conditions[66]. With a poor heat dissipation condition, it is also observed that the current on the cable line may exceed the total current carrying capacity at higher load conditions, causing overheated operation of cables which will cause fast aging of cable insulation and reduces the life of cables. To overcome these issues different reactive power compensation schemes area adopted which are discussed below.

- **Submarine Cable with Reactive Power Compensation at Ends**

The current at the sending end of a submarine cable depends on the reactive power compensation provided. If the reactive power compensation at the sending end is higher, the larger the current at the send end. On the other hand, the more the reactive power compensated at the sending end, smaller the current at the receiving end. The current and voltage distribution of submarine cable with reactive power compensation at sending end is given in Figure 47.

[66] JMSE | Free Full-Text | Study on Reactive Power Compensation Strategies for Long Distance Submarine Cables Considering Electrothermal Coordination (mdpi.com)

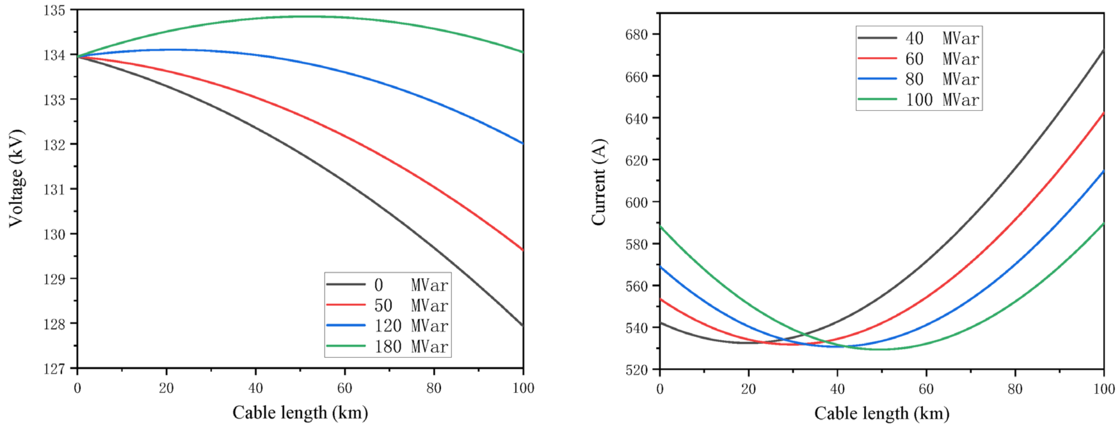


Figure 47: Voltage and Current distribution of submarine cables under full load with different reactive power compensation at the sending end

In the case of sending end compensation, the current will be maximum at the sending end or receiving end of the cable. Also, the voltage in the line will increase due to the application of sending end compensation and it will exceed the sending end voltage when the reactive power compensation reaches a certain degree. Incorporation of a certain amount of reactive compensation at the receiving end will increase the voltage at the receiving end which can prevent the low voltage of the junction point and improve the stability of the system. Nevertheless, the compensation applied on the receiving end does not change the current distribution of the line, but it can be used as a measure to improve the power factor of the junction point.

- ### Submarine Cable with Reactive Power Compensation at Middle Lines

Middle line reactive power compensation refers to the compensation provided on the subsea transmission cable in between sending end and receiving end. While comparing with the sending end or receiving end compensation schemes, the compensation equipment is installed in a separate offshore station. Since the submarine cable crosses the sea for long distance, there is a technical and economical requirement of compensation techniques at the middle. In some cases, the submarine cable may cross islands where the compensation can be built as an onshore station in the island section. The distribution of current in middle line compensation is depicted in Figure 48.

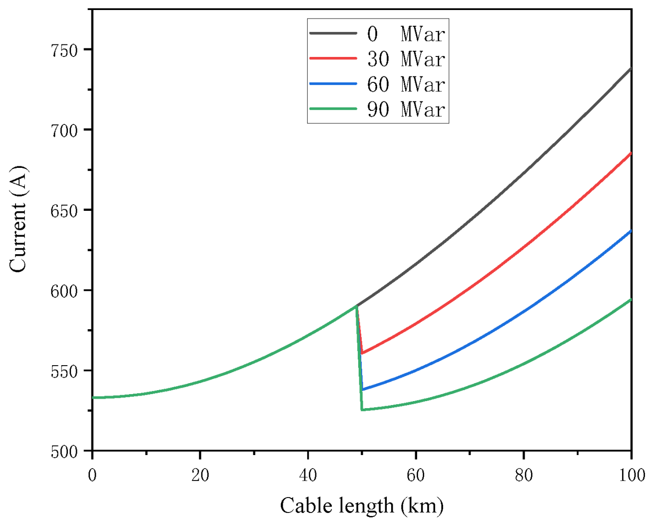


Figure 48: Current distribution of submarine cables under full load with different reactive power compensation at the middle line

In the case of middle line compensation, there is no change in the current distribution from sending end to middle line. But the reactive power compensation at the middle line will reduce the current distribution from middle line to receiving end. Since the middle section of the submarine cable line is usually sea area, the cost for construction and maintenance of reactive compensation equipment for the mid-line is high. Thus, compensation at the sending end would be considered normally to increase the transmission capacity of line. In the case of long-distance transmission cables, the sending end compensation may not be sufficient, and the mid-line compensation can be considered simultaneously Different reactive power compensation techniques are explained below.

- **Reactive Power Compensation Devices**

Reactive power compensation along the cable length can be provided by using flexible AC transmission system (FACTS) devices enabling an equal current flow at both the generation and load ends. Some of the FACT devices are discussed below.

- Mechanically switched capacitors (MSC): The most practical and efficient way for the utility to supply the reactive power demanded is through the installation of Mechanically Switched Capacitors (MSCs), more common know as shunt capacitor banks. It possesses simple design, low speed resolution for voltage control, and grid stabilization under capability under heavy loading. The installation of MSCs brings benefits concerning the reduction of system charging and electrical losses, system capacity release and also improvements in the power factor.
- Mechanically switched shunt reactors (MSR): Mechanically switched reactors (MSR) have the opposite effect of mechanically switched capacitors. MSR therefore decrease voltage at the point of connection. The shunt reactor is the most cost efficient piece of equipment for maintaining voltage stability on the transmission lines. It does this by compensating for the capacitive charging of the high voltage AC-lines and cables, which are the primary generators of reactive power. The reactor can be seen as the voltage control device which is often connected directly to the high voltage lines.
- (MSCDN): An advanced form of mechanically switched capacitor is the MSCDN. This device is an MSC with an additional damping circuit for avoidance of system resonances
- Static Var Compensators (SVC): SVC is a fast and reliable means of controlling voltage lines and system nodes. The reactive power is changed by switching or controlling reactive power elements connected to the secondary side of the transformer. Each capacitor bank is switched ON and OFF by thyristor valve (TSC). When system voltage is low, the SVC supplies capacitive reactive power and raises the network voltage. When system voltage is high, the SVC generates inductive reactive power and reduces the system voltage.
- Static Synchronous Compensators (STATCOM): STATCOM or Static Synchronous Compensator is a power electronic device using force commutated devices like IGBT, GTO etc. to control the reactive power flow through a power network and thereby increasing the stability of power network. STATCOM is a shunt device i.e., it is connected in shunt with the line.

▪ International Experience

The reactive power can be compensated by the wind turbine generator (WTG) using the internal capabilities. Following the cost benefit analysis, the reactive power compensation by WTG capabilities is the cheaper option[67]. The WTG will have a provision to set a point on the reactive current for which the turbines will work ensuring the compensation in the system. This method is adopted in the reactive power compensation techniques of Borssele I-IV offshore wind farm, Netherlands where the Transmission System Operator (TSO) is responsible for the compensation of reactive power.

In the Nysted OSW farm, Denmark Static VAR compensator were installed with a capacity of 65/+80MVAr, 132kV. In the project, the SVC supplied and installed onshore (at Radsted) primarily to comply with Grid Code requirements.

[67] Stakeholder consultation process offshore grid NL, TenneT, 2015

In Tanet OSW farm, UK, SVC Plus technology is used for the reactive power compensation and this is the first successful demonstration of technology. SVC Plus is an enhanced version of STATCOM which has a modular multilevel converter technology. SVC Plus can be operated individually or in parallel. The similar technology is used in Lincs which is incorporated in the onshore substation. OSW farms like Westermost Rough and Greater Gabbard, UK use the similar technology.

Though OSW farm – Hornsea One have long distant from offshore substation to the shore (more than 100 km) it uses HVAC transmission system. Due to the higher length in the transmission cable, high reactive power compensation is required in Hornsea OSW farm. Hornsea One's had three offshore substation platforms which are connect to a separate reactive compensation station (RCS) via three 220kV subsea cables with lengths of 68 km, 74 km, and 87 km respectively. This is considered as the world's first project where the separate RCS platform has been used. Further, the RCS is located at the midpoint of the export cables.

- **Technology roadmap evolution and maturity**

Voltage Source Converter (VSC) HVDC technology has been used in different project. For example, the DolWin1 project. VSC HVDC converters have different feature and benefits like a) more compact, b) do not require converter transformers and c) does not need a large AC switchyard to accommodate harmonic filters as the converter inherently produces a waveform with little harmonic content. VSC HVDC converters are capable to control active and reactive power flow, by which it can address flexibility requirements from the grid whilst managing an increased number of renewables with a low AC inertia.

- **Key suppliers and technology providers – Global & India**

Components	Suppliers	Website/URL
Mechanically switched capacitors (MSC)	Siemens Energy Global GmbH & Co. KG	Mechanically switched capacitor (MSC) | Flexible AC transmission systems (FACTS) | Siemens Energy Global (siemens-energy.com)
Mechanically switched shunt reactors (MSR)	Siemens Energy Global GmbH & Co. KG	Mechanically switched capacitor (MSC) | Flexible AC transmission systems (FACTS) | Siemens Energy Global (siemens-energy.com)
Mechanically switched capacitive damping networks (MSCDN)	Siemens Energy Global GmbH & Co. KG	Mechanically switched capacitor (MSC) | Flexible AC transmission systems (FACTS) | Siemens Energy Global (siemens-energy.com)
Static Var Compensators (SVC)	Hitachi Energy Ltd	Static Var compensation (SVC) | Hitachi Energy
	Siemens Energy Global GmbH & Co. KG	Flexible AC transmission systems (FACTS) | Portfolio | Siemens Energy Global (siemens-energy.com)
Static Synchronous	Siemens Energy Global	SVC PLUS (STATCOM) | Flexible AC transmission systems (FACTS) | Siemens Energy Global (siemens-energy.com)

Components	Suppliers	Website/URL
Compensators (STATCOM)	GmbH & Co. KG	
	Hitachi Energy Ltd	STATCOM - SVC Light® | Hitachi Energy
VSC HVDC	Siemens Energy Global GmbH & Co. KG	HVDC PLUS (VSC) – HVDC | IGBT, MMC | High-voltage direct current (HVDC) | Siemens Energy Global (siemens-energy.com)
	Mitsubishi Electric Corporation	HVDC | Transmission & Distribution | Energy Systems | Mitsubishi Electric
	Hitachi Energy Ltd	HVDC | Hitachi Energy

Key Takeaways

The key components of OSW transmission infrastructures are offshore substations, reactive power compensation equipment, and submarine cables which constitute the balance of the plant. The balance of the plant includes all components of the wind farm except the turbine.

The Substations are often delivered as one element of a contract to connect the wind farm generating assets to the onshore transmission grid and it will be comprised of electrical systems, facilities or auxiliary systems, substation foundations or sub-structures. The major classification of OSS is HVAC and HVDC. The basic consideration for the selection of the HVAC and HVDC would be the receiving end voltage at the onshore substation, the designated voltage of the transmission line envisaged which may depend primarily on the capacity of power to be evacuated and the distance of the OSW farm to the shore.

As per the proposed configuration options, the HVAC system is preferred up to 400 kV where the power evacuation capacity per circuit of export cable is 1000 MVA. The HVAC system can be configured even in lesser voltages like 66 kV, 132 kV and 220 kV. As a futuristic technology, 765 kV HVAC systems are being considered with a typical power evacuation capacity per circuit of export cable over 3000 MVA.

The HVDC system is preferred above 400 kV voltage with typical power evacuation capacity per circuit of HVDC export cable could be up to 3000 MVA. HVDC-VSC system can be used with a system voltage up to 500 kV. However, additional converters are required on the sending and receiving end which will cause an increase in the cost of the scheme. Therefore, it has been deduced that HVDC substations with cost analyses must be examined first for large-scale projects when the distance from the seashore is considerable.

The OSS can be also classified into fixed and floating based on the mode of fixing to the seabed. Presently, fixed mechanical structures are dominant and used to provide support and protection to the substation platform. As the depth of water increases the mechanical structures may not be suitable to anchor the platform into the seabed. In such cases, floating offshore substations can be considered which will offer the possibility to install wind farms in larger and deeper offshore areas with high wind potential. However, the technology of floating substations is in the developing phase. Further, submerged substations – Subsea Substations are in the phase of development and is expected to be available in the market by 2024.

The preference for HVAC transmission necessitates the need for reactive power compensation. Configuration Option 4, evacuation at 400 kV HVAC, requires the incorporation of reactive power compensation equipment. Usually, reactive power compensation equipment can be integrated with offshore substations. The reactive power compensation techniques are incorporated into the OSS primarily to increase the transmission capacity of the AC cables, reduce losses, and keep the system voltage within the limit.

Because of limitations of engineering conditions, the reactive power compensation can be applied centrally at the ends of the cable, or on the land halfway. Usually, the reactive power compensation is applied at the sending end where the current will be maximum at both sending end and receiving end. Also, the voltage in the line will increase due to the application of sending end compensation and it will exceed the sending end voltage when the reactive power compensation reaches a certain degree. Reactive power compensation at receiving end is incorporated to increase the voltage at receiving end which can prevent the low voltage of the junction point and improve the stability of the system. Even then, the compensation applied on the receiving end does not change the current distribution of the line. So reactive power compensation at receiving end can be used as a measure to improve the power factor of the junction point.

In the case of middle-line compensation, a dedicated reactive power compensation station needs to be constructed. Since the middle section of the submarine cable line is usually a sea area, the cost for the construction and maintenance of reactive compensation equipment for the mid-line is high.

Different reactive power compensation equipment devices used in the OSW industries are Mechanically switched shunt reactors (MSR), Static Var Compensators (SVC), and Static Synchronous Compensators (STATCOM) where the SCV and STACOM are dominant in the current industry.

Reactive power compensation does not require for HVDC systems but, as per the latest development, the converters used in HVDC systems are capable to provide reactive power compensation which will be beneficial to meet the grid code requirement.

5. Operation and Maintenance aspects of OSW Evacuation

5.1 Key areas for O&M for OSW Evacuation from international experiences

Operation & maintenance can be considered as a combined function that supports the ongoing operation of the wind turbines, balance of plant and associated transmission network during the lifetime of the OSW. O&M activities starts right after the completion of construction of the OSW and focused to ensure the safe operation by which physical integrity of the OSW assets are maintained and electricity generation is optimised. The OSW developer or owner is responsible for fulfilling the oversite operation and maintenance activities. O&M is primarily focused to ensure the health of personnel as well as the OSW thereby maximising the financial return from the owner's investment.

Around the clock operational support is provided to the OSW by the suppliers that include live turbine monitoring, weather monitoring, response to the unexpected events and faults. This support is provided remotely from control rooms which monitor the OSW through Supervisory Control and Data Acquisition (SCADA), outside the normal operating hours.

Scheduled and unscheduled activities are included in maintenance and services which require regular transfer of technicians and accessories to the offshore substation and OSW.

Wind turbines are typically under warranty period for the first five to ten years of operations[68]. So, a service level agreement will be executed between the suppliers and owner of the OSW during the said period to ensure the maintenance and services of the power plant. On expiry of the warranty period, the owner of the plant may maintain and service the OSW using their own in-house team, execute a separate agreement with Asset Management Company (AMC) or develop an intermediate arrangement with the supplier of the OSW where the OSW technicians are transferred to the OSW owner at the end of the warranty period.

5.1.1 Operations

The operations related to the OSW includes the a) assurance of health and safety of the assets, b) control and operation of asset which include wind turbine, balance of plant, c) remote monitoring of OSW, d) electricity sale, administration and supervision of marine operations, e) operation of vessels and infrastructure, and f) back-office works. A special-purpose vehicle will be created by the owner of the OSW which include several stakeholders one of which will play the lead role.

