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EVALUATING THE TECHNICAL FEASIBILITY OF WIND ENERGY TO ELECTRIFY OIL AND GAS PRODUCTION FACILITIES OFFSHORE NEWFOUNDLAND AND LABRADOR, CANADA

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1 INTRODUCTION

NEIA, NOIA and the Oil and Gas Corporation of Newfoundland and Labrador have sponsored the investigation of electrifying brownfield and greenfield oil and gas production facilities using floating wind farms offshore Newfoundland and Labrador. Electrification of floating host facilities eliminates or reduces the requirement for local power generation via turbine generators at the host facility, decreasing operational expenditure and total emissions from the facility. The results of this study are presented in this report.

This study has been performed using public domain information regarding the feasibility of using floating wind power for supply to Floating Production, Storage and Offloading (FPSO) hosts. A case has also been included to look at floating wind power to supply a brownfield GBS. This study includes investigation of existing projects, equipment requirements and technical readiness, floating wind array best practices, GHG emissions reduction and effect on Capital Expenditure (CAPEX).

The study comprises of the following activities:

- Investigation regarding floating wind turbine towers to date on Hywind Tampen
- Industry study regarding any similar projects currently underway
- Summary of modifications/additions required at the host facility for power supply by wind power array, detailed with requirements
- Summary of the differences between fixed and floating wind design and challenges associated with each option
- Assessment regarding the best arrangement for a floating wind power array supply
- Investigation of ongoing project work related to dynamic, disconnectable cables which will operate in the upper end of MVAC, HVAC or HVDC
- Avoided GHG emissions estimation
- One (1) brownfield scenario analysis (GBS)
- Three (3) greenfield scenario analyses (FPSO's)
- A summary of the supply chain capabilities and competencies required for the development of such projects.

2 ABREVIATIONS AND ACRONYMS

A	Ampere
AC	Alternating Current
API	American Petroleum Institute
CAD	Canadian Dollar
CAPEX	Capital Expenditure
CCTV	Closed Circuit Television
DBM	Distributed Buoyancy Module
DC	Direct Current
DNV	Det Norske Veritas
FPSO	Floating, Production, Storage and Offloading
GBS	Gravity-Based Structure
GHG	Greenhouse Gas
GW	Gigawatt
GWh	Gigawatt Hour
HV	High Voltage
HVAC	Heating Ventilation and Air Conditioning
HVAC	High Voltage Alternating Current
km	Kilometre
kW	Kilowatt
kWh	Kilowatt Hour
LDPE	Low-Density Polyethylene
LV	Low Voltage
LVAC	Low Voltage Alternating Current
m	Metre
MBO	Million Barrels of Oil
MVAR	Mega Volt-Amp Reactive
MW	Megawatt
MWh	Megawatt Hour
NL	Newfoundland and Labrador
OLS	Offshore Loading System
OPEX	Operational Expenditure
ORE	Offshore Renewable Energy
PA	Public Address
POD	Platform for Operational Data
SPAR	Single Point Anchor Reservoir
SOV	Service Operation Vessel
TLP	Tension Leg Platform
VAR	Volt-Amp Reactive
XLPE	Cross-Linked Polyethylene

3 HYWIND TAMPEN PROJECT SUMMARY

Hywind Tampen is a floating wind power project located approximately 140km off the Norwegian coast. It is intended to provide electricity for the Snorre and Gullfaks offshore field operations in the Norwegian North Sea and is under development by Equinor. It will be the world's first floating wind farm to electrify offshore oil and gas platforms. The field will include eleven (11) 8MW floating wind turbines with 167m rotors. The turbines will be installed in water depths of 260-300m

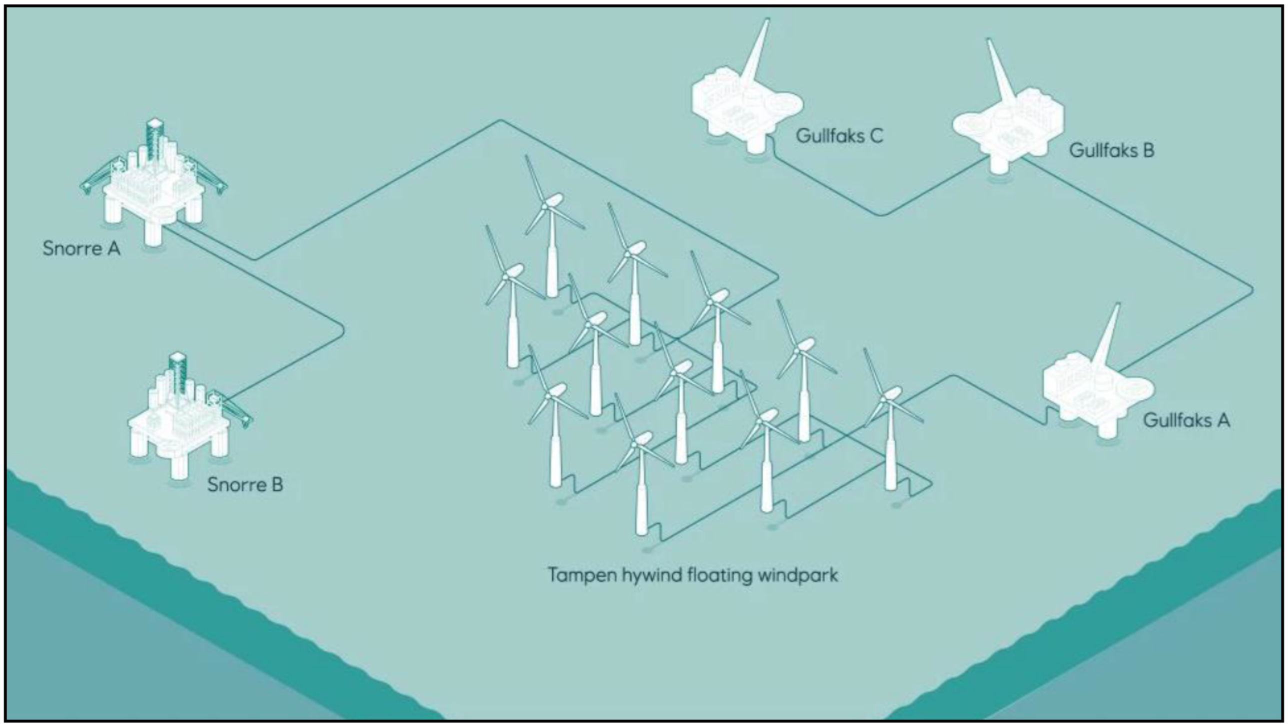


Figure 3-1: Hywind Tampen Wind Array Layout (Credit: Equinor)

Hywind Tampen has the added benefit of acting as the world's pilot project for electrification of offshore oil and gas fields and an essential step in reducing costs for future offshore floating wind power projects. A significant example is present in Equinor's statement that the total cost of Hywind Tampen was reduced by a predicted 40% with the application of learnings from Equinor's 30 MW Hywind Scotland floating wind project in the UK, the world's first commercial-scale floating wind farm in operation.