As a part of operation task, an onshore control room will be set up which provides access to the whole OSW systems via SCADA and other system that provides real time data and historical data for the wind turbines, Offshore substations, offshore crew, and vessels etc. Also, it will enable the operations duty manager to understand the locations of personals and vessels. OSW are remotely monitored on real-time basis using the SCADA and actively inspected periodically including the subsea infrastructure. Condition monitoring can help to ensure the preventive maintenance prior to the faults. A senior authorised person must be available all the times to coordinate the activities and responsible for the operations of all the equipment. Presently, the OSW industry is moving towards more advanced data driven approaches that maximise asset values, which include increased use of performance analytics.

Apart from the infrastructure related activity, monitoring of environmental parameters to assess the effect of OSW in the local environmental conditions and flora and fauna of the sea is also carried out.

The OSW can be broadly classified based on the base of the operation listed as below[69].

- OSW with an onshore base: An onshore base is typically applicable to OSW with a capacity less than about 400 MW with a daily assess to the wind farm using crew transfer vessel (CTV).
- OSW with an offshore base: This is usually applicable to OSW with a capacity greater than 400 MW which is likely to be a service operation vessel (SOV).

5.1.2 Maintenance

The operational integrity of OSW is assured by the proper maintenance and service of the plant which may include both planned and unplanned maintenance as a response to faults occurred. Maintenance and services are offered by a team that include owner's in-house personals, supplier of wind turbine and balance of plants and third party service providers. OSW industries are focused on optimization of the maintenance activities which can reduce the operational costs without compromising the performance of the OSW. The maintenance and services classified broadly in to two- a) turbine maintenance and services and b) balance of plant maintenance and services.

[68] Guide to an offshore wind farm Published on behalf of The Crown Estate and the Offshore Renewable Energy Catapult.
[69] Guide to an offshore wind farm - BVGA-5238-Guide-r2.pdf (catapult.org.uk)

- ### Turbine maintenance and services

The maintenance activities are divided into scheduled maintenance (preventive) and unscheduled service (corrective) works. The majority of preventive maintenance is performed during the low wind seasons to minimise the loss in the production which is not always achievable in practice. The corrective service is carried out in response to the faults occurred which is more critical in nature because of the uncertainty in the downtime until the fault has been resolved. Both mechanical and electrical engineering expertise are required to ensure the maintenance services along with the turbine maintenance skills. The maintenance includes the general inspection specifically on the bolt joints and replacement of damaged parts. The turbine maintenance, primarily, includes the following.

- Blade inspection and repair: Consists of the inspection of the condition of blades. Further, replaces or repairs the worn blades in a cost effective and timely manner.
- Nacelle component refurbishment, replacement, and repair: Consists of replacement or repair of large components such as gear boxes, transformers, and generators in a cost effective and timely manner.

- ### Balance of plant maintenance and services

Balance of plant is an integral part of the OSW. The maintenance of the balance of plant focused on the integrity and reliability of the assets of wind farms except the wind turbines which include foundation structures, array cables, offshore substations, subsea cables, scour protection and corrosion protection systems. Proactive maintenance of the components of OSW is the key aspect of reliability based preventive maintenance. Regular inspections of all the components are necessary to avoid emerging issues and to perform the proactive or reactive service to ensure the estimated generations. The balance of plant maintenance includes the following.

- Foundation inspection and repair: Identifies the structural problems and corrosion above and below the water which will be addressed as and when required. To inspect the structural components, the below mentioned vehicles are vital.
    - Remotely operated vehicle (ROV): Used to inspect the foundation structures below the water and the cable route.
    - Autonomous underwater vehicle: Offer low-cost survey below the water, preferably on balance of plant assets and foundation.
- Cable inspection and repair: Help to identify the faults in the cable and replace whole sections of cable. The exposed cable may be damaged due to the mechanical loads of wave and tidal action, anchors of fishing gear, transportation, and/or improper installations.
- Scour monitoring and management: Used to mitigate the risk of undermining seabed movements on subsea structure.

Substation maintenance and service: Helps to eliminate the interruption in the transmission of electricity due the electrical failure or structural problems.

5.2 Operational Performance parameters & standards for key components

It is important to monitor and assess the performance of OSW for which operational managers require highly condensed information. Thereby, underperforming turbines can be identified and the service or maintenance are prioritised based on the assessment. There are defined tools termed as key performance parameters (KPI) that provides insights to the performance of OSW.

The OSW plants are typically monitored round the clock from a central control room either in onshore or offshore. As a result, the control room will identify and respond to the unexpected faults and initiate appropriate mitigation measures. However, the long-term performance of the OSW, achievement against the targets must also be monitored as a part of successful operational management which necessitate the usage of KPIs. Standardisation of KPI offer an effective comparison of wind turbine through benchmarking and comparison of performance of a wind turbine to the historical best performance within the industry. KPIs are defined in a way to assess complete details related to the performance of wind turbine, both in offshore and onshore wind power plants[70]. It can be stated that, KPIs need to be relevant, specific, measurable, comparable, traceable in time, standardised and form a minimal complete set. Primarily the KPIs are classified into five categories, viz, performance, maintenance and reliability [71]which are discussed in detail in the next sections.

- **Performance**

Performance is the one of the most important parameter in which operators are interest. The important indicators are discussed below.

• Wind / Energy Index

This parameter is used to assess the availability of wind energy on a particular geographical area. It establishes a statistically" normal" period of yearly wind energy content, expressed as 100% along with the actual wind energy content can be used to understand the available input energy to the wind turbine. So that the operator can distinguish between under-performance OSW and wind strengths below expected levels; it allows for comparison of the production of an OSW with the available wind resource.

• Capacity Factor

Defined as the ratio of actual energy generated during a particular period to the ideal energy it could have been generated if the OSW would work for all the time. This is a valuable indicator during feasibility and development of wind project, still this is not an effective indicator for evaluating operational efficiency of OSW.

• P_{50} Deviation

During the process of wind resource assessment, the P50 energy yield gives the level of annual energy production that is expected to be exceeded with a probability of 50%. Many operators assess the deviations from the calculated P_{50} energy yield and actual energy generation.

• Time-based availability

Time based availability is defined as the ratio of accumulated time that the wind turbine is operational to the total period. This indicator is specific, since the observed value is clearly defined and is the time that a wind turbine is operational; measurable and easy to understand, it is relatively easy to distinguish periods of power production from periods of inactivity; strategies to reduce the downtime result in an increase of this metric. Furthermore, it does not provide information about efficiency of wind turbine or power losses due to unavailability.

• Energy-based availability

Energy based availability is defined as the ratio between the real energy production and the actual energy available. It can be considered as a more objective indicator for comparing different assets, but difficult to implement. It is easy to measure produced energy over a period. But it is quite difficult to

[70] Key Performance Indicators for Wind Farm Operation and Maintenance- (PDF) Key Performance Indicators for Wind Farm Operation and Maintenance (researchgate.net)
[71] Recommended key performance indicators for operational management of wind turbines (nrel.gov)

define actual energy available for the time period. So, presently rely on the SCADA data from which theoretical production data can be generated from an operational power curve.

- **Reliability**

Applied to a wind turbine, its reliability can be defined as its ability to perform properly, without failures, during specified site wind conditions for the whole lifetime (defined to be at least 20years) or in a specific time window. OSW uses different indicators to assess the reliability of system as discussed under.

- ### Mean Time between Failures (MTBF) & Failure Rate

The MTBF expresses the total operational hours divided by the number of failures for a specific component or for the whole wind turbine. The term MTBF is frequently used to describe reliability, as well as its reciprocal value, the failure rate.

- ### Mean Time to Repair (MTTR) & Repair Rate

The MTTR is the average time to return a wind turbine to its functional state This can imply either a repair or a full re-placement of the faulty component, leading to the term of restoration, as defined in. This indicator can be assessed by dividing the total time of restoration by the number of failures.

- ### Mean Time to Failure (MTTF)

The MTTF is like MTBF, but it is used to describe reliability of non-repairable systems. Non-repairable refers to systems that are replaced after a failure because there is no possible maintenance action that can make them work properly.

- ### Availability

The time-based availability can be defined as the ratio of amount of time that a system or component is available for use to the total amount of time in the period of operation.

- **Maintenance**

Maintenance activities are crucial to keep a system in good condition. Maintenance indicators assess the quality of the maintenance, in terms of time consumed for different interventions and related costs. The important indicators are presented as following.

- ### Response time

Defined as the time between failure occurrence and maintenance intervention, it informs about the efficiency in maintenance planning. Since it is often difficult to detect the failure starting time, it can be redefined as the time between failure detection and intervention.

- ### Corrective maintenance

Defined as the ratio of the purely corrective interventions over the total number of interventions, this indicator meets all the properties and defining a standard is possible.

- ### Schedule compliance

It is defined as the ratio between the scheduled maintenance tasks completed on time and the total number of tasks. This indicator fulfils most of the properties and a standard can be easily defined.

- ### Overtime jobs

Defined as the ratio between the overtime working hours and the planned working hours (working hours per worker and per size of the work force), this metric can be measured on different time-scales. It is comparable and a standard can be defined.

- ### Backlog

It can be defined as the list of maintenance work that still needs to be completed. Hence, its size might sound like a very intuitive way to measure the effectiveness of maintenance execution.

- ### Labour costs versus total maintenance costs (TMC)

The labour costs, expressed as a percentage of the total maintenance costs (TMC), inform about the effectiveness of maintenance execution.

- ### Cost of spare parts versus total maintenance costs

The cost of spare parts, expressed as a percentage of the TMC, is directly related to the number of failures followed by replacements.

- ### Total annual maintenance cost versus annual maintenance budget

Setting the TMC in relation to the annual maintenance budget (AMB) can give insight into the quality of maintenance planning and is therefore relevant to stakeholders.

5.3 Spare parts and inventory management practices

OSW has downtime related to the maintenance and services which may cause huge financial losses to the owner. So, it has a prime consideration to reduce the downtime of the OSW as much possible[72]. One of the strategies to reduce the downtime would be forecasting the requirement of different spare parts and keeping the required number of spare parts in the inventory. The maintenance team will assess the failure symptoms to predict the approximate time of failure that will help to purchase, and stock required spare parts systematically. Still, there will be a trade-off between ordering cost, holding cost and shortage cost. The proper inventory planning is important, that offer savings to the owner or developer of the OSW by avoiding the placing of expensive emergency orders. So, spare parts management system would be a critical element of the operation and maintenance of OSW farm which is influential on the life cycle of project.

Optimisation of spare parts management will help the developer to improve the performance index. The different opportunities related to the spare parts management is given below[73].

Unscheduled down time: Any unplanned downtime occurring on a wind turbine because of a component failure or protectionary shut down is termed as unscheduled down time. The downtime will reduce the availability and operational time of OSW which will reduce the generated energy and has a contractual repercussion for the developer of wind turbine projects.

Spare parts availability: The spare parts availability at the store at site will be ensured. This will enable the site maintenance coordinator to perform the corrective action in the next available site visit.

Inventory management: best practices in inventory management ensures and verifies the access to spare parts and maintenance required during occurrence of faults to effectively operate and maintain the OSW. This includes the optimisation of wind farm spares to keep in an O & M warehouse. The decision has been taken based on the inventory management about the spares to be maintained centrally.

Response time: An evaluation of how quickly the operational control team is able to respond to a fault or alarm and how quickly the parts required remediating the fault can be assembled.

Abortive work- Parts delayed: This is an assessment of time duration required to make the spare parts available at site for the rectification of faults/issues occurred.

5.3.1 Opportunities for Improvement in Supply Chain Management

This section will provide further details of opportunities for improvements in supply chain management.

- **Criticality of Spare Parts**

The important element of effective spare parts management is to have a better knowledge on the criticality of spare parts. The knowledge on the criticality of spare parts includes the usage of spare parts, likely demand on the spare parts, redundancy, delay in availability and the impact of delay to accessing parts in time. It is also important to develop and maintain the knowledge base for the spare parts criticality.

[72] Spare parts control strategies for offshore wind farms: A critical review and comparative study, Md Imran Hasan Tusar, and Bhaba R Sarker
[73] Spare Parts Management in Offshore Wind, Catapult

In the offshore wind industry, a significant hurdle to improve spare parts criticality there by demand on parts is a is a lack of knowledge on failure modes and effect criticality analysis (FMECA). Better data sharing will help the OSW industry to address the uncertainty in the failure rates. Further, there is a lack of engineering failure modes and effect analysis. This inhibits root cause analysis of failures,

which issues should be prioritised and understanding of which spare parts are required to repair specific failure modes. This barrier is further complicated by the rate at which new technology is being designed, developed and implemented in the field.

- **Supply Chain Engagement and Relationship Management**

In the supply chain engagement and relationship management with the vendors the effective communication and collaboration will be a challenge because the supply chain for an industry involving complex rotating and electric machinery with high volumes of components will inevitably involve a multifaceted network of suppliers and service providers and generate vast amounts of data. The assurance on delivery of spare parts can be improved by engaging in better communication with suppliers. Also, overall performance can be improved by rapidly addressing the issues related to supply and demand and proactively mitigating the risk on the same.

- **Optimisation of Inventory Mix**

Selection of an inventory mix is an outcome of multidimensional optimisation problem that aims to minimise the excess inventory at the same time ensures the availability of spare parts at site when they are required. In the OSW industry, this task can have many unknown parameters involved. It is necessary to consider the historical data and a targeted performance to arrive on the optimal inventory levels using the best fit distribution and user parameters for demand and cost segments.

5.4 Port logistics support requirements

Ports play an important role in the economic growth. Ports and allied infrastructure facilitate trade, technologies, and services. Being at the coastal regions, they support the large industrial bases in the hinterland and facilitate the movement of goods and crew. On similar lines, ports are the backbone of the offshore energy sector, in particular the offshore wind industry. It supports diverse activities within OSW by handling all its components and supporting the operation and maintenance including development of offshore power transmission infrastructure.

5.4.1 Ports as an important infrastructure in OSW

Ports are strategic hubs in the offshore wind farm supply chain and the characteristics of available ports and vessels are critical for defining and optimising OSW installation strategies and logistical operations.[74]

Ports facilitate OSW related services across all the stages, from surveys to construction, operation and maintenance and managing the activities under uncertain events. The ports that handle the activities of construction are dedicated to those activities within construction and may also be designed to handle other responsibilities and services. This includes the movement of material and equipment and the handling equipment for construction on the vessels. The construction ports well-assist this stage through the dedicated vessel and port calls. The installation ports have different handling capabilities

[74] Supply chain, Port infrastructure and logistics study, for offshore wind farm development in Gujarat and Tamil Nadu, the European Union, June 2016

which largely cover the need of unloading and loading, pre-assembly (through staging ports) and storage, limited to the installation works.

OSW projects involve diverse activities at the installation and the O&M stage. The activities include both, the onshore and offshore logistics. It involves right from the surveys, construction, and the day-to-day maintenance of the offshore assets (turbines, foundations, and electrical elements), other operations and back-office administration in keeping with the operation of a large offshore wind farm. Most of the work is focused on addressing the construction needs and the operational needs (scheduled and unscheduled maintenance requirements) of the wind turbines. Though during the operational phase, inspections and remedial works of various components vary in terms of frequency and the extent but, the systems at the ports are to be kept in a state to handle these.

The ports represent a key strategic gateway for the erection of wind farms in the sea. Considering the large size of offshore wind turbines, other components and the transport problems associated with them on land, ports are also important production sites.

Those ports, with sufficient supply of surface area for production halls, storage, assembly and loading areas - are well-placed to meet the requirements of offshore wind industry developers looking for an onshore base. Since all the components and its parts may not be produced at a port, it is important that the port is well-connected to the hinterland by means of an efficient transport infrastructure (roads, rail, waterways where applicable). With respect to offshore wind farms, a qualifying criterion for offshore ports is that they are fitted with suitable infrastructure facilities such as loading cranes, as well as equipment for loading and delivery of wind turbine components or raw materials.

It is important to note that offshore ports are not merely locations for storage and shipping of offshore wind turbines and components; they are also used as a base for execution of erection, service, operation, and maintenance works. The availability of surface area and facilities for vessel deployment, to be able to transport personnel to the offshore wind farms and substations quickly, is therefore a critical factor. Ports also function as moorings for various offshore vessels with dedicated purpose and utility in the whole offshore wind project.