With a power generation capacity of 88MW, Hywind Tampen will be the world's largest offshore floating wind field when it comes online in 2022 (planned).

Hywind Tampen will utilize Siemens Gamesa 11 SG 8.0-167 DD turbines which are the largest that have been used in floating wind systems. Each turbine will have three 81.5m long blades and have a swept area of 21,900 m^2. The turbines will be mounted on floating concrete spar type ("Hywind" type) substructures and will share anchors with each other. It will be an important test bed for installation methods, simplified moorings, concrete substructures and integration between gas and wind power generation systems. Hywind Tampen will use a lithium-ion backup power concept (battery capacity not yet published) to integrate renewable power generation into the existing gas-fired power system, essentially creating a renewable microgrid.

The project is estimated to meet, on average, 35% of the annual power demand of five offshore platforms; Snorre A and B, and Gullfaks A, B and C. During periods of higher wind speed, this percentage may be significantly higher.

3.1 Project Status

Equinor and its Snorre and Gullfaks partners submitted two updated plans for development and operation of Hywind Tampen to Norwegian authorities in October 2019. In April of 2020, the Norwegian Ministry of Petroleum and Industry approved the plans for development and operation, giving the project a path forward. The project currently plans to start procurement of long lead items in December 2020.

Assembly of the foundations and wind turbines/towers is scheduled to start in February 2022 with offshore construction starting shortly after in March 2022. Offshore cable installation is currently planned for June 2022 with first power expected in Q3 of the same year. Completion of the project commissioning is expected in October 2022. Siemens Gamesa Renewable Energy will service the turbines for five years after initial commissioning.

The total investment in Hywind Tampen will be approximately €497.3 million (CAD $780.9 million), a significant portion of which is being provided by Norway's low-carbon project-financing program Enova CAD (€231 million (CAD $363 million)) and the NOx Fund (€54 million (CAD $84 million)) which is a consortium of Norwegian businesses that wants to reduce nitrous oxide emissions.

3.2 Design Efficiency Improvement and Cost Reduction Features

- One of the major aims for the Hywind Tampen project is to reduce the total CAPEX and OPEX cost by 40% compared with the existing Hywind Scotland project. To achieve this, several modifications will be implemented on the Hywind Tampen project. ([Ref 12])

  - On Hywind Scotland, Equinor used a large Saipem 7000 crane vessel to lift the fully assembled turbines onto the substructures, in one lift. The Saipem 7000 measures more than 200 metres in length and is equipped with two cranes capable of lifting to 14,000 tons. For Hywind Tampen, the partners will use a land-based ring crane to perform turbine installation. The substructure is first deployed at quayside, then using land-based ring crane (working on land) to lift the tower piece by piece and stack them on the substructure one by one, finally install the turbine and the blade., This land-based method which offers an attractive day rate compared with the offshore? vessel-based method.

- Equinor has also switched to concrete substructures for Hywind Tampen floating foundations. They are cheaper than the steel substructures used on Hywind Scotland and they also remove some of the complexity when it comes to the nearshore marine operations.

- Hywind Tampen will also feature a simplified mooring system which uses shared suction anchors, reducing the number of anchors from 33 to 19 based on the layout of the wind turbines and mooring system. This can significantly reduce the cost for anchors procurement, transportation and installation.

- A Service Operation Vessel (SOV) will be used for corrective maintenance of the wind farm and planned annual services. To mitigate safety risks, Equinor will use a walk to work (W2W) vessel to perform operations and maintenance. W2W vessels use active heave compensated gangways to provide safer transfer to the offshore platform. Equinor will share the vessel with oil and gas operations.

- For major component replacement, the turbine will be towed to shore. Floating wind developers have yet to develop a cost-efficient on-site method for major component repairs.

- The Hywind Tampen project was restricted to 11 turbines to avoid large modifications of the existing electrical infrastructure at the platforms.

Figure 3-2: Hywind Tampen Concrete Foundation (Credit: Equinor)

- **Utilization of dynamic 66kV (versus the standard 33kV) inter array cable:** JDR Cable Systems has signed a contract with Equinor for the Hywind Tampen Project. JDR is designing and manufacturing eleven 66kV dynamic inter-array cables and two static export cables, each equipped with a JDR designed breakaway system (BSR Latch and T-Connector Break Away System (T-BAS), which protects the floating wind tower in the unlikely event of a mooring line failure. They will also provide a range of cable accessories for full delivery in 2022. The 2.5 km long 66kV dynamic array cables will connect to the eleven turbines in a loop and the two static 12.9km and 16km export cables will be used to connect the array to the Snorre A and Gullfaks A platforms. The greater water depth means the cables and cable components will be designed to withstand higher water pressures than traditional offshore wind power cables. According to JDR, the cables present a challenge due to the high dynamic stress they will have to withstand, leading to copper sheaths instead of lead. In 2018, the company completed what it claims was the world's first application of dynamic 66-kV technology and breakaway system to the WindFloat Atlantic floating wind farm.

Figure 3-3: JDR's 66kV Dynamic Cable with Copper Sheaths (Credit: JDR)

3.3 Current Project Challenges

A primary challenge that Hywind Tampen has had is the scope breakup of operation of the renewable power system. The integration of the wind turbines and power storage technology with the existing gas-fired power system on the platform requires significant interface with the oil and gas platform operators. Equinor currently plans to control marine and logistics, electrical safety and asset integrity while Host facility operators will control the power feeders and their own system power distribution.

Other challenges include the microgrid arrangement. The microgrid will include challenging volatile loads, randomly determined anomalies, trips and frequency irregularities. The architecture of microgrid control is generally designed in two different approaches; centralized and decentralized. A centralized control microgrid relies on a large amount of information between units and then the control is performed at a single point. It would present a large problem in the case of Hywind Tampen implementation as the interconnected power systems involve an enormous number of units. In a decentralized control microgrid, each unit is controlled by its local controller without knowing the situation of others.

The floating structure will require a slightly larger subsea inspection scope than bottom-fixed projects and the remote location of Hywind Tampen brings some additional project challenges. This could be solved by adding the subsea inspection scope to the routine maintenance of the oil and gas platforms to which the Tampen wind farm will provide power.

The mean significant wave height (Hs) of 2.8 m makes accessing the turbines extremely challenging. Sea state limits for accessing offshore floating wind turbines are dependent on vessels utilized for inspection and maintenance. High sea states could be accounted for by using larger vessels with heave compensate capability. The vessel could be shared with the nearby oil and gas platforms.

4 INDUSTRY STUDY OF SIMILAR ONGOING PROJECTS

There are currently no other worldwide projects as close in similarity for offshore FPSO or platform electrification as Hywind Tampen. However, there are multiple past and ongoing floating and arctic wind projects that can be studied to aid in future development of FPSO/platform electrification via floating wind power.

4.1 List of Related Projects and Status of Each

4.1.1 Hywind Scotland

Hywind Scotland project was the first commercial floating wind project in the world to generate power to shore. The project was commissioned in October 2017 [Ref 3.]. It is located 29 km (18 mi) from Peterhead, Scotland and consists of five 6-megawatt turbines in water depths of up to 129m. It is operated by Hywind (Scotland) Limited, of which Equinor holds a 75 percent share and the United Arab Emirates' clean energy vehicle Masdar holds the other 25 percent. Hywind Scotland achieved a capacity factor of 65 percent in the first winter of operation, beating Equinor's initial estimates [Ref. 4]. Over the course of a year, it's capable of generating 135 GWh of clean electricity, enough for 20,000 Scottish homes. The wind farm is tied into the onshore power grid via a 30km submarine export cable and 2km onshore export cable.

Figure 4-1: Hywind Scotland Floating Offshore Wind Farm (credit: Equinor)

In 2015, the company received permission to install the wind farm in Scotland. Manufacturing for the €188 million (CAD $294 million) project started in 2016 in Spain, Norway and Scotland. The turbines were assembled at Stord, Norway in the summer of 2017 using the Saipem 7000 floating crane, and the finished turbines were moved to near Peterhead. The final turbine was installed in August of 2017. Three suction anchors on the seabed hold each turbine in place. Hywind Scotland's towers rise 175 metres (574 ft) from sea surface to wingtip, with rotor diameter at 154 metres (505 ft). Approximately one-third of the structure is submerged and ballasted by 5,000 tons of iron ore with chains anchoring it to the seafloor. A 1 MW battery nicknamed the "Batwind" system has been hooked up to smooth out power flow. The total weight of each floating tower is near 12,000 tonnes.

Hywind Scotland's first encounter with harsh weather conditions was the hurricane Ophelia in October 2017 when wind speeds of 125 kilometres per hour (80mph) were recorded. These wind speeds were surpassed during Storm Caroline in early December 2017 when gusts exceeding 160 km/h (100 mph) and waves in excess of 8.2 metres (27 ft) were recorded. During the heaviest weather conditions, the wind turbines were shut down for safety reasons, but they automatically resumed operation afterwards. A pitch motion controller is integrated with the Hywind turbine's control system and will adjust the angle of the turbine blades during heavy winds which aids in mitigation of excessive motions of the tower.

Hywind Scotland's pilot project status has spawned data sharing agreements between supply chain businesses and academia through the Offshore Renewable Energy (ORE) Catapult's Platform for Operational Data (POD) service. The POD service is designed to offer comprehensive data sets from offshore wind demonstrator sites across the UK to improve understanding of how offshore wind farms operate in real-world conditions and support innovative research, projects and product development. Under this agreement between Equinor, Masdar and ORE Catapult, subscribers can access a pre-defined set of full-scale measurements from one of Hywind Scotland's five turbines. [Ref. 5]

4.1.2 WindFloat Atlantic

WindFloat Atlantic is an offshore floating wind farm located 20km (12.4 miles) off the coast of Viana do Castelo, Portugal with a water depth of 100 metres (328 ft). The project was commissioned in January 2020 and is the world's first semi-submersible floating wind farm. It is also the first floating wind farm in continental Europe.

The wind farm is being developed by the Windplus consortium that includes EDP Renewables (54.4%), Repsol (19.4%), Engie (25%) and Principle Power (1.2%). The WindFloat Atlantic project includes three turbines installed on floating foundations. Each of the three turbines has a capacity of 8.4 MW, with a total installed capacity exceeding 25MW. The wind farm is expected to supply electricity to approximately 60,000 households, once fully operational.

The European Investment Bank (EIB) granted a €60m (CAD $93.7m) loan to the Windplus consortium for the project development in October 2018. The project also received €29.9m (CAD $46.6) from the European Commission under its NER300 innovative low-carbon energy funding program. The Government of Portugal provided €6m (CAD $9.4m) in funding through the Portuguese Carbon Fund. The consortium estimates the total cost of the WindFloat Atlantic project at €121.4 million (CAD $189.5m).

The installation of the first turbine on the floating platform of the WindFloat project was completed in October of 2019. The first platform began supplying clean energy through a 20km export cable to the substation of Viana do Castelo in January 2020. The second platform was transported to the wind farm site from the Port of Ferrol in Spain in December 2019 for installation next to the first foundation.

Like Hywind Scotland, WindFloat Atlantic will also contribute to progressing future floating projects in the offshore wind industry, this time with a semisubmersible foundation technology.

Figure 4-2: WindFloat Atlantic Offshore Floating Wind Tower (Credit: WindFloat)

4.1.3 Tahkoluoto

Tahkoluoto is Finland's first offshore wind farm and the world's first offshore wind farm built for icy conditions. It commenced operation in October 2017.