This study attempts to address the port infrastructure and logistics aspects of the power evacuation component of an offshore wind farm. While the power evacuation component may not involve a dedicated staging port like the preassembling for the nacelle, turbine and blades, a certain section of the port is directly involved in this but also, the cable laying that may involve vessel-based activity as well. A construction port may still be important as the O&M port for the power evacuation activities.

In general, the O&M ports are much smaller than those required for construction and are situated as close to the site as reasonably possible to minimise day-to-day transit time. The shore-side services are vital to support offshore logistics, and all offshore wind farm O&M activity needs access to port facilities such as load-out and work boat mooring. The other activities related to maintenance are a scheduled process with periodic inspections.

For development of OSW farm, there are different kinds of ports which are critical to the installations and O&M. The following subsections of this chapter attempt to discuss the port infrastructure and logistics, specifically, for the transmission component of OSW.

5.4.2 Categories of ports for OWF power evacuation and O&M

Offshore ports can be classified into three main categories, independent of their offshore wind energy functions.

- Large component ports (production ports with manufacturing facilities, installation, and base ports for pre-assembly, import and export ports for transhipments, ports of refuge)
- Ports for servicing and maintenance (bases for servicing, maintenance, and repair purposes)
- Research ports (ports with areas for offshore prototypes and test turbines, training, and instruction facilities)

The categories of ports that are essential to power evacuation of offshore wind farm and O&M are,

- Offshore substation facilitation port
- Operations & maintenance port
- Installation port

For any operations, the OSW farm needs specific onshore facilities from design and handling aspects. To simplify, the requirement for OSW power evacuation and O&M port would vary, and all these requirements are to be considered and integrated while planning and developing ports for OSW projects.

5.4.3 Various methods for the delivery of power evacuation components for offshore wind farm

There are several methods for the delivery of wind farm components from the original equipment manufacturers' (OEM) premises to the offshore wind farm site. However, the suitable methods to transport and deliver the components and parts for power evacuation are described below.

- *Loading of components onto a transport vessel or barge at the manufacturer's premises and off-loading onto a floating barge in a sheltered harbour* near the offshore wind farm site, to be stored, awaiting transfer to the installation vessel.
- *Loading of the components directly onto the installation vessel at the manufacturer's premises,* and installation at the offshore wind farm site.
- *Loading and off-loading of components onto quayside storage areas in ports, at the manufacturers* and marshalling (or staging) site respectively[75]

These become relevant when considering staging of foundation, array cable installation, export cable transportation and laying, receipt of parts, cables, and other fixtures, etc.

The offshore wind farm, the industrial bases for supply chain and port infrastructure are inter-linked. This inter-linkage has the access component which is through the vessels. These aspects are inter-linked also in the sense that as the offshore wind industry matures the role of ports and the ability to cater would also evolve. This is driven by markets which have various factors such as the availability of vessels, facilities, OWF components, weather windows and the location (distance) of the site/s.

[75] Supply chain, Port infrastructure and logistics study, for offshore wind farm development in Gujarat and Tamil Nadu, the European Union, June 2016

5.4.4 Major activities on the shore and sea for power evacuation

A broader list of components within power evacuation may include,

a) Port based unloading & loading, handling and storage of parts and equipment.
b) Pre-assembly, if involved
c) Subsea cable laying
d) Offshore substation- set up and platforms including the large size HVDC convertor platforms.
e) Array cable as well as power export cables
f) Movement of equipment and personnel
g) If a manufacturing base is attached to the port, the use may vary.

Cables transmit the power from the turbines to the offshore pooling substation and then on to the shore. Array cables connect strings of offshore wind turbines to the offshore substation and are typically at 66kV and may go upto 132kV with high-capacity wind turbines. The power is then stepped up to an extra high voltage in the offshore substation before the export cables transmit the power to the shore. Historically export cables have been AC, but in the future driven by increasing wind farm size & distances from shore, DC cables will begin being used.

Offshore substations are the single heaviest item of plant, weighing thousands of tonnes. The platform level is about 25m above the sea and has an area of typically 800m2. The platform sits on a foundation, typically a jacket design.[76]

5.4.5 Activities in brief

a) Port based unloading, handling and storage of parts and equipment.

- Unloading, loading and storage

  - In includes, unloading of secondary components (fixtures, electric components, etc.), inspection and subsequently moving it to the storage (in buildings, if weather sensitive). If any components that are pre-assembled, the loading is carried out.
  - Storage of the cables, fixtures, parts and equipment for substations, and tools required for installation and laying and O&M spare-parts; Sub-assembly of secondary components, if any in a closed-space.
  - Load-out (loading components onto the installation vessel).

Figure 49: Windmill blades handled at port[77]

[76] https://kis-orca.org/renewable-energy/windfarms-overview/wind-farms-design-of-structures-installed/
[77] V.O. Chidambaranar Port, Tamil Nadu, India handles longest windmill blades, Marine Insight News Network, January 25, 2022

Figure 50: Final components departing from the port[78]

b) Pre-assembly

- If any pre-assembly is involved or certain parts are to be placed before the substation is installed in the sea.
- Quality control walk-down and hand-over documentation.
- Pre-commissioning, where systems are verified for functional operability to achieve readiness for the commissioning (and shorten the duration of the process in offshore environment).

The functions of the pre-assembly area and the load-out area can be merged where the berth space is limited. The important aspect is of the scheduling of vessels which must be suitably coordinated to avoid any interference with any other operation. The layout of these areas can be suitably done based on the project as it varies on a project-to project basis. This is to be considered when a port is already handling other products and goods.

c) Subsea cable laying

Installing a submarine transmission cable is a costly and challenging work. The lifetime of a submarine cable might be tens of years and the technical interventions for its repairing in case of faults are also costly and difficult.

Therefore, the cable route must be carefully surveyed and selected to minimize the environmental impact and maximize the cable protection. The laying down the transmission cable on the seafloor or beneath the sea floor is done by specialized vessels. In the most active vessels used for such operations are from different vessels providers (E.g., the Skagerrak (owned by Nexans), Giulio Verne (Prysmian), Team Installer (Topaz Energy and Marine) and C.S. Sovereign (Global Marine

[78] Global Energy celebrates another milestone as the final components for Scotland's largest windfarm depart from the Port of Nigg. Tuesday 28th September 2021, Glonal Port Services. The reference link was visited on 17.02.2023.
https://globalportservices.co.uk/news/global-energy-celebrates-another-milestone-as-the-final-components-for-scotlands-largest-windfarm-depart-from-the-port-of-nigg

Systems Ltd)[79]. They are all equipped with a turntable for at least 4000 tons of cable and have the appropriate gear to handle it.[80] The actual selection of cable, its weight and length is project dependent.

To minimise the risks for damages, the cables are buried in the seabed or in trenches. The trenches in which the cables are placed are dug by a submarine plough, and later covered by sediment or rocks.

Installing a submarine transmission cable is a costly and challenging work, mainly because it is very large in size, larger diameter drums, venturing in the sea with these heavy sized components, the time involved with precision and the risk in terms of personnel safety and the overall cost. Thus, to minimize the environmental impact and maximize the cable protection the cable routes are to be carefully surveyed and selected.

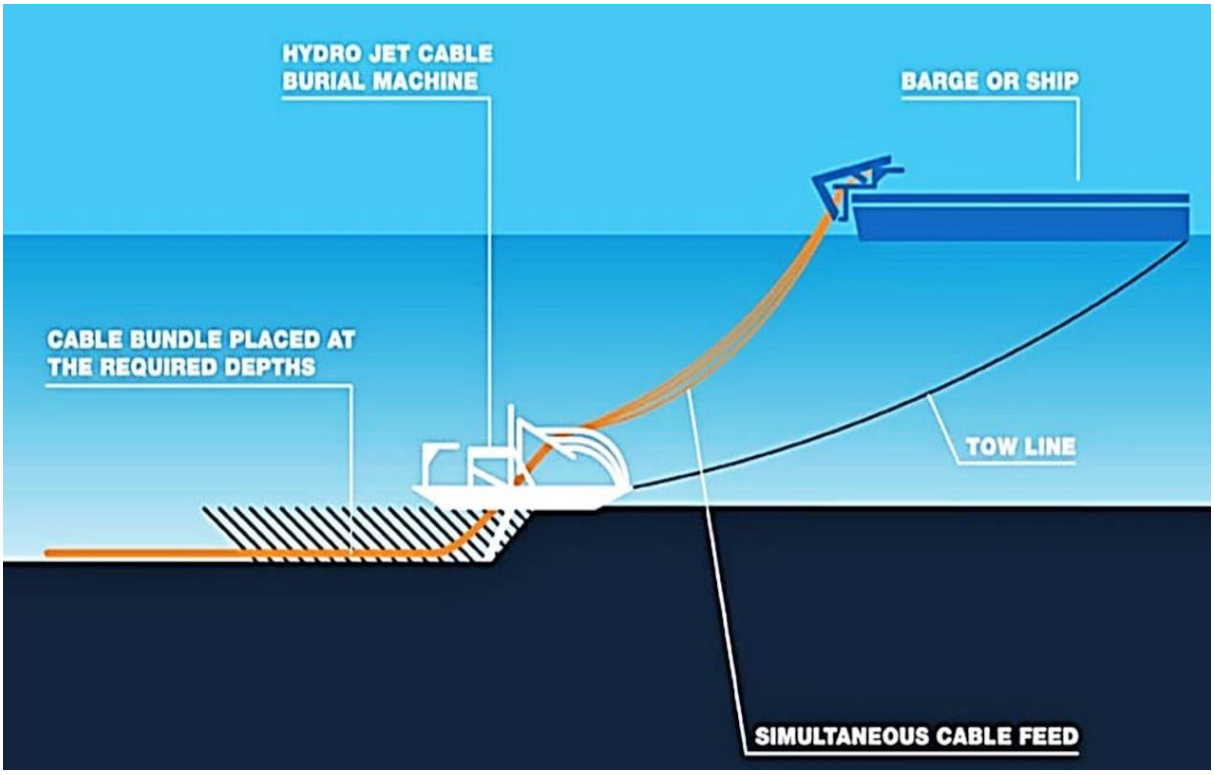


Figure 51: Submarine transmission cable installation[81]

The cable laying process involves coordinated work through specialists from different fields, such as marine specialists, marine engineers, structural engineers, geophysicists, oceanographers, geologists, etc. The component of survey too is important before the cable laying. Special structural engineers have the responsibility of executing the cable-laying work on the seafloor. For shallow waters divers might be deployed to assist the installation while for deep water remotely operated vehicles (ROVs) are manipulated. This work is done with the help of acoustic instruments such as echo-sounders and accurate Global Positioning System (GPS) and differential GPS.

[79] https://electrical-engineering-portal.com/installing-submarine-transmission-cable
[80] https://electrical-engineering-portal.com/installing-submarine-transmission-cable
[81] Installing a submarine transmission cable, how they do it, By Edvard, Electric Engineering Portal , September, 11th 2017, https://electrical-engineering-portal.com/installing-submarine-transmission-cable

The ROVs dig the trench in which the transmission cable is laid, fix the cable on the right route, and cover the cable with sediment. Burying the cable in the seabed is a slowly and costly operation but it is paid back by its reliability and extended lifetime.

The main threats to a submarine transmission cable are external impacts due to predominantly anchors and fishing gears. To minimise the risk of a cable tear due to a vessels' anchoring, a "cable protection zone" or CPZ is established along the cable's path. These zones are legally defined and marked on nautical charts. In these areas activities that might damage or harm the cables are strictly regulated and controlled.

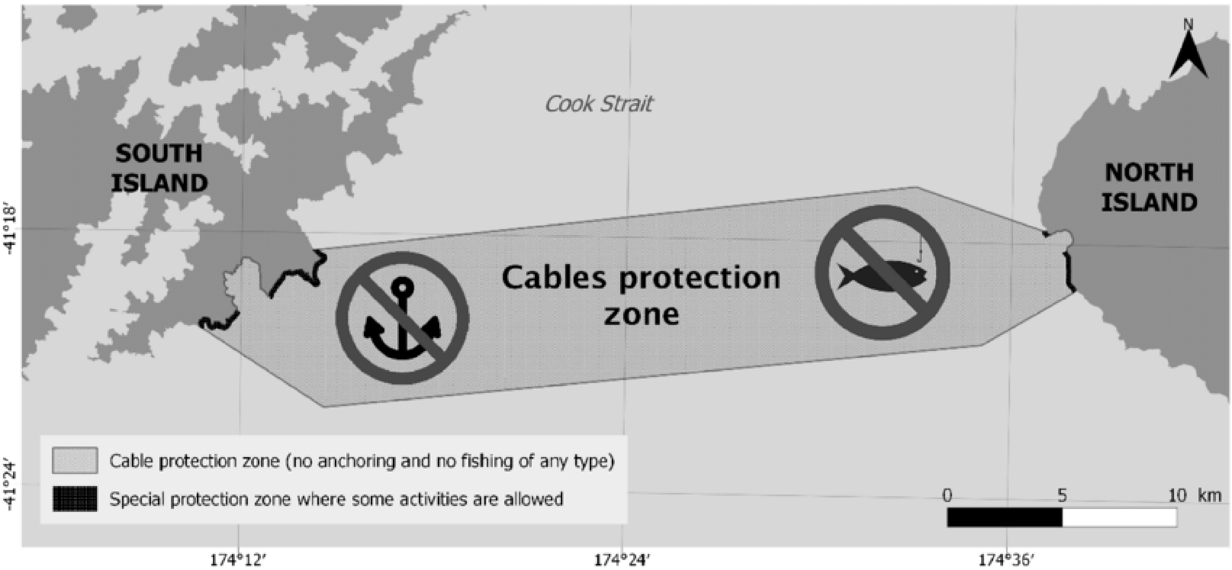


Figure 52: Cable protection zones[82]

Some points for reference with respect to cable laying in marine environment[83]

- The rate at which the cable is laid down depends on the type of the cable, the complexity of the cable configuration, the depth, and properties of the seafloor (heterogeneous bathymetry and geology).
- Due to the size of the transmission cable and the volume of work, which is usually bigger, power cables are installed at a lower rate. For power cables the average burial speed is about 0.2 km/h and depends largely on the seabed conditions
- The depth of the trench is usually of 1 m, only exceptionally more, up to 10 m. With increasing size of ships channels will have to be dredged or deepened.
- So in places the cables must be protected for such future works they have to be buried at a safe depth in the sediment. This is the case of the 30 km power transmission cable that connects the Malaysian island of Pulau Ketam with Port Klang which was buried 14 m under the seabed.
- The cables are buried in the seabed sediment up to depths of 400-600 m, below this depth they are simply laid down on the bottom of the sea. In places with strong sea currents or steep slopes they are fastened to the seabed.
- In order to check the cable security periodic surveys are envisaged.

[82] Potential impacts of submarine power cables from marine renewable energy projects on benthic communities, by Bastien Taormina, Institute of Marine Research in Norway, December 2019, DOI:10.13140/RG.2.2.31061.04326, Thesis for: PhD. Publication reference sourced from the following link of Research gate (As on 17.02.2023) https://www.researchgate.net/figure/Protection-zone-of-three-SPC-and-one-fibre-optic-cable-situated-across-Cook-Strait-New_fig8_345330154
[83] Installing a submarine transmission cable, how they do it, By Edvard, Electric Engineering Portal , September, 11th 2017, https://electrical-engineering-portal.com/installing-submarine-transmission-cable

d) Offshore substation installation

Offshore substations — the systems that collect and export the power generated by turbines through specialized submarine cables — are an essential component of offshore wind farms, especially at large, multi-megawatt sites.

The early substations for offshore wind farms consisted of simple topside frames with basic modules installed on top or as a covered deck. These structures were intended to operate unmanned and required few visits from personnel. In many cases, these substations weighed as little as 400 tons. With the advancement in this, these structures weigh upwards of 10,000 to about 22,000 tons. These substations are more fully developed and consist of a topside or a deck installed on monopole or jacket structures. Options today include self-floating and self-installing structures that eliminate need for expensive marine lifts or cranes.[84] However, in the early state of India's OSW industry, this may not be the case. Being one of the heaviest components an offshore substation may need dedicated facility onshore as well to handle it, carry it, lift it and install it. The feeder barge loads and fastens components (monopile or topside) on deck at port using the port crane. The default time for fastening each component to deck varies. Careful logistical planning is the key.