The Tahkoluoto installation includes 10 turbines with a capacity of 4.2 MW each. The farm, located in the Gulf of Bothnia, the northern-most arm of the Baltic Sea, off Finland's west coast, has an estimated annual power production of approximately 155GWh with average power production 43 percent of maximum capacity. The rotor hub height is approximately 90 metres and the rotor diameter 130 metres.

The fixed offshore wind project total cost was reported to be approximately €120m (CAD $187.3m).

The project was undertaken by Finnish company Suomen Hyötytuuli, and the technology development has been on-going since 2010. Conditions for offshore wind power in Finland involve a sea that freezes, a shallow coastline, a hard seafloor and less wind than the North Sea.

A key development in the case of Tahkoluoto was the gravity-based steel foundations designed to handle ice loads manufactured locally by Technip Offshore Finland. Following preparation of the seabed to provide a level surface, the hollow gravity base foundations weighing up to 500 tons were installed. A Sync hoist load positioning system from Enerpac Heavy Lifting Technology was used for the installation to ensure the foundation remained as close to vertical as possible. This prevented damage to the leveled seabed and facilitated the subsequent addition of the turbine tower.

The project’s main co-operation partners were: Siemens Gamesa (turbines), Technip Offshore Finland Oy (offshore foundations), ABB Oy Power Grids (substation), Pori Energia Sähköverkot Oy (grid connection), Prysmian Finland Oy (offshore cable), Jan De Nul NV (marine operations), Finnish Sea Service Oy (offshore cable installation), and Blue Water Shipping Oy, Finland (port operations/ logistics).

4.1.4 Prototype Pilot Projects

A variety of smaller pilot projects exist in floating offshore wind consisting of single prototype floating towers to demonstrate a design concept. Among these, Hywind Demo (installed in 2009), FloatGen Demonstrator (installed May 2018), and WindFloat Demo (installed October 2011) are examples of development of floating wind test demonstrations.

Hywind Demo – Equinor - In 2009, Equinor installed the Hywind Floating Demo located offshore at Karmøy, Norway. The demonstration turbine has a 2.3 MW turbine, and the diameter of the blades is 85 metres. Through eight years of successful operations the demo has confirmed and verified the Hywind concept identified in Section 3.

The total cost for development of the Hywind Demo was reported to be approximately €52.7 million (CAD $82.3m).

The Hywind Demo had a capacity factor of 50% in 2011 and has produced more than 40 GWh since start-up. Regarding resistance wind and wave activity, the tower has experienced wind speeds of 144 kph (89 mph) maximum wave height of 19 m (62 ft). Equinor has decided that the demo system integrity has been verified and analysis tools have been validated. In February 2019, the test turbine was sold to Unitech for testing high-voltage cables for power to offshore installations.

Figure 4-3: Hywind Demo Offshore Floating Wind Tower

FloatGen Demonstrator – Ideol – FloatGen is a 2MW floating wind turbine demonstrator installed off the coast of Le Croisic on the offshore experimentation site of the Ecole Centrale de Nantes (SEM-REV). The project was developed by seven partners. This project is being supported by the European Union as part of the FP7 funding program. Floatgen is France's first offshore wind turbine which supports 5,000 inhabitants with its electricity.

No cost information was found regarding the Floatgen demonstrator project.

Ideol’s Damping Pool floating foundation has an area of 36 square metres and draught of 7.5 metres. It is also the world’s first floating barge designed for offshore wind. Another significant innovation is the synthetic fiber (nylon) mooring lines, which is a world first for a permanent mooring system of this size.

Ideol is currently applying the floating damping pool concept to offshore substations as well. The substation development is a partnership between Ideol, Atlantique Offshore Energy, Chantiers de l’Atlantique Business Unit specialized in Offshore EPCI projects and ABB. This substation will be suitable for both bottom-fixed and floating offshore wind farms at depths of 40 metres and above.

Figure 4-4: Floatgen Demonstrator Towing to Location (Credit: Ideol)

Aside from the floating offshore wind turbines, Ideol has also used the shallow-draft damping pool concept to provide a foundation for a floating substation. This design utilizes AOE's certified electrical offshore substation concept SeeOs, which is a universal floating offshore substation engineered to operate in the world most extreme environments and to offer maximum modularity. This solution offers several advantages, such as installation of the topside onto the floater at quayside, testing and pre-commissioning at quayside and installation without heavy-lift offshore operations.

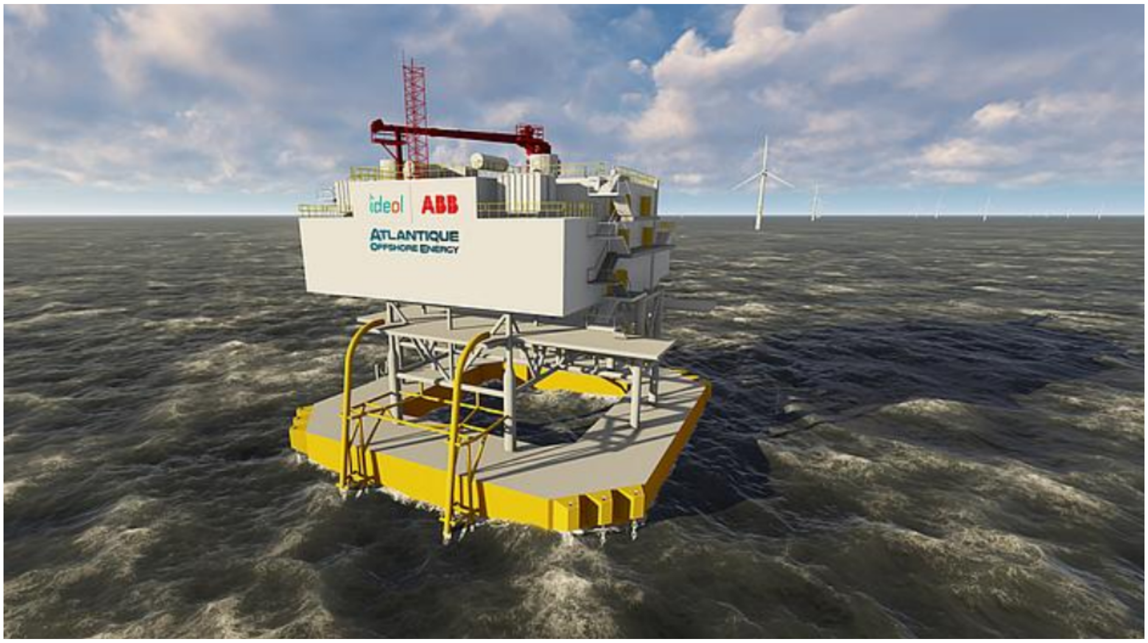


Figure 4-5: Floating Substation with Shallow-Draft Damping Pool Foundation Concept (Credit: Ideol)

WindFloat Demo - Principle Power – In October 2011, Principle Power deployed a full-scale 2 MW WindFloat prototype 5 km off the coast of Aguçadoura, Portugal. The structure was completely assembled and commissioned onshore before being towed some 400km along the Portuguese coast. It was assembled at a facility near Setubal, Portugal. Additionally, certification (or class) was an area of focus in the prototype design as it will be a future requirement for commercial projects. To date, the system has produced more than 16 GWh of electricity. Power is delivered by subsea cable to the local grid. Principle Power gained valuable operational data and experience for use in future WindFloat systems world-wide through this demo project.

The project total cost was reported to be approximately €100 million (CAD $156.1m).

The WindFloat's successful 5-year deployment in the open ocean of the Atlantic has proven that the technology can meet future goals and was ready for commercialization. In July 2016, having completed all its project objectives, Principle Power initiated the WindFloat decommissioning process. In the five years of operation, it has encountered 17 m (56 ft) wave heights and 111 kph (69 mph) winds.

Dounreay Tri – Hexicon - Hexicon is the global leader amongst multi-turbine platforms. These multi-turbine platforms are semisubmersible and have distributed columns in a truss structure to provide enough buoyancy. In addition, a mooring system is installed to the platform to enable alignment with the wind to avoid wake losses. The main project called Dounreay Tri is planned to be deployed at the North coast of

Scotland with two 5 MW turbines installed on the platform. Construction started in March 2017 but was stopped and the project is currently on hold.

Hexicon, through their joint venture CoensHexicon is working with Shell in early development of the 200MW floating wind project Donghae TwinWind Project, which will be located offshore Korea.

Figure 4-6: Dounreay Tri Demonstration Graphic

GICON-SOF – GICON - The GICON-SOF project led by the engineering company GICON is the first developer of the TLP foundation for offshore floating turbines. The GICON-SOF demonstration project will be equipped with a 2.3 MW wind turbine but has not been fully constructed or installed yet. This project was initiated due to the drawbacks of large manufacturing sites for semi-submersible platforms and the deep drafts of spar buoys. A TLP does not have these challenges and is therefore a preferred alternative. In addition, the TLP foundations have a low structural weight and high stiffness and result in lower cost. The GICON-SOF has four vertical taut-leg mooring lines and four support mooring lines all connected to the four columns of the platform to provide stability. The operational depth of the GICON-SOF is expected to be between 40 m and 250 m offering flexibility for installation sites. The TLP foundation has its own challenges when it comes to installation. Temporary buoys and winches might be used to avoid the hull losing stability during installation.

GICON's research partner LWET receive funding from the European Commission program Marinet2 in January 2020 for tank tests in Edinburgh, Scotland, scheduled for late summer 2020. The tests will validate and optimize the innovative self-installation of the cost competitive Tension Leg Platform (TLP) under development.

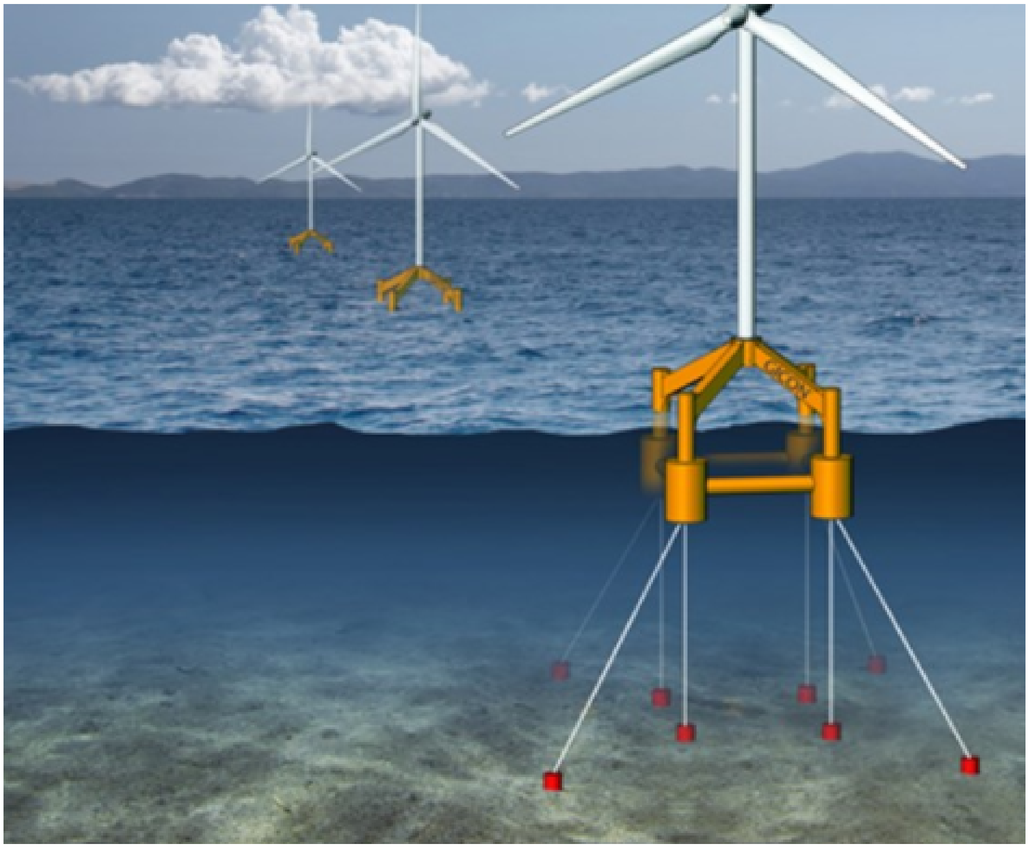


Figure 4-7: GICON-SOF TLP Concept

4.2 Similarities Regarding Project Challenges and Goals

4.2.1 Floating Wind Power Projects

Each of the existing floating wind power projects have similarities to project challenges associated with electrification of an FPSO or platform. Key similarities of the associated challenges are as follows;

- Challenges associated with dynamic cabling at different water depths include design and qualification of dynamic cable which will last the duration of the project life without fault. Also, determination of best cable configuration and array layout can be a challenge as minimizing stress on cabling and enabling a lower duration installation is important (see Section 6.3.2). Determination of the best suited support structure (floating foundation) for each field. Generator size can have a significant effect on the tower's performance in heavy wave action.