The topside will be fully fabricated and assembled onshore. Once it is ready for the load-out, the topside is transported from the fabrication shop or assembly area to the dockside to perform the load-out onto the installation barge. Loadouts are usually performed by means of SPMTs. There are alternative methods like skid tracks or crane depending on their availability and final weight of the Topside.

The following parameters will affect the requirement for the load-out stage.

- Topside weight
- Tidal range
- Quayside dimensions
- Barge freeboard

e) Array cable laying

Inter array cables – or the subsea cables linking one offshore wind turbine to another. Nowadays, the array cables are typically of 66kV and in some cases going upto 132kV, whereas earlier it used to be of 33 kV as well. An increase to 66kV and higher voltage means more capacity can be connected whilst reducing cable lengths and switchgear bays (on substations).

There will be a host of accessories and design options dependent on the project, whilst protection for the cables (both during and after installation) is also essential. to determine route and identify seabed conditions, route clearance, transporting the cables to site, cable-laying vessels, cable burial, cable pull-in (to the turbine, substation, or shore), electrical testing and termination, and cable protection systems, etc. would need dedicated vessels, including survey vessels, installation vessels, and O&M vessels as well.[85]

[84] Article on, "Making of the modern offshore substation", October 26, 2016, by Michelle Froese, By Maryruth Belsey Priebe, IQPC GmbH, Wind power engineering development. Web link visited as on 17.02. 2023 https://www.windpowerengineering.com/making-modern-offshore-substation/

85 https://kis-orca.org/renewable-energy/windfarms-overview/wind-farms-installation-methods/

5.4.5 Areas within a port and their use during the power evacuation works.

The present study focuses on transmission and power evacuation; the three stages highlighted in blue are of significance. Of the various activities, the transmission and power evacuation would involve cable laying, the construction of offshore substations, the array cables, etc. An OWF would involve various sub-activities within these. The identified potential ports should be able to cater to these requirements.

Table 22: Need of ports across various stages of OSW projects.

Stage	Activities which are port-dependent
Planning (including design, development and consenting)	Survey vessels, test areas, installation of wind measurement equipment
Manufacturing and procurement	Loading, unloading and storage of main components (turbine, foundations, cables, etc.) to/from production facilities. Fabrication of substation (foundation and topsides). Export, import and transhipment of components;
Installation	Pre-assembly and staging of turbines and foundations;
Operation and maintenance	Berthing of O&M vessels, hosting of spare parts storage and crew charter;
Decommissioning and disposal	Break-up and recycling
Note: the blue colour text indicates the stages and activities involved in the power evacuation works	

For reference, a diagrammatic representation of port plan (for installation) is provided below to understand, which portion/area of the port layout would be of significance from the power evacuation purpose.

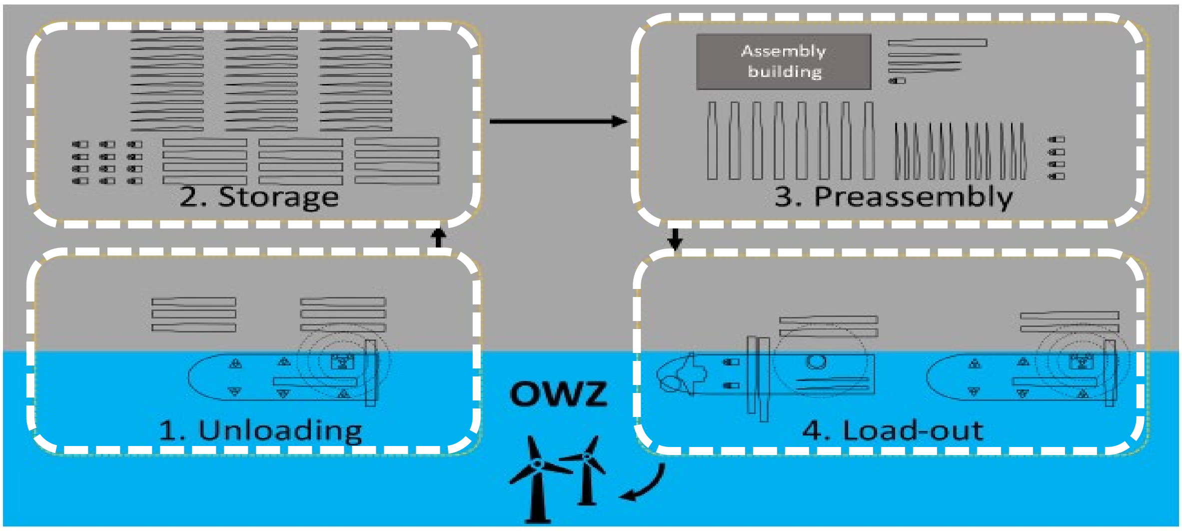


Figure 53: Diagrammatic layout for an installation port[86]

[86] Offshore Wind Port Infrastructure Study for India An assessment of existing ports to serve the installation and O&M of offshore wind projects in Gujarat and Tamil Nadu, Centre for Excellence for Offshore Wind and Renewable energy, 19 November 2022

5.4.5.1 Handling and Logistics

Considering power evacuation component, the electrical works, offshore substations, fixtures, cable laying, etc. the installation port may be suitably adapted while planning and developing. The port plan must integrate these requirements of power evacuation in an installation port. While the diagram shown above is representative in nature, an actual installation port which is considered for power evacuation activities and subsequent O&M must address the need of these activities.
In general terms, a typical offshore wind terminal can be divided into four zones, each with a distinct function. The following points attempt to address the utility-wise aspects of power evacuation works that are covered under these areas of a port.

- **Unloading and loading area**
  In includes,

  - The unloading of secondary components (fixtures, electric components, etc.), inspection and subsequently moving it to the storage (in buildings, if weather sensitive).
  - If any components that are pre-assembled, the loading is carried out.

- **Storage area**
  - Storage of the cables, fixtures, parts and equipment for substations, and tools required for installation and laying and O&M spare-parts.
  - Sub-assembly of secondary components if any in a closed space.
  - Warehouse and administration buildings may also be in this area.

- **Pre-assembly area**
  - If any pre-assembly is involved or certain parts are to be placed before the substation is installed in the sea.
  - Quality control walk-down and hand-over documentation.
  - Pre-commissioning, where systems are verified for functional operability to achieve readiness for the commissioning (and shorten the duration of the process in offshore environment).

- **Loadout area**
  - Load-out (loading components onto the installation vessel)

The functions of the pre-assembly area and the load-out area can be merged where the berth space is limited. The important aspect is of the scheduling of vessels which must be suitably coordinated to avoid any interference with any other operation. The layout of these areas can be suitably done based on the project as it varies on a project-to project basis. This is to be considered when a port is already handling other products and goods.

Of all the major components involved, the power evacuation has two major components, viz. the handling of cables and substation

- **Handling and transport of export cables**

  Export cables, which connect the offshore substation to the onshore substation, and array cables, which connect individual WTGs to the offshore substation, are usually directly transported in cable installation vessels from the manufacturing site to the offshore wind farm for installation. Although relatively shorter distances for the shipment of export and array cables from manufacturing site to the OWF can provide a minor reduction in the overall development costs of an OWF, it is expected that the significant investment required for developing new specialized cable manufacturing facilities directly in the region will greatly outweigh any potential savings on shipping costs.[87]

- **Handling and transport of substation**

The substation topside is generally transported directly from the manufacturing port to site. In some cases, foundation components are stored on barges at the installation port, not using any of the staging area. The size and weight of the components vary, depending on project specific conditions (water depth, soil conditions, and proposed capacity). Along with this, the product type and the manufacturer also play a role.[88]

5.4.6 The acceptable and recommended features for ports and harbours for O&M

The study also highlighted the features for ports and harbours for operations and maintenance. A certain criterion may be required to be met to have effective operations.

The following table highlights the features a port and harbour for O&M should have. These are indicative and may be useful in assessing the suitability of a certain port with respect to OSW.

Table 23: Indicating the acceptable and recommended features for ports and harbors for O&M[89]

Property	Unit	Acceptable	Recommended
Distance to OWF	Km	<100	<50
Depth at channel (entrance) at MLLW	M	4+	6+
Harbour entrance width	M	15+	50
Presence of lock/gate	y/n	Tolerable	Preferable No
Vertical clearance	M	15+	>20
Turning circle	M	40	60-75
Depth at berth	M	4+	6+
Adjacent area	ha	0.5	0.75-1.5

[87] Offshore Wind Port Infrastructure Study for India- An assessment of existing ports to serve the installation and O&M of offshore wind projects in Gujarat and Tamil Nadu, Centre for Excellence for Offshore Wind and Renewable energy, 19 November 2022

[88] Offshore Wind Port Infrastructure Study for India- An assessment of existing ports to serve the installation and O&M of offshore wind projects in Gujarat and Tamil Nadu, Centre for Excellence for Offshore Wind and Renewable energy, 19 November 2022

[89] Offshore Wind Port Infrastructure Study for India an assessment of existing ports to serve the installation and O&M of offshore wind projects in Gujarat and Tamil Nadu, Centre for Excellence for Offshore Wind and Renewable energy, 19 November 2022

5.4.7 Candidate ports for offshore wind in Tamil Nadu and Gujarat

The feasibility of a port to carry out offshore wind logistics and handling depends on its current characteristics, capacity, and design, if it is not a dedicated port for offshore wind. However, if a port is to be suitably developed or redeveloped in a manner that it becomes capable enough to carry out the services described above, in the earlier subsection.

The earlier studies for port infrastructure and logistics, identified a few ports from both the states, and have also highlighted the improvisation required. The following tables describe about this. These are suggestive of offshore based processes of installation and other services. However, utilising these ports in a dedicated manner would need much of attention to the port planning and redevelopment.

Table 24: Candidate ports for Tamil Nadu offshore wind[90]

	Tuticorin Port	Vizhinjam Port
Status	- Proximity to the Tamil Nadu OWZ - Current master plan of the port does not indicate any area dedicated for an OW terminal.	- Vizhinjam Port located to the north-west of the Tamil Nadu OWZ is located adjacent in Kerala State and is currently under development. - The port has good connectivity to highways. - The master plan features a proposed rail connection as well. - Currently, the master plan does not consider development of an OW terminal
Improvement suggested	- Extensive dredging, construction of concrete grid-connected-pile supported quay and berths, and seabed strengthening for WTIV jack up support	- Extensive dredging, construction of concrete grid-connected-pile supported quay and berths, and seabed strengthening for WTIV jack up support.
Other suggestion/s indicated	-	- To utilise the port's existing plans for phased development to the advantage of developing an OW terminal. - This could be achieved by building the next phase of pile supported quay deck to handle the significantly higher loading capacity needed for OW and omitting the final paving. - As the container yard grows over time due to increased demand, the OW terminal could, over time, also be pushed further south. - As the development is already planned for the container terminal development, an OW terminal would only require relatively minor additions of a strengthened quay structure and likely seabed strengthening for Wind Turbine Installation Vessel (WTIV) jack up operations at the berth

[90] Offshore Wind Port Infrastructure Study for India- An assessment of existing ports to serve the installation and O&M of offshore wind projects in Gujarat and Tamil Nadu, Centre for Excellence for Offshore Wind and Renewable energy, 19 November 2022

	Tuticorin Port	Vizhinjam Port
Specifications suggested	- Berth length: 900 m - Yard area: 50 ha - Indicated duration: 30 months. - Indicated cost: 961 INR Crore/117 Mill USD	- Berth length: 450 m - Yard area: 18 ha - Indicated duration: 21 months. - Indicated cost: 732 INR Crore/89 Mill USD

Table 25: Candidate ports of Gujarat[91]

	Hazira Port	Pipavav Port
Status	- Located in the east of the Gujarat OWZ is a multi-use port that is operated in conjunction with Adani Group, Gujarat Maritime Board and Shell.	- Located directly adjacent to the Gujarat OWZ - A multi-use port and follows the public-private-partnership model
Improvement suggested	- Extensive dredging, construction of concrete grid-connected-pile supported quay and berths, and seabed strengthening for WTIV jack up support.	- Minor dredging, construction of concrete grid-connected-pile supported quay and berth, and seabed strengthening for WTIV jack up support.
Other suggestions/s indicated	- It is noted that the master plan for Hazira Port currently does not consider development of an OW terminal	- The port master plan currently does not consider development of an OW terminal. - The study by DEA considers redevelopment of an existing coal berth (Berth1) that is expected to be closed in the coming years with ultimate redevelopment as a container berth.
Specifications suggested	- Berth length: 600 m - Yard area: 35 ha - Indicated duration: 24 months. - Indicated cost: 760 INR Crore/92 Mill USD	- Berth length: 330 m - Yard area: 28 ha - Indicated duration: 21 months. - Indicated cost: 622 INR Crore/75 Mill USD

Multiple O&M ports were identified for both the Tamil Nadu and Gujarat OWZs. For Tamil Nadu OWZ both Kudankulam and Muttom are viable options with respect to distance, sheltered area, ease of navigation, water depth and yard area.[92]

For Gujarat OWZ, Pipavav is a viable option due to its proximity and since it presents enough water depth and easy access for vessels, as well as a sheltered area (which is not present at the other locations), local industry, and hence more likely access to qualified workforce.
The study also provides a brief on the marshalling terminals as well. For development of OW ports adjacent to the Gujarat and Tamil Nadu OWZs, it indicates that the idea of adopting the so-called "Developer driven model" for the initial offshore wind projects can be worked out. The so-called

[91] Offshore Wind Port Infrastructure Study for India an assessment of existing ports to serve the installation and O&M of offshore wind projects in Gujarat and Tamil Nadu, Centre for Excellence for Offshore Wind and Renewable energy, 19 November 2022
[92] Offshore Wind Port Infrastructure Study for India An assessment of existing ports to serve the installation and O&M of offshore wind projects in Gujarat and Tamil Nadu, Centre of Excellence for Offshore Wind and Renewable energy, 19 November 2022

"Cluster model" has many interesting features and benefits and could be a potential model to consider as the build-out rate increases together with firm investor confidence.

5.5 Requirements of Service providers

Connection to the port facilities becomes an essential component to bring the network of movement and execute the activities in the sea. The lifecycle of an offshore port project has various stages under which the vessels that are used are different and very specific to the activities. The vessel types for installation services are described below.

5.5.1 Types of vessels

The types of vessels required for installation services consist of the following:

- Tugs & barges for shore landing services and transport services of offshore pieces.
- Heavy lift capable vessels for handling and installing offshore structures, deployment of generator assemblies and associated piece parts.
- Cable lay capable vessels for laying and burial of power cables required for inter-field connection and power transport to shore.
- Sub-sea capable vessels with ROV or diving assets to perform inspection services of the subsea plant.[93]

Based on the vessels required in different phases, it may be a survey vessel- required for geotechnical, geophysical, and environmental survey; Logistics vessel of diverse kind; personnel transfer vessels and Heavy maintenance vessels.

5.5.2 Stages and vessels

The vessel-based activities during the construction and O&M stage are described below.

Lease award and Pre-construction

Once a developer has obtained a lease, they will start to appraise the zone or lease area. This requires several surveys to be completed including boat or aerial based bird and marine mammals' surveys, benthic grabs, and fish surveys.

In addition, data on meteorological factors such as wind speeds, tides and waves are collected, usually through a met mast and wave buoys. This data is used to help the wind farm developer to design the project and help support the consent application.

Once the consent is granted more detailed geotechnical and geophysical surveys will be undertaken. In this stage, there will be increased vessel traffic on site as survey activity is completed on the potential site and cable route. A met mast fixed structure may also be installed. There may also be floating wave buoys or in the future floating wind speed measuring devices called LIDAR.[94]

5.5.2.1 During construction

Once a wind farm enters construction there will be multiple activities, with the potential for up to 50 boats to be working on the wind farm at any one time. During construction a 500m rolling safety zone is placed around the main installation vessels.

[93] https://cdn.b12.io/client_media/n8KzZTRM/b0590e9e-d2e8-11eb-be12-0242ac110002-Energy_Ocean_08_3U_Technologies_080619.pdf
[94] https://kis-orca.org/renewable-energy/windfarms-overview/wind-farms-installation-methods/

The types of vessels could include:

- *Substation Installation Vessel* – often a heavy lift crane vessel. This transports and lifts the substation onto the pre-installed foundation.
  Offshore substation installation is a heavy lift operation (2,000t plus) requiring vessels with sufficient crane capacity. Vessels with the necessary lift capacity typically do not have the deck space to accommodate a substation platform. The substation is therefore floated out of the substation fabrication facility on a barge, usually directly to the wind farm site. The substation foundation, which is installed prior to the topside structure, may be a monopile or a jacket and the installation may form part of the turbine foundation installation package.