- Determination of the best anchoring solutions for each floating wind tower can have a significant impact on reliability, but also an impact on CAPEX for procurement and installation of anchors and mooring lines.

- Optimizing the power storage has been a significant challenge for offshore wind projects in general. The electrification aspect of this will only exacerbate the challenge. It will be a balance between weight, battery storage size, available real estate and required capacity.

4.2.2 Wind Power Projects in Sea ice and Icing Conditions

Tahkoluoto was Finland's first offshore wind farm, and the world's first offshore wind farm built for icy conditions. Research done in the Gulf of Bothnia has indicated average ice thicknesses in the drift ice zone up to about 1.3m and ridges growing up to several metres thick. ([Ref. 24]). The gravity-based steel foundations were equipped with a cone at the waterline designed to allow the structure to withstand ice ridges up to 25 metres thick ([Ref. 23]).

The cold weather marine conditions could cause challenges to different aspects of the project. Some of the key challenges are listed as below ([Ref 14]):

- Manufacturers face challenges with transporting the blades to installation sites and are considering segmented blade designs which can be bonded on-site before final installation due to the available open water installation window. The proposed increased size of turbine blades is limited by weight, meaning that lighter materials such as thermoplastic foams and alternative composites are being considered. Lighter blades allow for easier installation and repair as well as improving performance. However, there are inherent difficulties with composite manufacture, such as the misalignment of fibers and inconsistent resin distribution, which can lead to lowered fatigue strength in addition to the higher cost.

- Leading edge erosion is caused by the repeated impact of rain, atmospheric ice/snow, spray ice and particulate matter which leads to a loss of aerodynamic efficiency and can compromise the structural integrity of the blades, leading to water ingress and UV damage. Even a small amount of leading-edge erosion can result in a ~5% drop in annual energy production.

- Heavy accumulation of atmospheric or spray ice can result in a total stop of the turbine. Ice can last considerably longer on the blades than the time at which icing conditions occur. Consequently, at harsh ice condition at sites, the annual power loss may grow up to 20-50%.

- Ice throw risk in the form of ice shedding may pose a major safety hazard in certain environments. This may affect the safe operations of the turbines in wind parks because of the possibility of thrown ice pieces causing injury to personnel or damage to facilities.

- Ice can also cause problems such as: inefficient or inoperative wind measuring equipment (both during wind assessment and turbine operating phase); rapid performance degradation; increased noise level; increased fatigue on wind turbine and foundations; down time due to excessive vibrations.

- Cold weather packages from a turbine manufacturer are typically adopted for cold climate sites. The aim of the technical solutions is to widen the operating temperature range of a selected wind turbine. This may solve the temperature related issues, but not other issues associated with icy environments.

- At sites with a high probability of icing (e.g. several weeks per year), systems that ensure the operation of turbines should be installed to avoid long stoppages during icing weather events. An active or passive de-icing or anti-icing system for the rotor blades is recommended for these areas.

- Floating and pack ice on the water surface and atmospheric icing can expose the wind turbine to excessive vibrations. Ice drift and interaction with the foundation may trigger structural vibrations or even damage by exciting the tower. A structures' icing will excite flap wise the blades, but the main effect is felt on the tower.

5 SUMMARY OF MODIFICATIONS OR ADDITIONS REQUIRED AT THE HOST FACILITY

For electrification of the offshore production facility, by either modification for an existing facility or design of a purpose-built facility will be driven by the type of the installation. The subsea cables must be interfaced with the platform electrical system. The solution for a geostationary platform and weathervaning ship-shaped FPSO will be vastly different.

5.1 Brownfield Approach

In a brownfield scenario, the concept would be electrical power supply to an installed and operating FPSO or platform. The host facility will be equipped with power generators (gas turbines or reciprocating engines). These power generators are typically dual fuel turbines running on low pressure fuel gas from the production well or liquid diesel fuel from the storage tanks. Majority of the time, the power generators run on low-pressure fuel gas during production due to availability of gas from the production stream. Diesel is intermittently used during startup, commissioning or plant maintenance period.

The sizing basis for the wind generated power supply will be driven by the design factors of the host facility. Following are some of the factors:

1. Total electrical load demand on the facility.
2. Source of heat for process plant and heat load demand. Typically, heat is generated from waste heat recovery units attached to exhaust of the gas turbines.
3. Driver selection of compressors and large motors, i.e. turbine driven, or motor driven.

Based on the design utility requirements of the host facility, the power supply from wind source would be partial or 100% of operating electrical load of the platform. The platform switchgear would be capable of handling variable power supply from wind generated power.

The brownfield approach has not yet been implemented in offshore developments. The two projects with some degree of similarity are the Goliat FPSO and Gjoa platform. Both projects were greenfield and power supply was from an onshore electrical grid.

The existing facilities will need modifications to pull the power supply cable from seabed, terminate the cable on the process deck and transmit the power to the main switch board of the platform. The switch gear will require modifications to handle power supply from subsea cable and onboard power generation. The layout of the platform will require changes to accommodate the additional electrical gear, cable pull winches, cable trays, etc. Interface between the subsea dynamic cable and the platform pull tube slot is the key interface. The above mentioned FPSO and semisubmersible platforms are geostationary. Weathervaning turret moored FPSOs have a unique challenge of requiring swivels capable of handling high voltage transmission. Such swivel technology is currently qualified with Medium Voltage (MV) but will require qualification prior to application for High Voltage. In a brownfield turret moored FPSO, turret swivel modifications will require replacement of the swivel to transmit power from the subsea cable to the FPSO. Replacement of the turret swivel can be a complex job given the busy layout of the turret decks.

5.1.1 Substation Equipment

In the brownfield scenario, the substation is assumed to be a small floating structure separate from the FPSO (but located close by). Substation equipment for offshore wind power energization is required for transforming, switching, filtering, storing and compensating for reactive power so that the FPSO can tie the incoming power into the main host facility power grid. In addition to the standard components of a substation, power storage equipment is required as well to compensate for the inconsistent nature of wind power generation. There are options regarding power transmission from the substation to the FPSO, such as stepping voltage down for the cable between the substation and host, but equipment associated with tie-in to the host will still be required at the host facility itself. If real estate and capacity are available on the host, it is generally preferable for substation equipment to be located on the host facility (due to cost of the separate substation platform).

Offshore wind power substations are generally unmanned with minimal amenities for support and maintenance staff on site (lighting, restrooms, etc.).

Offshore substations have traditionally been located very close to the associated wind power array due to the desire to step up to high voltage for the entire step-out distance to shore. In the case of electrification with export power at array voltage (33/66kV), it is more desirable to include the substation as close to the host facility as possible (approximately 2km) to allow for the option of stepping down voltage for the cable between the substation and host (Figure 5-1). Distance from the host facility would need to be evaluated on a development by development basis given future development potential, operations and ice management in and around the host facility.

An exception to this would be if the electrification wind array was a significant distance from the host and utilizes an HVAC export system like traditional large wind farms. In this case it would be more beneficial to keep the substation near to the wind power array.

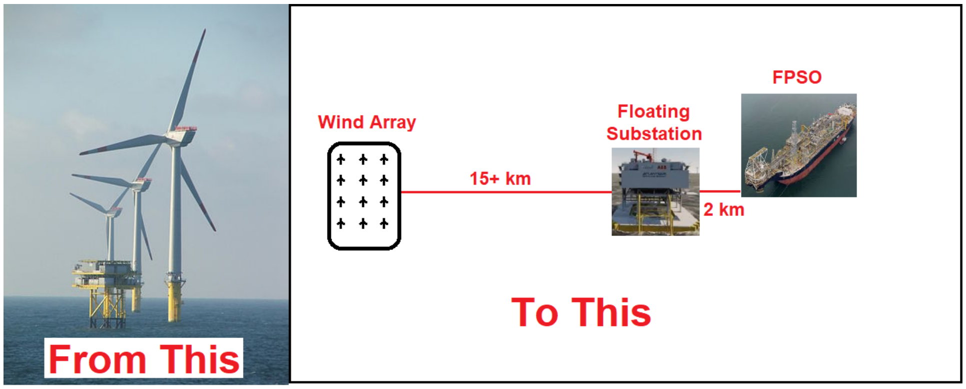


Figure 5-1: Substation Location for Electrification

The following substation equipment will need to accompany the wind power tie-in to an FPSO. For the brownfield scenario, this equipment is assumed to be located on both the host facility and a separate, stand-alone floating substation.

- Helideck;
- Power systems, including:
    - Power Transformers – Step-down from array voltage to usable voltage of the FPSO main switchgear.
    - Auxiliary Transformers – Used to further step-down voltage after the main transformers to power utilities on the substation itself.
    - Switchgear – Contains the power bus-bars circuit-breakers and disconnectors used for branching and switching power.
    - MVAC and LVAC cables and bus duct systems for running cable throughout the substation.
    - Battery System (including associated rectifier) – Used for storing excess power from wind turbines. The capacity of battery power would be determined based on project specific total wind power generation capacity, expected capacity factor of the field and percentage of host power generated by wind power. It is assumed that lower total percent generated by wind power would require lower battery capacity.
    - Shunt Reactors – Reactors provide compensation for the reactive power (Volt-Amps Reactive, or VARs) of the cable providing power from the wind array. Shunt reactors are the same as power transformers, but they only have one winding per phase as compared

to power transformers. Shunt reactors are used to increase the power and energy system efficiency as it absorbs and compensates the reactive power in cables and transmission lines. It can be directly connected to the power line or tertiary winding of a transformer. Generally, the shorter the incoming export cable, the less compensation is required.

  - Harmonic Filters - Harmonics are one of the more common power quality issues presented by wind power because of the high switching frequency of the power converters and the possible nonlinear behavior from electric machines (generator, transformer, reactors) within a power plant.

- Auxiliary Systems, including:
  - Auxiliary Generators (generally 480 V) – Used to provide backup power generation to all substation auxiliary equipment and control/monitoring system.
  - DC and UPS Systems – Provides backup battery power for the control/monitoring systems auxiliary equipment in case of power disruption.
  - Lighting and Sockets Systems – provides lighting and access to “small power” via 110V or 220V sockets.
  - Earthing, Bonding and Lightning Protection Systems – Provides protection against extreme weather condition such as lightning.
  - Station Control System - The Supervisory Control and Data Acquisition (SCADA) system is used to monitor all onboard substation equipment as well as equipment in each individual offshore turbine. Interconnection between the substation and FPSO control system is required for control and monitoring of the offshore wind power system from the FPSO.
  - Public Address and General Alarm System – Used to provide general alarm and intercom system within the offshore substation.
  - CCTV System - The Closed-Circuit Television (CCTV) system provides active security video surveillance of critical areas on the substation.
  - Meteorological Measurement System – Used for gathering wind resource characteristics and external metocean conditions at the heights and depths relevant to wind turbines and their associated structures and components. Knowledge of these conditions enables appropriate action to be taken for wind turbine structures and components, so they can produce with maximized efficiency and withstand the loads expected over a project’s

lifetime. Human safety, vessel navigation, and project construction and maintenance activities are strongly tied to the metocean environment.