Figure 54: Substation installation vessels[95]

- *Foundation installation vessel* – the type of vessel used will vary with foundation type. For monopiles and jackets the most common type of vessel are purpose designed jack up vessels. These vessels will often transport the foundations from the quay side to the site and secure them to the seabed, usually by piling. Gravity base foundations are perhaps easier to install and can use less specialist barges to put them in position.

[95] Image sourced from reNews Biz.com. The news article showed image of Parkwind, 50Hertz install Arcadis Ost substation, 2380t platform was installed by the Scaldis crane ship Gulliver on its monopile foundation in the Baltic Sea, 15 June 2022 [Image: 50Hertz]. The reference link was visited as on 17.02.2023.
https://renews.biz/78468/parkwind-50hertz-install-arcadis-ost-substation/

Figure 55: Installation Jack-up96

- *Array and export cable laying vessels* – Although the same vessel can be used for both, the export cable is larger and so requires a bigger carousel. Barges can be used although it is becoming more common to see large purpose-built dynamic positioning vessels. The cables are usually ploughed into the seabed, although in more difficult terrain Remotely operated vehicles (ROVs) or mattressing /rock dumping can be used.

Figure 56: Longest submarine cable laying[97]

[96] HMSJU 178: DP 2 Windfarm Service / Installation Jack-up/Construction Jack-up, Harmony Marine Shipbrokers. The reference link was visited on 17.02.2023. https://www.hmsbroker.com/vessels-for-charter/windfarm-turbine-installation-jackup/

[97] Nexans Delivered North America's Longest Submarine Cable to Provide Cleaner Energy to Eastern Canada, Nexans Skagerrak on the Beatrice Offshore Wind farm, Jan 18, 2018, Weblink: https://www.nexans.com/en/newsroom/news/details/2018/01/Nexans-Delivered-North-America-Longest-Submarine-Cable-to-Provide-Cleaner-Energy-to-Eastern-Canada.html

Laying down the transmission cable on the seafloor is done by specialized vessels. The most active vessels used for such operations are Skagerrak (owned by Nexans), Giulio Verne (Prysmian), Team Installer (Topaz Energy and Marine) and C.S. Sovereign (Global Marine Systems Ltd). They are all equipped with a turntable and have the appropriate gear to handle it.
Array cables interconnect wind turbines with the offshore substation. With the increasing size of wind turbines, the cable sizes are increasing too, and array cables are typically 66kV nowadays. Installing these cables is a delicate task and requires the right asset.

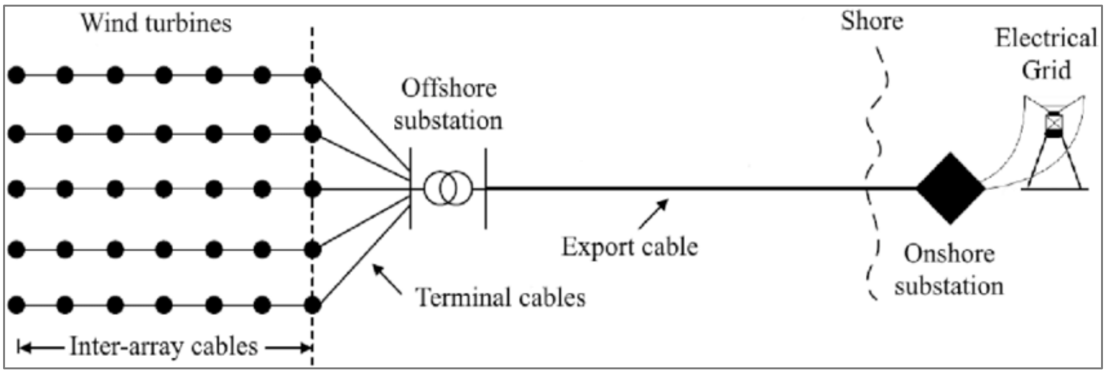


Figure 57: The difference in array cables and export cable in use (*only for representation purpose)[98]

As inter-array cable installation vessels spend most of their time offshore installing cables, they are built with a state-of-the-art cable lay system specifically designed for repeating installation sequences of large amounts of array cables, including the latest cable protection systems.

The vessel represents just a part of the required gear needed for laying down the cable. It carries the cable and stands for the command centre. But once the cable is in the water other submersible equipment performs the task of settling the cable on its path.

- *Sea-based support* – a range of vessels are used to support the installation process. These include crew vessels, anchor handling, barges, dive support and ROV handling.99

Construction and transport may also be carried out through barges. A barge is flat bottom boat used to transport heavy bulk cargoes as well as in offshore construction. Barges are either ocean-going or river barges, and they are typically non-self-propelled vessels. Barges are either construction or transport barges. Construction barges are used in offshore construction projects, including in offshore wind installation. These barges typically have cranes on board, either permanently mounted, or temporary ones that are loaded on board for a specific operation.

Transport barges are built to transport heavy cargo. Their open design makes the loading and unloading of large-sized and unusually shaped cargoes relatively easy. Barges are a comparably cheap option to transport supplies and wind turbine components from a staging port to the

[98] Original paper on "Parametric study of dynamic inter-array cable systems for floating offshore wind turbines", January 2020, Marine Systems & Ocean Technology 15(1), by *Manuel U. T. Rentschler, Frank Adam, · Paulo Chainho, Kilian Krügel and Pedro C. Vicente,* DOI:10.1007/s40868-020-00071-7.
Marine Systems & Ocean Technology https://doi.org/10.1007/s40868-020-00071-7
Weblink visited: https://www.researchgate.net/publication/338743324_Parametric_study_of_dynamic_inter-array_cable_systems_for_floating_offshore_wind_turbines

[99] https://kis-orca.org/renewable-energy/windfarms-overview/wind-farms-installation-methods/

offshore wind installation site. Compared to supply vessels and TIVs, transport barges are much slower and more sensitive to bad weather.

Figure 58: A barge carrying the parts and equipment – Port feeder barge[100]

5.5.2.1 During operations & maintenance

Various activities that are involved in the O&M stage include, configuration of a substation, its access points, and storage areas for maintenance equipment are important when considering the design for use at an offshore wind farm. These factors impact how often a substation may require servicing and its accessibility. But the factors are also difficult to assess because of extreme weather conditions and vibrations an offshore substation must endure, so routine O&M is typically a guess.

The site will be serviced by smaller crew transfer vessels, typically up to around 24m long and carrying 12 technicians. Technicians traditionally access turbines by vessels pushing up against the turbine ladder and a technician will then step across. New access techniques are being developed now.

Occasionally more major maintenance work may be carried out. This will require a larger installation vessel.

Vessels are not allowed to anchor or fish in this area and the protection zone is constantly monitored from sea or air. Such infringements can be avoided by effective monitoring which leads to a 'no fault' situation due to human activity

[100] Assessment of Vessel Requirements for the U.S. Offshore Wind Sector, prepared for the Department of Energy as subtopic 5.2 of the U.S. Offshore Wind: Removing Market Barriers, 24th September 2013

Figure 59: Vessels for array cable and export cable laying[101]

The cable laying process involves dedicated vessels, but the sub-site level laying differs for array cable and export cable. A representative image for the same is provided above.

The O&M vessels may differ in terms of its use and handling facilities. A typical O&M vessel would take the equipment and personnel to the site of maintenance and deploy the necessary actions.

Figure 60: Operation and Maintenance vessel at the site[102]

[101] Article on "How do cable lay vessels work?", by Sarah Whileford, Onestep power, March 5, 2021. Reference visited as on 17.02.2023. https://www.onesteppower.com/post/cable-lay-vessels

[102] Article from renews. Biz, "Offshore O&M spend to hit '€11bn by 2028', Wood Mackenzie research says biggest portion is related to turbine problems", 12 June, 2019, [Image: reNEWS]. The reference link was visited on 17.02.2023. https://renews.biz/53689/offshore-om-spend-to-hit-11bn-by-2028/

5.6 Best practices for Environment management

Offshore wind industry being at the nascent stage in the country, it is necessary to highlight the larger policy and institutional framework governing the ocean infrastructure in general and offshore wind energy. Both the Union Government and the state governments in the country govern the marine resources. While the National Offshore Wind Energy Policy 2015 and the Draft Offshore Wind Energy Lease Rules 2019 refer to direct environmental and social considerations concerning offshore wind energy deployment in the country, there are other laws and regulations governing the marine environmental systems that have a bearing, albeit indirectly, on the offshore wind energy deployment in the country. However, offshore wind energy projects have never been developed in the country before, thus, it needs a thorough review of the processes to give environmental clearances to the project and verify and validate its operations in line with environment, safety, and inclusivity once the project reaches its execution stage.

Given the study's focus on power evacuation component and roadmap for transmission, the targeted capacity of 30 GW would cause some impacts. The earlier sections describe about the port led activities and the sea-based activities. At a broader level, the impact from subsea cable laying, array cable laying, substation installations, and all the onshore activities to support the sea-based activities would lead to some effects on the environment. While it can be only assessed at macro-level about the possible effects, this section attempts to describe the possible effects, and how are they mitigated.
This would help refer to the best practices, mitigation measures and how it can be suitably adapted in case of India.

5.6.1 Possible impacts

There are three major works which are part of the power evacuation component. These are the submarine cable laying, array cable laying and substation installation.

However, broadly the impacts can be categorised based on the stage.

- Impacts during port logistics.
- Impacts during foundation installation.
- Impacts during cable-laying installation.
- Environmental impacts of the operation and maintenance stage

5.6.1.1 Impact due to Port logistics[103]

- Port logistics comprise several specific transportation activities; for instance, the transport of equipment and turbines is responsible for increasing the vessel traffic and generating loud noises, affecting other economic activities, as well as the biodiversity.
- Increased marine traffic affects activities such as fishery and the marine transport of commodities and other manufactured goods.
- Loud noise might cause hearing damage and, in some cases, hearing loss in marine mammals.
- Increased vessel traffic might cause loud noises, for instance, due to the emitted noise by propeller cavitation (source level < 180 dB at 1 m distance).
- Background noise in the long term might cause cumulative effects in masking communicative abilities. Additionally, a reduction of marine mammal populations due to the high density of sensitive resident marine mammals

[103] O. Mauricio Hernandez C, Milad Shadman, ∗, Mojtaba Maali Amiri, Corbiniano Silva, Segen. Estefen, Emilio La Rovere, Environmental impacts of offshore wind installation, operation and maintenance, and decommissioning activities: A case study of Brazil, Renewable and Sustainable Energy Reviews

5.6.1.2 Impacts during foundation installation[104]

- Offshore substations need to have base supports and so a foundation is crucial to it.
- Foundations may cause impacts on the submarine environment, including seabed morphology, biodiversity (benthic flora and fauna, fishes, and marine mammals), and economic activities (principally fishery). For reference, indicate pile driving as the most critical activity generating loud noise that may cause behaviour or habitat disturbances.
- The sounds of pile driving might reach 228 dB in situ and 189 dB at 400 m away from the site.
- Although these impacts are temporary and occur for a few days per turbine, their cumulativeness could cause hearing damage or loss on fishes and marine mammals.
- It is also possible that cumulative impacts caused by more than one wind farm on the population levels, might affect marine mammals.
- foundation installation also includes removing and modifying the seabed. Those activities may release particles, causing habitat disturbances as sediment dispersal and sedimentation, principally because of gravity foundations. These disturbances might affect submarine geomorphology and the benthic flora.

5.6.1.3 Impacts during cable-laying installation

There are three cable-laying techniques: trenching, burial, and rock dumping. However, the environmental analyses in the literature use a generic term denominated cable trenching.

- In a trenching activity, specialized vessels or barges clean and excavate the seabed and then bury the cables about one meter into the seabed.
- The process may increase water turbidity and may cause sedimentation or modify superficial layers of the seabed. Trenching activities may cause direct habitat loss, principally benthic flora, and fauna.
- The export cable laying would involve off-take from offshore to onshore, which may also affect the coral reefs and the mangroves. This becomes important for both the states, Tamil Nadu, and Gujarat.

Marine power cables are specifically designed to transmit electric currents either as Alternating Current (AC) or Direct Current (DC). Monopolar, bipolar, or three-phase systems are different technical solutions in use. Depending on their design the diameter of power cables may vary. This would decide on the buffer zone left around the cables.

Potential environmental impacts associated with subsea cables are disturbance, underwater noise, heat emission, electromagnetic fields, and contamination (OSPAR 2008a, 2009, 2010) including release of nutrients.[105] Across different stages, the environmental impacts of submarine cables may occur. It may happen during their laying, operation, and removal as well as in the case of accidents. Based on the site, and as a part of detailed environmental impact assessment, the nature, extent, and significance of these potential impacts can be determined.

The specific impacts which can be identified at macro-level include,

- Disturbance by the placement of cables
- Underwater noise

[104] O. Mauricio Hernandez C, Milad Shadman, Mojtaba Maali Amiri, Corbiniano Silva, Segen. Estefen, Emilio La Rovere, Environmental impacts of offshore wind installation, operation and maintenance, and decommissioning activities: A case study of Brazil, Renewable and Sustainable Energy Reviews
[105] Guidelines on Best Environmental Practice (BEP) in Cable Laying and Operation, (Agreement 2012-2), (Source: OSPAR 12/22/1, Annex 14), OSPAR Commission.

- Heat emission of power cables
- Electromagnetic fields generated by power cables.
- Contamination
- Cumulative effects

5.6.1.4 Environmental impacts of the operation and maintenance stage[106]

The O&M stage is a long-term one, lasting about 20 to 30 years.

- The O&M stage includes power generation (including the parked situation, when there is no power generation, caused by extreme conditions), submarine energy transmission, and maintenance.
- It may include the overall impacts, including acoustic disturbance, habitat gain, electromagnetic fields, and fisheries exclusion areas, caused by an OWF on the marine environment during its operation.

5.6.1.5 Impact during submarine energy transmission[107]

- Submarine transmission may affect the marine environment through transmission cables during the operational stage.
- As a positive impact, the transmission cables can act as an artificial reef, attracting marine life and increase diversity. On the other hand, the electromagnetic field may cause behavioural disturbances such as avoidance or poor hunting performance in demersal and benthic fish species.

5.6.1.6 Impacts during maintenance[108]

- Lubricant and fuel spills–which cause water pollution and, consequently, a decrease of vulnerable species, are the most important impacts of the maintenance activities.
- The introduction of alien species may affect marine mammals and fishes because of competition for feeding, reproduction, or breeding, causing local extinction.
- The disturbance over communities predated by birds might disturb bird populations. It might also cause fishery collapse, affecting the local communities that depend on it.

The following section attempts to provide reference guiding points on the best practices for environmental management. To understand this better, the "Guidelines on Best Environmental Practice (BEP) in Cable Laying and Operation by the OSPAR Commission", by OSPAR Commission[109] has been referred. It describes about the possible impacts related mitigation measures.

The table below shows the activities which are to be planned, monitored and managed as a part of mitigation measures.

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[106] O. Mauricio Hernandez C, Milad Shadman,, Mojtaba Maali Amiri, Corbiniano Silva, Segen. Estefen, Emilio La Rovere, Environmental impacts of offshore wind installation, operation and maintenance, and decommissioning activities: A case study of Brazil, Renewable and Sustainable Energy Reviews
[107] O. Mauricio Hernandez C, Milad Shadman,, Mojtaba Maali Amiri, Corbiniano Silva, Segen. Estefen, Emilio La Rovere, Environmental impacts of offshore wind installation, operation and maintenance, and decommissioning activities: A case study of Brazil, Renewable and Sustainable Energy Reviews
[108] O. Mauricio Hernandez C, Milad Shadman,, Mojtaba Maali Amiri, Corbiniano Silva, Segen. Estefen, Emilio La Rovere, Environmental impacts of offshore wind installation, operation and maintenance, and decommissioning activities: A case study of Brazil, Renewable and Sustainable Energy Reviews
[109] Guidelines on Best Environmental Practice (BEP) in Cable Laying and Operation, (Agreement 2012-2), (Source: OSPAR 12/22/1, Annex 14), OSPAR Commission.

5.6.2 Mitigation measures

Certain mitigation measures may be very specific to a stage, while certain are possible to be applied across different stages and activities. This section attempts to highlight on suitable mitigation measures which are among the best practice suggested from the experience of other places. It emphasises on the cause and effects and how the effect can be minimised.

5.6.2.1 Disturbance by placement of cables

To mitigate the effects of disturbances, the route selection and route planning can be carried out suitably. Selecting the route (including landfall) with the lowest environmental impact and highest resource efficiency by comparing different alternative routes based on sound and comparable data (avoiding sensitive areas, etc.) is one of the most important steps towards realising best environmental practice of a cable project.

When selecting a route corridor, it is necessary to consider engineering issues as well as

environmental concerns, such as existing protected areas and other ecologically important and sensitive areas, and other uses, such as existing cables, offshore wind farms, shipping, dumping sites, natural resources (e. g. sand and gravel extraction sites) and fishery.

While executing it, the following points may be considered to minimise the impact.

- areas which are sensitive, such as protected areas, environmentally sensitive and/or valuable areas with e.g., habitats and species sensitive to physical disturbance or damage where the cable laying activity or operation would result in adverse effects should be avoided;
- the shortest possible length to be chosen.
- bundling with existing cables and pipelines, where it is safe to do so.
- minimal number of crossings with other cables or pipelines to reduce the number of crossing structures.
- After a route corridor has been selected, an appropriate level of site investigation is essential to ensure that the optimum route and burial methods are selected for the cable.
- Baseline information on the distribution of protected and sensitive habitats and species within the construction area should be used also to plan the positioning of the anchor arrays for the cable-laying ship (BERR 2008). In this way, exclusion zones for anchoring should be established if necessary.[110]

5.6.2.2 Burial technique/Burial depth

The burial technique and burial depth are closely related to each other. Two points play an important role in the selection of the burial technique and/or burial depth from an ecological point of view:

- Reduction of sediment displacement and
- Avoidance of sediment and morphology changes. [111]

[110] Guidelines on Best Environmental Practice (BEP) in Cable Laying and Operation, (Agreement 2012-2), (Source: OSPAR 12/22/1, Annex 14), OSPAR Commission
[111] Guidelines on Best Environmental Practice (BEP) in Cable Laying and Operation, (Agreement 2012-2), (Source: OSPAR 12/22/1, Annex 14), OSPAR Commission

- Reduction of sediment displacement: Where there are species that are sensitive to increases in suspended sediment occurring close to positions of cable burial, it is recommended that the technique that would result in the lowest release of sediment is utilized whenever this is possible (BERR 2008).
- Avoidance of sediment and morphology changes: Morphological changes of the sediment may under certain circumstances occur when cables are laid in soft substrates. Whenever possible, cable should be buried, also to reduce the impacts of heat dissipation and magnetic fields (see below). At the same time the burial techniques applied should resuspend as little sediment as possible so that the trench closes naturally shortly after burial. Otherwise, the trench should be backfilled with on-site or comparable material.

- Construction times: Once the cable route and burial technique have been selected there are limited further measures that can be adopted to reduce sediment disturbance. The precise timing of the works (e.g., over a spring or neap tide) is crucial for tidal flats, where limited time windows and shallow waters require good synchronisation of laying and burial operations. In these cases, burial should take place at low tide with e. g. vibration ploughs whenever possible. Further offshore the speed at which the burial proceeds may have some influence on the sediment disturbance.

  Particularly near the coast, including landfall, it is necessary to specify times of the year during which work should not be carried out since many areas are at certain times of the year habitats of species that react sensitively to disturbances. These include resting grounds during bird migration, wintering and moulting areas of e.g. sea ducks, feeding and coastal breeding habitats, spawning grounds of fish and sandbanks where seals give birth to their young.[112]

5.6.2.3 Underwater noise

There are no clear indications that underwater noise caused by the installation of sub-sea cables poses a high risk of harming marine fauna. There is a potential for disturbance of fish and marine mammals. However, knowledge gaps still exist.

- Route selection and Construction times
  If the route selected is crossing areas especially relevant for species sensitive to underwater noise appropriate scheduling of cable-laying activities to avoid feeding, spawning and/or nursery areas at sensitive times of the year will minimise the potential for noise-related impacts on these species

- Burial technique
  Burial techniques involving substantial noise generation should not be employed. Blasting in rocky subsoil should be avoided.[113]

5.6.2.4 Contamination

- Route selection
  Contamination arising from seabed disturbance is only a risk in heavily contaminated locations. Again, avoidance of such areas would be an appropriate mitigation measure (OSPAR 2009). The application of burial techniques with minimized sediment resuspension in areas where

[112] Guidelines on Best Environmental Practice (BEP) in Cable Laying and Operation, (Agreement 2012-2), (Source: OSPAR 12/22/1, Annex 14), OSPAR Commission
[113] Guidelines on Best Environmental Practice (BEP) in Cable Laying and Operation, (Agreement 2012-2), (Source: OSPAR 12/22/1, Annex 14), OSPAR Commission

sediment is found to have elevated levels of pollutants will minimise pollution risk (BERR 2008).[114]

5.6.2.5 Heat emission

The reduction of generated heat is by far more important regarding power cables than telecommunications cables. Heat dissipation from fibre-optic cables is supposedly negligible even though modern cables are equipped with electrical power supplies (OSPAR 2008a, 2009).

- Route selection
  In general a bundled system of comparable capacities or a coherent marine transmission grid will reduce the number of individual power cables (e.g. linking different offshore wind farms together by using sub-sea cables with a high transmission capacity). In this way the overall space used as well as the total area affected by temperature increase and by other possible physical and chemical impacts will be reduced.

- Burial depth
  The cable-induced temperature increase of the upper layer of the seabed depends, amongst other factors, on the burial depth of the cable. To reduce temperature, rise an appropriate burial depth should be applied.

- Cable Type
  To reduce the environmental impact of thermal radiation, suitable mitigation measures on the choice of cable type can include the use of HVDC transmission systems instead of AC-cables for interconnectors and wind farm-connectors. In addition, the use of a bipolar transmission system instead of two separate monopolar cables will lead to a reduction of the heated area.[115]

5.6.2.6 Electromagnetic fields

- Cable type
  Directly generated electric fields are regarded to be controllable by adequate shielding, e.g., steel plates, sheaths within the cable insulating the conductor etc. However, an induced electric field generated by the magnetic field may occur. In case of high current flows during power transmission the electric fields near the cable significantly exceed values typical under natural conditions.

- Burial depth
  Because the strength of both magnetic and (induced) electric fields declines as a function of the distance from the cable, an additional reduction of the exposure of marine species to electromagnetic fields can be achieved by cable burial. The sediment does not have any screening effect, but burial of the cables reduces the exposure of sensitive species to electromagnetic fields by increasing the distance of the animals to the cable.

5.6.2.7 Contamination

- Cable Type
  Release of contaminants into the environment from the cable itself can only occur if cables are not removed after decommissioning or if operational cables are damaged, if fluid-filled cables are damaged. However, the present technology of XLPE does not have this issue.
- Removal

[114] Guidelines on Best Environmental Practice (BEP) in Cable Laying and Operation, (Agreement 2012-2), (Source: OSPAR 12/22/1, Annex 14), OSPAR Commission
[115] Guidelines on Best Environmental Practice (BEP) in Cable Laying and Operation, (Agreement 2012-2), (Source: OSPAR 12/22/1, Annex 14), OSPAR Commission

After the decommissioning of the projects, the cable may not be removed if the removal involves additional or adverse environmental impacts that roughly correspond to those during construction stage. However, this must be suitably addressed.

5.6.2.8 Cumulative effects

- Strategic planning and route selection
  In general, a bundled system of comparable capacities or a coherent marine transmission grid will reduce the number of individual power cables (e.g. linking different offshore wind farms together by using sub-sea cables with a high transmission capacity). As a result, cumulative impacts are reduced (SCHREIBER et al. 2004). Overlapping of electromagnetic fields is already avoided by virtue of the necessary safe distances between the cables.
- Construction times
  By coordinating construction times, it is possible to avoid reinforcement of impairments due to the burial of several cables either simultaneously or immediately after each other.
- Other measures
  Avoidance of impacts in specific projects will also mitigate or eliminate possible cumulative impacts. This applies to the burial technique, the burial depth as well as the type of cable.[116]

The existing practice In India is described below.

5.6.3 Existing practices for Environment management in India

- *Existing processes and practices in India:*

India has specific set of regulations which are applicable to projects, both, onshore and offshore, however, specifically for offshore wind energy (OSW) projects, there are no such guidelines or rules to be followed for conducting an environmental impact assessment (EIA) study.
The various sectoral projects, for which an EIA study is a mandate have been identified by the MoEF&CC, however, there are two aspects to that.

a) No mandate of EIA study for RE projects to seek clearance. No separate sector specified for RE projects under NABET's list of sectors to conduct EIA study.
b) No specific sector identified by NABET relevant to offshore wind energy projects in the list of sectors which makes it a mandate for the various agencies to have accreditation for that particular sector.

OSW industry being new to India, this comes as among the first set of steps to be addressed, with respect to environmental and social safeguards. Though the absence of a specific sector in the NABET list exists as a gap, the other laws which are assumed to be applicable are described below. The following section attempts to provide a brief on the process for Environmental and CRZ clearance.

- The near coast/marine ecosystems are governed under the Coastal Regulation Zone (CRZ) Act, 2019, especially for the projects proposed and/or implemented in these areas. Under this, the coastal zone management plans are made at the state level. However, the governance is under the purview of the Centre and the States. The state government is responsible for the Coastal zone management plans and setting up the State Coastal Zone Management Authority (SCZMA). The SCZMA is supported by the Coastal Zone Management Committee (CZMC), which functions at the district level. For any CRZ clearance of the Project, the submitted EIA report passes from the CZMC to SCZMA only or may extend further to the CZMA (the central level authority) under the Ministry of Environment, Forest and Climate change (MoEF&CC). The project specificity in terms of area covered, type of activity, and envisaged impact, the

[116] Guidelines on Best Environmental Practice (BEP) in Cable Laying and Operation, (Agreement 2012-2), (Source: OSPAR 12/22/1, Annex 14), OSPAR Commission

project is considered under the purview of the State CZMA (SCZMA) or the Central CZMA (CZMA).

- This process remains similar in case of Environmental Clearance (EC). The Projects are broadly classified as Category 'A' and Category 'B' projects, which are under the purview of the Central and the State authorities, respectively. The Category 'A' projects are mostly the Project with broader scope, wide-spread area of the project site, involves critical processes and activities and/or fall under the jurisdictions which are beyond the state administration. The EIA report is submitted to the State or Central authorities based on this classification. The Category 'A' projects are reviewed by the Expert Appraisal Committee (EAC), which is a central level committee, directly under the MoEF&CC, while the Category 'B' projects are reviewed by the State Expert Appraisal Committee (SEAC). The EIA reports are reviewed by these committees under the respective categories for the Environmental Clearance (EC).
- Category A projects require mandatory environmental clearance and thus they do not have to undergo the screening process. Category B projects undergo a screening process and are further classified into B1 (Mandatorily requiring EIA) and B2 (Not requiring EIA).
- It is to be noted that for those projects which involve the coastal region and/or any activities which are implemented in the regulated zones, the CRZ Act, 2019 is applicable. Under this condition, the project proponent must follow the process which begins with the CRZ clearance and then the Environmental Clearance. This is not the process for land-based activities or activities which do not involve any activities or development in the coastal zones. The CRZ Act has specific set of rules mentioned under the CRZ Rules.
- The framing of these notifications falls under the umbrella legislation of the Environmental Protection Act, 1986 (the EPA, 1986). This includes the Environment Impact Assessment (EIA) Notification, 2006 and the subsequent Amendments of it, as well. Also, the various acts and rules applicable for the safety of the environment fall under the EPA, 1986. Apart from this, the Water Act and the Air Act are applicable separately (since they came in act before the EPA came in).
- It is to be noted that all the Environmental standards for air, water, soil, etc. would be applicable for OSW projects also, with necessary revisions at places where the activities of OSW projects may cause unidentified (at this stage) effects on the aquatic and terrestrial ecosystems.

However, offshore wind energy being a new industry (in India), it lacks any guidelines or notifications which talks specifically about the processes and the impacts. While the sector remains unrecognised in the list of sectors by NABET for EIA to be done, this comes out as a clear indicator that there is a need for identification of a sector which specifically fulfils the needs and requirements for carrying out a detailed EIA like that of for an offshore oil & gas exploration and offshore oil and gas pipeline projects. For that matter, most of the industries including the power plants which generate energy from conventional sources have been identified as a sector for EIA study.
With the current development in OSW industry in India, it needs to be identified as a separate category of industry with specific criteria for environmental consultants for the same. Currently, the environmental consultants practicing under the existing list of sectors by NABET accreditation may not be having a certification to conduct and EIA for an OSW project in India. This may be supported with policies, guidelines, and laws to regulate and implement offshore wind Projects in India.

In spite the lack of guidelines and laws specific to the offshore wind industry, the aspect of environment would be addressed with a similar approach, which is by recognising the activities or sub-projects, which help in the identification of the impacts across various stages. The identification of impacts would be followed by identification of mitigation measures.

5.6.4 Suggestions for better environmental management in OSW projects in India

5.6.4.1 Suggestions to fill the regulation and policy gaps

- To develop environmental guidelines for OSW projects in India
- To establish clear processes and regulations with respect to environmental and CRZ clearance for OSW projects in India
- To introduce a dedicated sector in the list of sectors by the NABET to conduct EIA studies for OSW projects
- To provide necessary training and sensitisation for effective environmental clearances with respect to OSW
- To develop guidelines for occupational safety at OSW project sites.

5.6.4.2 Suggestions for minimising the environmental impacts

- To conduct detail environmental and ecological surveys and studies for the OSW potential zones and the coast of the states to identify possible impacts at macro level with the objective of identifying the sensitive areas which may witness the changes with the planned projects.

It is to be noted that the environmental impacts may pose risk to certain socio-economic indicators of the region. These changes can be short-term or long-term, immediate or gradual in type, severe or moderate, and direct or indirect. While assessing the environmental impacts it is crucial to first establish the linkage to the possible socio-economic impact due to a project. Thus, the social impact assessment remains as important as the environmental impact assessment. The following section attempts to discuss this dimension of OSW projects.

5.7 Best Practices for Social and Gender diversity inclusion

Globally it is a major push to address the sustainability aspects irrespective of the sector or industry dealt with. As described above the necessary steps and efforts in the initial stage of developing the OSW industry in India will pave path of a much-expected sustainability within. Over the years the world may witness major changes across various dimensions of human development given the changes in the climate. Of the various assumed changes, it won't be unrealistic to assume that the vulnerable set of the larger global community would be the most affected, irrespective of an industry project and/or the changes in the climate. The larger implications on socio-economic front would be more witnessed by the vulnerable set of community and settlements.

Generally speaking, within the local community of any Project Affected Region (PAR), a certain set of community such as the elderly, differently abled, women and children would be the most vulnerable ones. Along with this vulnerable set of people, the community which is highly dependent on the local resources for livelihood, food and nutrition, etc. may be assumed as one another set of vulnerable set of people. Within this community which depends on the local resources, mainly for livelihood and economy, there are other effects at the household level of these earners (at times they are the sole-earners of a household). The socio-economic indicators at household level as well as the regional level may be affected (affected villages or area). It works like a chain process!

- *The bottom-line is that the vulnerable community may witness changes which may lead to an even worse situation than what they might be experiencing across social and livelihood fronts without any major project development in the area.*

While the socio-economic effects across the various sections of the community would be addressed within a detailed social impact assessment study, it becomes important to identify that the women in the project affected areas (as one set of the vulnerable community in rural India) are also a potential set of human resources, if trained and provided the equal opportunity. This goes true for considering the youth as well.

The global push on Energy transition has been well-taken in the plans of national interest by many countries; women should not be left behind from contributing effectively to the development of an industry. With the development of OSW in India, the country should push effectively for active contribution of women to the industry. While there are various aspects and dimensions of a development project, it is important to bring the right linkage between environment and socio-economic impact for any proposed project. Given this fact, the existing environmental regulations and practices need to be reviewed and aligned with respect to offshore wind energy projects.

For reference, the practices in social safeguards include the following.

5.7.1 Existing practices for Social and Gender diversity inclusion

Presently, all those projects which involve relocation or displacement of settlements/community, attract the R& R Act. This makes it a mandate for these Projects to submit an SIA report with the EIA report. The process for clearance remains the same as mentioned above.

The SIA involves a detailed baseline study which is done prior to preparing an SIA report. The practice for the same is described below.

Required studies and assessment for identifying the impacts, risks and vulnerability

- Socio-economic baseline study (predominantly rural area profiling): To create a profile of the study area in terms of Population and demography, households, dependents, occupation, caste, income, land ownership, access to basic facilities, etc.
- Regional and urban profiling: To understand the relation of the rural and urban areas around to address the vulnerability and mitigation plan.
- Social Impact Assessment: To prepare a social impact assessment report which will help identify the target groups, vulnerable community, risk prone settlements, major areas of interventions.

To conduct the studies major tools that may have to be followed include,

- Stakeholder consultation with local, block and district agencies, local NGOs, etc.
- Socio-economic questionnaires (household surveys) and village surveys
- Interviews and focused-group discussion with identified target groups which may be more vulnerable to the changes in the livelihood, habitation, relocation for work or residence, etc. Target groups could be women, farmers, fishermen, landless labourers, landowners, etc.

** Note: These would be part of a larger activity*

To understand the approach and process for this a couple of projects have been referred which include,

- The Environmental and social impact assessment on La Gan offshore wind farm in Vietnam (niras.com)[117]- it provides an understanding on conducting the studies for required assessments.

[117] Environmental and social impact assessment on La Gan offshore wind farm in Vietnam (niras.com)

- The Rampion offshore wind project[118] provides an understanding on engagement with fishing communities and the locals while carrying out the construction. Also, it throws some light on approach to carry out effective health and safety aspects around the site.

5.7.2 Target groups

The target group to be largely affected with offshore cable allaying, port-based activity, offshore substation involvements are.

- Fishing community
- Elderly
- Children
- Local artisans if any
- Women
- Youth
- Differently abled

5.7.3 Possible impacts

It is difficult to say that possible effects, but a tentative list of points may include,

- Loss of land, if land is procured for port expansion.
- Loss of livelihood if the land is source of income for the local community
- Loss of fishing grounds
- Relocation for residence and/or work
- The vulnerable would be more affected, such as children, elderly, women, differently-abed.
- Loss of income if skills are limited to fishing and agriculture.
- Host vs. migrant issues, leading to socio-cultural changes.
- Mixing of socio-cultural parameters, may be positive too.
- Opportunities for new work from skill-development in youth and women
- Development of facility in the sea to be useful for all

5.7.4 Possible areas of interventions

- Referring to the existing experience of the other countries to mitigate the impacts can be across the following areas of interventions.
- Conducting young men and women for training and skill-building
- Avoiding areas of livelihood such as fishing grounds or land under-use of agriculture
- Providing child, women, and elderly with common areas for medical check-ups
- To have participatory approach to avoid resistance from the local community.
- The approach of development should be inclusive and holistic.
- Special vocational courses for the work they have been doing.
- Enhancing the work of artisans through local financial inclusion methods and marketing their products.

For reference, the practices in social safeguards include the following.

[118] https://www.rampionoffshore.com/environment/environment/fisheries/

5.7.5 Applicable major laws and regulations- at National level (For social safety)

(*These don't just address environmental implications, but people who live around and depend on the resources available there)

1. The EIA Notification, 2006 and subsequent Amendments: Because it deals with the locational criteria as well, considering safe distance and buffers from certain sensitive areas. (People and their well-being, their livelihood and dependency on the local resources, etc. To be established through Social Impact Assessment)

1. The CRZ notification, 2011 and subsequent Amendments: Because it deals with provisions and development of facilities and infrastructure for the local community and permissions for all the different zones of CRZ (As per the notification). This will also help identify permissible activities within different zones as per the CRZ notification. Suitable planning may help avoid major implications on the community as well as on the Project as certain activities are permissible only for the locals. (This indicates the livelihood of an individual and the settlement, with dependents on the sole-earner. For e.g., Fishermen community and their households)

2. The Right to Fair Compensation and Transparency in Land Acquisition Resettlement and Rehabilitation Act, 2013: Because it deals with the mitigation of impacts on the community which either owns land, or depends on it for livelihood, or is a tribal settlement, etc. It also talks about compensation which is usually covered by the Project through compensatory frameworks under their CSR Intervention Plan.

3. The Forest (Conservation) Act, 1980 and subsequent Amendments: Because it deals with the rights of the forest dwelling community (if the site falls in vicinity to an identified forest with a community dwelling in it or a community depends on the forest products) [Site-specific aspect, it is].

4. Occupational safety standards by OHSAS and ISO, and NIOH guidelines may be referred for safety of workers: This is important because social inclusion also includes workplace safety, safeguarding workers' rights to safety and security. This is an indirect way to ensure security of the dependents of the workers. Social inclusion covers larger perspective, which includes the directly and indirectly affected people.

However, a generic list for reference is provided as Annexure-V

5.7.6 Suggestions for management of socio-economic aspects in OSW projects

5.7.6.1 Suggestions for policy and regulations

- To establish a mandate for detailed Social Impact Assessment for OSW projects in India together with Environmental Impact Assessment for clearance
- To develop guidelines for social management of OSW projects for Project Affected Areas and making the process participatory and inclusive in nature
- To develop guidelines for fishermen's access to fishing zones through project corridors and safeguard the livelihood practices of the local community.
- To develop guidelines for safeguarding the vulnerable sections of the local community during the OSW developments in a region.

5.7.6.2 Suggestions for baseline studies

- To conduct a macro level socio-economic mapping of the regions that would fall under the coastal areas which would be witnessing OSW related developments.

Key Takeaways

Operation and Maintenance aspects of OSW Evacuation

Operation & maintenance (O&M) can be considered as a combined function that supports the ongoing operation of the wind turbines, the balance of plant, and associated transmission network during the lifetime of the OSW. O&M activities start right after the completion of construction of the OSW and are focused to ensure the safe operation by which the physical integrity of the OSW assets is maintained, and electricity generation is optimised.

Operation and maintenance include different key aspects which are essential for effective O & M management. These include,

- Operational Performance parameters and standards for key components
- Spare parts and inventory management practices
- Port logistics support requirements
- Requirements of Service providers

The operations related to the OSW includes the a) assurance of health and safety of the assets, b) control and operation of asset which includes wind turbine, balance of plant, c) remote monitoring of OSW, d) electricity sale, administration and supervision of marine operations, e) operation of vessels and infrastructure, and f) back-office works.

The operational integrity of OSW is assured by the proper maintenance and service of the plant which may include both planned and unplanned maintenance as a response to faults occurring. Maintenance and services are offered by a team that includes owner's in-house personnel, supplier of wind turbines and balance of plants, and third-party service providers. OSW industries are focused on optimization of the maintenance activities which can reduce operational costs without compromising the performance of the OSW. The maintenance and services are classified broadly into two- a) turbine maintenance and services and b) balance of plant maintenance and services.

OSW has downtime related to the maintenance and services which may cause huge financial losses to the owner. So, it has a prime consideration to reduce the downtime of the OSW as much possible. One of the strategies to reduce downtime would be forecasting the requirement of different spare parts and keeping the required number of spare parts in the inventory.

To facilitate the operations and maintenance, ports and vessels play a crucial role in the overall execution and management of activities. Power evacuation is an essential component of OSW, it needs certain types of ports that provide specific services across various stages of development. Ports facilitate services of a wide range from surveying to construction, installation, operation and maintenance, and support services during uncertain events. Since the current target of 30 GW is envisaged for the two states, Tamil Nadu and Gujarat, the identified candidate ports should suitably adapt to the requirements of OSW for these regions. The earlier studies indicate the need to suitably utilise the existing ports by proper planning for redevelopment, utilising the existing berths, sparing certain berths and terminals for OSW-specific activities, etc. However, it is also realised that not all these ports may integrate OSW-specific redevelopment for various reasons.

The important point this report tries to emphasise is that it is not one type of port that can serve all the requirements of OSW projects or specifically power evacuation within OSW also. It largely involves diverse kinds of ports that can deal with the services required across the various stages of OSW development. Very specifically power evacuation in OSW would need at least three to four broad category ports, which include the construction ports, offshore substation facilitation ports, installation ports, and operation and maintenance ports. Further, to bring the very point that the identified candidate ports would have to be suitably considered to be re-planned and utilised as one of these categories of ports and/or as combination ports that cater to more than one service.

Repurposing or upgrading the existing berths and yards may not be a feasible option, instead, the development of a purpose-built terminal may be considered. Apart from the berths and the yards, it is important to understand that the roads, the curves in the alignment of roads, and the space for the movement of parts and components at these ports should be in line with the requirements. This becomes important if the manufacturing bases for certain components come up in the nearby areas of these ports in the future. Under this condition, getting these parts through roadways might be a viable option, and not through the sea. For example, the movement of blades (component with length) and other such parts from nearby facilities to the unloading area within the port/s may be thought about for the long-term planning.

Considering various aspects, port planning (in terms of both, the infrastructure within the ports and their catering capabilities) must be looked into as a critical dimension of OSW development in India, and to begin with, the ports of Tamil Nadu and Gujarat to meet the requirements of OSW projects as envisaged. Also, a well-developed guidance manual on the use of ports and vessels for offshore wind may be of much use to the emerging industry personnel, to facilitate the process of OSW development.

Ports have a critical and continuous role in OSW stages and activities, which are mostly supported through vessel services. Like ports, the type of vessels required across the various stages of OSW development is different. Describing the vessels required for the power evacuation component is even specific.

Currently, the ports deal with the vessels that are suitable for the products handled and operations at the port, however, OSW-specific requirements for vessels would differ. As discussed, the types of vessels vary, based on the stage and the activities. Based on the identified ports for OSW development, the specific vessels that are required and manageable by the port for an activity (OSW) would be selected. It is to be noted that there are certain activities such as cable-carrying, cable-laying, and offshore substation installation, which are highly vessel dependent, and are to be addressed while planning for the power evacuation of an OSW project. While these are activities that are part of the installation stage within power evacuation, the monitoring and maintenance of these components would need a separate set of vessels, which are to be suitably integrated with the power evacuation planning for OSW. Thus, it would need a dedicated vessel planning for all the stages and activities covered within an OSW project.

While executing the project, and with the regular operation and maintenance, there is a certain level of risk to the environment and the socio-economic aspects of the region. At a macro level identification of precise impact is difficult, but certain impacts can be perceived at this stage, based on the activities. Though power evacuation includes the onshore and offshore activities the marine activities cover a larger timeframe with multiple sub-activities within. The existing EIA regulations need to have offshore relevant standards and processes defined.

The possible impacts and mitigation measures are activity-dependent; however, a micro-level study of possible effects would be important while trying to reach the targets of OSW capacities in the two states, Tamil Nadu, and Gujarat. The possible impacts in both these states are highly dependent on the baseline conditions in terms of the geography, climate, biodiversity, environmental regulations and governance, and other agents of negative and positive effects on the environment, for example, coastal areas surrounded by large industrial bases, which may add to the offshore wind project effects, ultimately causing diverse and cumulative effects. The impacts and the mitigation measures are highly case-specific, yet the precision to identify them is very much dependent on the approach and methodology adopted. A well-planned sustainable development may potentially help facilitate environmental conservation in a more effective manner.

As a part of the mitigation measures for socio-economic impacts, the feasibility of a particular measure to work depends on the baseline studies carried out. The social impact assessment report at the project level may support these interventions based on the accuracy of the assessment and the inclusion of appropriate parameters. The central approach must be inclusive, considering the long-term perspective. It becomes important to identify the right need of the community and provide accordingly. Social impact assessment (SIA) should be considered a mandatory requirement along with the environmental impact assessment (EIA) report, which is a mandate, irrespective of whether any displacement of the community is involved or not.

The overall approach must be to propose and develop sustainably and make it more with a regional development perspective. Women, children, youth, and differently abled should be among the target groups that are at the receiver end to gain benefits of the development, and the elderly are to be safeguarded suitably. The positive impacts that OSW as an industry may offer can be grabbed as an opportunity for the overall development in a holistic manner.

6. Summary

India has over 7,600 km of coastline with significant potential available for Offshore Wind (OSW) development. During the initial assessment of the National Institute of Wind Energy (NIWE) in the identified zones, there is a potential of almost 70 GW of OSW that exists off the coast of Tamil Nadu and Gujarat. Considering the OSW potential available along its coastline, the Government of India (GoI) has announced to install 37 GW of OSW generation capacity by 2030 with a defined trajectory for the auction of OSW projects discussed in Chapter 1.

6.1 Transmission Plan development initiatives in India and status

- A transmission plan for the evacuation of 10 GW of offshore wind (Transmission Schemes for 5 GW Off-shore Wind Farm in Gujarat and Transmission Schemes for 5 GW Off-shore Wind Farm in Tamil Nadu) has been developed and made public by CEA based on the discussed planning criteria.

- Relevant ISTS and InSTS system strengthening has been emphasized, which will directly and indirectly help in evacuation of OSW power across the nation.

- The above discussed planning criteria and the transmission planning guidelines will eventually help all the stakeholders for OSW transmission planning based on power system studies, power system model for simulations, time horizon, generation, demand, despatch, and short circuit studies.

- The transmission planning considerations are integral to realise the envisioned OSW development in India.

- 10 GW OSW evacuation planning for Gujarat and Tamil Nadu will be serving the need of upcoming projects, but a roadmap needs to be developed for evacuation of 30 GW OSW capacity.

- It is necessary to discuss the technology alternatives available at present in commercial scales as well as the upcoming technologies.

- From a planning perspective, coordination, and integration of OSW with onshore facilities is essential for optimising the cost of transmission.

- There is a need for a long-term planning in case of OSW looking not just at the target year 2030 but also beyond 2030 to ensure the maximum utilisation of OSW as a resource.

- From the international experience it is well understood that long term planning is the key to successful OSW transmission planning.

- practice of mutual collaboration of public-private actors in co-designing and co-developing policies through stakeholder consultation is key to accelerated adoption of transmission policies and regulations.

- India has a strong transmission planning philosophy. What we can assimilate from international learning especially from UK is that OSW specific planning for offshore-onshore coordinated transmission planning is an essential element to reduce cost. Number of connection and landfall points and overall impact in marine ecosystem.

- International approaches for long term transmission planning for OSW projects needs to be investigated to evolve planning paradigm in Indian context which is extensively discussed in this report.

6.2 Planning paradigm for OSW Evacuation for India

The summary below provides the Configuration Option for an integrated approach for the OSW projects in Tamil Nadu. The mapping of evacuation schemes is based on Table 12. The similar approach can also be worked out for Gujarat. The different configuration options discussed are based on different physical, technology and developmental attributes, and environmental footprint. The suitable configuration options would be

- Config Option 3 (Alt 1.3 + Alt 2.1): 220 kV OSS & export cable + 765kV OSS > 50 km, 10 groups of 1 GW near shore zones or 5 groups of 2 GW near shore zones or 3 groups of 3 GW near shore zones combined with 1 GW near shore zone + 4 groups of 3 GW far shore zones.

- Config Option 4(Alt 1.4 + Alt 2.1): 400 kV OSS & export cable + 765kV OSS > 50 km, 5 groups of 2 GW near shore zones or 3 groups of 3 GW near shore zones combined with 1 GW near shore zone + 4 groups of 3 GW far shore zones

- Config Option 5 (Alt 1.3 + Alt 1.5): >220 kV OSS & export cable + HVDC Stn > 50 km, 10 groups of 1 GW near shore zones or 5 groups of 2 GW near shore zones or 3 groups of 3 GW near shore zones combined with 1 GW near shore zone + 5 groups of 2 GW or 4 groups of 3 GW far shore zones

- For the combination options using future Technology of UHVDC- system up to 640 kV, the commercial availability and viability cannot be visualised for a recommendation.

Further these options are elaborated below to analyse the suitability

1. The integrated planning of transmission system is a must for immediate 5 GW OSW projects in Gujarat and Tamil Nadu, which needs to align with the long-term planning for evacuation of 30 GW OSW capacity in these states. This integrated planning approach is proven internationally to bring in cost efficiencies and optimise on the country resources such as land for onshore sub-stations, submarine cable corridors, offshore substation platforms and the environmental footprints for a sustainable development of the sector. The integrated planning approaches further brings visibility of scale of operations to facilitate establishment of indigenous supply chain and increase the employment opportunities and capacity building of the persons in the development cycle.

2. The evacuation options investigating applicability of HVAC and/or with combination of HVDC for offshore transmission system while working out long-term transmission planning approaches is considered based on zone potential, physical distances of OSW projects from the shore and its compatibility with onshore transmission for effective integration, auction

strategy, the technology readiness, indigenisation opportunities gain, capacity building measures and investment channelisation for transmission system. These evacuation options further grouped to devise the Configuration Options and evolve an integrated planning approach while qualitatively validating each of the Configuration Options with the physical, technology, development, and environment parameters.

3. The Configuration Option 4 comes out with a clear advantage for an integrated approach to implement for its effectiveness to for uprating possibilities i.e., to charge the 400 kV line at lower voltage 220kV during initial phase and later with OSW capacity enhancement, the same transmission corridor capacity could be used to cater for subsequent phases. Only cons would be upfront loading of capital cost for initial phases. With the OSS cost are to be socialised, the integrated approach favours 400 kV OSS system under Configuration Option 4 over 220 kV OSS under Configuration Option 3.

4. The Configuration Option-5 with HVDC system, can be advantageous considering its modularisation flexibility in OSW capacity augmentation and enhance reliability as against Configuration Option 4, however needs to be dwelled into detail on cost effectiveness for involvement of additional converter stations and environment footprint.

5. The Configuration Option 1 and 2 involving 66 kV and 132 kV system are not right candidates for integrated planning considering its development will lead a fragmented planning and will cost heavily on environment and social aspects. While the Configuration Option 6 cannot be validated considering its commercial unavailability as on date.

6. The Configuration Options developed needs further investigations through technical pre-feasibility studies and cost assessment, environment, and social impact assessment to undertake relative assessment between Configuration Options 4 and 5.

6.3 Development and Implementation aspects of OSW Evacuation

The key components of OSW transmission infrastructures are offshore substations, reactive power compensation equipment, and submarine cables which constitute the balance of the plant. The balance of the plant includes all components of the wind farm except the turbine.

The Substations are often delivered as one element of a contract to connect the wind farm generating assets to the onshore transmission grid and it will be comprised of electrical systems, facilities or auxiliary systems, substation foundations or sub-structures. The major classification of OSS is HVAC and HVDC. The basic consideration for the selection of the HVAC and HVDC would be the receiving end voltage at the onshore substation, the designated voltage of the transmission line envisaged which may depend primarily on the capacity of power to be evacuated and the distance of the OSW farm to the shore.

As per the proposed configuration options, the HVAC system is preferred up to 400 kV where the power evacuation capacity per circuit of export cable is 1000 MVA. The HVAC system can be configured even in lesser voltages like 66 kV, 132 kV and 220 kV. As a futuristic technology, 765 kV HVAC systems are being considered with a typical power evacuation capacity per circuit of export cable over 3000 MVA.

The HVDC system is preferred above 400 kV voltage with typical power evacuation capacity per circuit of HVDC export cable could be up to 3000 MVA. HVDC-VSC system can be used with a system voltage up to 500 kV. However, additional converters are required on the sending and receiving end which will cause an increase in the cost of the scheme. Therefore, it has been deduced that HVDC substations with cost analyses must be examined first for large-scale projects when the distance from the seashore is considerable.

The OSS can be also classified into fixed and floating based on the mode of fixing to the seabed. Presently, fixed mechanical structures are dominant and used to provide support and protection to the substation platform. As the depth of water increases the mechanical structures may not be suitable to anchor the platform into the seabed. In such cases, floating offshore substations can be considered which will offer the possibility to install wind farms in larger and deeper offshore areas with high wind potential. However, the technology of floating substations is in the developing phase. Further, submerged substations – Subsea Substations are in the phase of development and is expected to be available in the market by 2024.

The preference for HVAC transmission necessitates the need for reactive power compensation. Configuration Option 4, evacuation at 400 kV HVAC, requires the incorporation of reactive power compensation equipment. Usually, reactive power compensation equipment can be integrated with offshore substations. The reactive power compensation techniques are incorporated into the OSS primarily to increase the transmission capacity of the AC cables, reduce losses, and keep the system voltage within the limit.

Because of limitations of engineering conditions, the reactive power compensation can be applied centrally at the ends of the cable, or on the land halfway. Usually, the reactive power compensation is applied at the sending end where the current will be maximum at both sending end and receiving end. Also, the voltage in the line will increase due to the application of sending end compensation and it will exceed the sending end voltage when the reactive power compensation reaches a certain degree. Reactive power compensation at receiving end is incorporated to increase the voltage at receiving end which can prevent the low voltage of the junction point and improve the stability of the system. Even then, the compensation applied on the receiving end does not change the current distribution of the line. So reactive power compensation at receiving end can be used as a measure to improve the power factor of the junction point.

In the case of middle-line compensation, a dedicated reactive power compensation station needs to be constructed. Since the middle section of the submarine cable line is usually a sea area, the cost for the construction and maintenance of reactive compensation equipment for the mid-line is high.

Different reactive power compensation equipment devices used in the OSW industries are Mechanically switched shunt reactors (MSR), Static Var Compensators (SVC), and Static Synchronous Compensators (STATCOM) where the SCV and STACOM are dominant in the current industry.

Reactive power compensation does not require for HVDC systems but, as per the latest development, the converters used in HVDC systems are capable to provide reactive power compensation which will be beneficial to meet the grid code requirement.

6.4 Operation and Maintenance aspects of OSW Evacuation

Operation & maintenance (O&M) can be considered as a combined function that supports the ongoing operation of the wind turbines, the balance of plant, and associated transmission network during the lifetime of the OSW. O&M activities start right after the completion of construction of the OSW and are focused to ensure the safe operation by which the physical integrity of the OSW assets is maintained, and electricity generation is optimised.

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- Spare parts and inventory management practices
- Port logistics support requirements
- Requirements of Service providers

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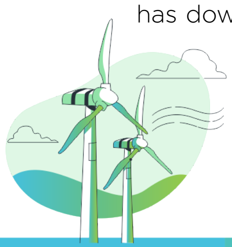

owner. So, it has a prime consideration to reduce the downtime of the OSW as much possible. One of the strategies to reduce downtime would be forecasting the requirement of different spare parts and keeping the required number of spare parts in the inventory.

To facilitate the operations and maintenance, ports and vessels play a crucial role in the overall execution and management of activities. Power evacuation is an essential component of OSW; it needs certain types of ports that provide specific services across various stages of development. Ports facilitate services of a wide range from surveying to construction, installation, operation and maintenance, and support services during uncertain events. Since the current target of 30 GW is envisaged for the two states, Tamil Nadu and Gujarat, the identified candidate ports should suitably adapt to the requirements of OSW for these regions.

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Repurposing or upgrading the existing berths and yards may not be a feasible option, instead, the development of a purpose-built terminal may be considered. Apart from the berths and the yards, it is important to understand that the roads, the curves in the alignment of roads, and the space for the movement of parts and components at these ports should be in line with the requirements. This becomes important if the manufacturing bases for certain components come up in the nearby areas of these ports in the future. Under this condition, getting these parts through roadways might be a viable option, and not through the sea. For example, the movement of blades (component with length) and other such parts from nearby facilities to the unloading area within the port/s may be thought about for the long-term planning.

Considering various aspects, port planning (in terms of both, the infrastructure within the ports and their catering capabilities) has to be looked into as a critical dimension of OSW development in India, and to begin with, the ports of Tamil Nadu and Gujarat to meet the requirements of OSW projects as envisaged. Also, a well-developed guidance manual on the use of ports and vessels for offshore wind may be of much use to the emerging industry personnel, so as to facilitate the process of OSW development.

Ports have a critical and continuous role in OSW stages and activities, which are mostly supported through vessel services. Like ports, the type of vessels required across the various stages of OSW development is different. Describing the vessels required for the power evacuation component is even specific. Currently, the ports deal with the vessels that are suitable for the products handled and operations at the port, however, OSW-specific requirements for vessels would differ. As discussed, the types of vessels vary, based on the stage and the activities. Based on the identified ports for OSW development, the specific vessels that are required and manageable by the port for an activity (OSW) would be selected. It is to be noted that there are certain activities such as cable-carrying, cable-laying, and offshore substation installation, which are highly vessel dependent, and are to be addressed while planning for the power evacuation of an OSW project. While these are activities that are part of the installation stage within power evacuation, the monitoring and maintenance of these components would need a separate set of vessels, which are to be suitably integrated with the power evacuation planning for OSW. Thus, it would need a dedicated vessel planning for all the stages and activities covered within an OSW project.

While executing the project, and with the regular operation and maintenance, there is a certain level of risk to the environment and the socio-economic aspects of the region. At a macro level identification of precise impact is difficult, but certain impacts can be perceived at this stage, based on the activities. Though power evacuation includes the onshore and offshore activities the marine activities cover a larger time-frame with multiple sub-activities within. The existing EIA regulations need to have offshore relevant standards and processes defined.

The possible impacts and mitigation measures are activity-dependent; however, a micro-level study of possible effects would be important while trying to reach the targets of OSW capacities in the two states, Tamil Nadu, and Gujarat. The possible impacts in both these states are highly dependent on the baseline conditions in terms of the geography, climate, biodiversity, environmental regulations and governance, and other agents of negative and positive effects on the environment, for example, coastal areas surrounded by large industrial bases, which may add to the offshore wind project effects, ultimately causing diverse and cumulative effects. The impacts and the mitigation measures are highly case-specific, yet the precision to identify them is very much dependent on the approach and methodology adopted. A well-planned sustainable development may potentially help facilitate environmental conservation in a more effective manner.

As a part of the mitigation measures for socio-economic impacts, the feasibility of a particular measure to work depends on the baseline studies carried out. The social impact assessment report at the project level may support these interventions based on the accuracy of the assessment and the inclusion of appropriate parameters. The central approach has to be inclusive, considering the long-term perspective. It becomes important to identify the right need of the community and provide accordingly. Social impact assessment (SIA) should be considered a mandatory requirement along with the environmental impact assessment (EIA) report, which is a mandate, irrespective of whether any displacement of the community is involved or not.

The overall approach has to be to propose and develop sustainably and make it more with a regional development perspective. Women, children, youth, and differently abled should be among the target groups that are at the receiver end to gain benefits of the development, and the elderly are to be safeguarded suitably. The positive impacts that OSW as an industry may offer can be grabbed as an opportunity for the overall development in a holistic manner.

The suggested Configuration Options are proposed to be deliberated with key stakeholders, under this ASPIRE program, for bringing in consensus on the most suitable long-term planning approach as a way forward to develop the Roadmap for Offshore Wind Power Evacuation and Grid Integration, 2030 for India.

7. Annexure

7.1 Annexure-I

RE Installed Capacity (MW) as on 31.10.2022

Category	RE Installed Capacity (MW) as on 31.10.2022
Hydro	46,850
Wind	41,844
Solar	61,624
Small Hydro	4,924
Bio	10,701
Total	1,65,943

7.2 Annexure-II

Details of the transmission system for 55.08 GW ISTS connected RE capacity.

Transmission scheme	RE capacity (GW)	Status of Transmission Scheme
Transmission schemes for 20 GW RE capacity in Rajasthan under Phase III	14	Transmission schemes are under bidding.
	6	The transmission scheme comprises of 6000 MW, + 800 kV HVDC system between Bhadla-III and Fatehpur. The scheme has been recommended by NCT in its 9th meeting held on 28.09.2022. Subsequent activities are in progress for initiating bidding of the scheme.
Transmission scheme for 13 GW Leh RE park	13	The transmission scheme comprises of + 350 kV, 5000 MW VSC based HVDC link from Pang to Kaithal. Scheme allocated to PowerGrid in January 2022, for implementation through RTM route
Transmission scheme for 880 MW Kaza Solar Park, Himachal Pradesh	0.88	Transmission system planned. To be taken up for implementation in matching timeframe of RE Generation
Transmission scheme for additional 17.2 GW RE capacity from Khavda and 4 GW RE capacity from Dholera, Gujarat	21.2	Transmission system planned. To be taken up for implementation in matching timeframe of RE Generation
Total	55.08	

7.3 Annexure-III

With the additional inter-regional corridors under implementation/planned, the inter-regional capacity is likely to be 149,850 MW in 2030 as detailed below.

Inter-regional corridor capacity by 2030[8]

Inter-region	Capacity (MW)
West-East	22,790
West - North	62,720
West - South	28,120
North-East	22,530
South-East	7,830
East-Northeast	2,860
Northeast- North	3,000
Total	1,49,850

7.4 Annexure-IV

Current rating for single-core submarine export cables

100-420 kV XLPE single-core cables		
Cross section mm2	Copper conductor	Aluminium conductor
	Current (A)	Current (A)
185	580	445
240	670	505
300	750	560
400	845	620
500	950	690
630	1065	760
800	1180	830
1000	1290	895

7.5 Annexure-V

Current rating for three-core submarine export cables with steel wire armour

100-300 kV XLPE 3-core cables		
Cross section mm2	Copper conductor	Aluminium conductor
	Current (A)	Current (A)
300	530	430
400	590	485
500	655	540
630	715	600
800	775	660
1000	825	720

7.6 Annexure-VI

Challenges and Interventions

General challenges in integrating the onshore wind power projects are categorised into the following phases:

1. Planning and Design phase
2. Construction phase
3. Operations phase

Figure 61: Challenges for Onshore wind power evacuation

Above figure illustrates the various challenges pertaining to onshore wind grid integration during early grid integration which may also be applicable to the OSW. Hence, some possible interventions are suggested in Table 26 pertinent to the OSW.

Table 26: Challenges in Onshore wind and potential interventions for OSW grid integration

Stage	Challenges in Onshore wind	Potential Interventions for OSW
Planning and design stage	• Inadequate representation of onshore wind during the transmission planning. • Lack of flexibility in plans to further augmentation of wind.	• Adopt integrated approach for planning of transmission-generation and load demand at national and state level with due focus on OSW grid integration. • Amendments to CEA Planning Codes by SERCs and insistence for adoption of special planning criteria for OSW as per CEA manual by STUs. • Active involvement and participation of wind generators/wind associations in the grid coordination committees. • Annual review and revisions of the transmission plans to facilitate growth of RE.
Construction stage	• Non-uniform grid interconnection processes	• Development of standard interconnection process manual under aegis of Forum of Regulators (FoR).

Stage	Challenges in Onshore wind	Potential Interventions for OSW
	• Lack of adequate RE transmission development model. • Addressing right of way and other local issues.	• Exploring PPP model or Private Transmission Company (IPTC) model for the development of RE transmission schemes. • According to highest priority status to RE transmission projects and continuous monitoring of progress of such projects.
Operation Stage	• Lack of implementation framework for Forecasting and Scheduling. • Managing resource variability and intermittency. • Grid instability. • Reactive power management issues.	• Establishing visibility and communication links between wind farm pooling stations and SLDCs. • Establishing REMCs/coordinating agencies. • Developing and operationalizing ancillary services market mechanism and inter-state and inter-regional coordination frameworks. • Undertaking reactive compensation requirements at Pooling S/S and grid and developing pilot schemes including storage – active/reactive. • Developing reactive energy pricing framework and pricing signals to address reactive energy management issues.

7.7 Annexure-VII

List of applicable acts and rules:

a) Applicable Environmental and Social Laws, Regulations, and policies

- The Environment (Protection) Act, 1986:
- Forest (Conservation) Rules 2003:
- EIA Notification S.O 1533, Dated 14.09.2006:
- The Air (Prevention and Control of Pollution) Act, 1981:
- Hazardous and Other Wastes (Management & Transboundary Movement)
- Rules, 2016:
- Noise (Regulation and Control) Rules 2000 amended in 2010
- Land Requirement / Diversion:
- The Building and Other Construction Workers' (Regulation of Employment and
- Conditions of Service) Act 1996
- Central Electricity Authority (Safety Requirements for Operation, Construction and Maintenance of Electric Plants and Electrical Lines) Regulations 2008, (CET)
- Workmen's Compensation Act, 1923 & Rules 1924
- The Contract Labour (Regulation and Abolition) Rules, 1971
- ESIA of 300 MW Wind Power Project- Kutch iii
- Minimum Wages Act, 1948
- The Child Labour (Prohibition and Regulation) Act, 1986
- The Companies Act, 2013
- Wildlife Protection Act, 1972
- Resettlement and Rehabilitation Act 2013
- The Scheduled Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act, 2006 and Forest Rules 2007

b) Applicable Environmental Standards

- Ambient Air Quality
- Primary Water Quality Criteria for Designated-Best-Use-Classes
- Ambient Noise Standards

c) Contractors' HSE Policy

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