  - Communication Systems for IP VOIP, VHF and AIS – The IP VOIP system allows for digital voice communication over internet protocol networks (the internet). The VHF system allows for Digital Voice Communication in the Maritime VHF Band. The Automatic Identification System (AIS) is an automatic tracking system that uses transceivers on ships and is used by vessel traffic services (VTS). When satellites are used to detect AIS signatures, the term Satellite-AIS (S-AIS) is used. AIS information supplements marine radar, which continues to be the primary method of collision avoidance for water transport.
  - Access Control System -The access control system determines who can enter or exit the substation, where they are allowed to exit or enter, and when they are allowed to enter or exit.
  - Navigation Marking Systems – Provides navigation marking for any vessels or aircraft in the area. Navigation marking is often performed with buoy systems to mark the location of any major obstacle (such as an offshore wind tower).
  - IT Network - The IT network is a computer network, or a group of computers that use a set of common communication protocols over digital interconnections for sharing resources located on or provided by the network nodes.
- Mechanical systems, including:
  - Small Cranes for the Cable Deck – Sized for maximum lifting of equipment on the cable deck.
  - Main Crane for Roof Deck - Sized for maximum lifting of equipment on the roof deck.
  - Crane/s for the HV GIS Rooms - Sized for maximum lifting of equipment in the HV GIS rooms.
  - Crane/s for the MV GIS Rooms - Sized for maximum lifting of equipment in the MV GIS rooms.
  - Diesel Storage Tank – Generally sized for a given amount of diesel generator run time (for example, 14 days).
  - HVAC System - used to provide climate control and circulation in any area on the substation that requires it.

- Fire and safety systems, including:
    - Fired detection and alarm system (FDAS).
    - Firefighting Systems – Sprinklers and suppression systems.
    - Safety equipment and lifeboats.

5.1.2 Power Interfaces and Tie-in

The power supply from the wind array will be tied into the host facility's electrical system. In a brownfield scenario, the following interfaces must be addressed:

- Subsea power cable-pull through pull tubes in geostationary facilities or into dry-mate connectors or swivels in the turret/hull structure for weathervaning FPSOs.
- Subsea cable termination on the facility.
- Transformers (step up or step down) on the facility.
- Cable trays/layout interfaces on the process deck for inboard run to the facility switchboard.
- Modifications to facility HV switchboard.
- Modifications to power management system for parallel operations of host GTGs and wind power.

5.1.3 Redundancy in Power Supply

In a brownfield scenario, the host facility shall have a power generation package with appropriate sparing for maintenance and down time. The power generation machines offshore are typically dual fueled gas turbines coupled to AC generators. With a wind power supply to the host facility, the existing gas turbines can either be retained or individual machines may be removed to optimize the facility layout. The gas turbines would be operated in parallel to supplement the power supply from the wind farm. The power management system of the host facility will need modification for parallel operation with the incoming wind power supply. The system will have redundancy to provide power supply to the platform in the event of reduced or disruption of wind power.

Battery storage is an option for short duration redundancy. While acting as a buffer for the wind power array, power storage is very large and can only support an average sized FPSO for 1 to 2 hours per 40ft long, container sized battery unit. The result is that providing significant storage comes with an added CAPEX as the substation size and weight will increase and battery storage equipment has an associated cost.

Primary sources of power storage include providing operating reserves to the FPSO facility, avoiding fuel cost, emissions and wear and tear incurred by cycling on and off gas-fired power plants. In the case of wind power electrification, the battery system benefits by being smarter than standard storage. Hywind Scotland is currently using a smaller scale (1MW) battery system that holds back and stores electricity and, on demand, provides power to the grid. This technology will be very beneficial to optimizing the supply of power to the host facility.

5.1.4 Real Estate Requirements

The facility process deck layout will need relocation of equipment, cable trays, pipes and pipe support to accommodate additional cabling for electrification. Additional equipment may require reconfiguration of deck space or addition of decks. The switchboard room may need additional space to accommodate modifications to the facilities switchboard. New equipment will need to meet the appropriate hazardous area classification requirements on the process deck. Potential space saving can be achieved by removal of spare gas turbines on the host facility. The modifications on the facility must be scheduled to minimize the disruption or shutdown of the platform.

5.2 Greenfield Approach

In a greenfield approach for electrification of an offshore development, power supply from a wind array will be integral part of facility design. The process deck layout will be optimized to reduce the need for heavy equipment to be located in the wind farm. Process rotating equipment for gas compression or water injection pumps will be electrical motor driven instead of gas turbine. Electrical heaters may be selected to reduce requirement of waste heat recovery units on gas turbines for platform heating load. Gas turbine sizing and sparing will consider the power supply from wind farm.

5.2.1 Substation Equipment

In a greenfield scenario, the substation could be incorporated into the FPSO or be a small, separate structure from the FPSO (but located close by). If the substation is kept as a separate structure, then the equipment list shown in Section 5.1.1 applies. If the substation equipment is included on the FPSO, the equipment that must be added to the FPSO is as follows:

- Power systems, including:
    - Power Transformers – Step-down from array voltage to usable voltage of the FPSO main switchgear.
    - Auxiliary Transformers – Used to further step-down voltage after the main transformers to power utilities on the substation itself. Note that additional auxiliary transformers are not

required but may need to be expanded to accommodate areas with the additional electrical equipment.

  - Switchgear – Contain the power bus-bars circuit-breakers and disconnectors used for branching and switching power.

  - MVAC and LVAC cables and bus duct systems for running the additional electrification cable in the FPSO.

  - Battery System (including associated rectifier) – Used for storing excess power from wind turbines. The capacity of battery power would be determined based on project specific total wind power generation capacity, expected capacity factor of the field and percentage of host power generated by wind power. It is assumed that lower total percent generated by wind power would require lower battery capacity. If the FPSO has limited real estate for battery storage, then it may guide the philosophy regarding the amount of battery storage on the host.

  - Shunt Reactors – Reactors provide compensation for the reactive power (Volt-Amps Reactive, or VARs) of the cable providing power from the wind array. Shunt reactors are the same as power transformers, but they only have one winding per phase as compared to power transformers. Shunt reactors are used to increase the power and energy system efficiency as it absorbs and compensates the reactive power in cables and transmission lines. It can be directly connected to the power line or tertiary winding of a transformer. Generally, the shorter the incoming export cable, the less compensation is required.

  - Harmonic Filters - Harmonics are one of the more common power quality issues presented by wind power because of the high switching frequency of the power converters and the possible nonlinear behavior from electric machines (generator, transformer, reactors) within a power plant.

- Auxiliary Systems – Most auxiliary systems are assumed to already be present in an FPSO. Additional auxiliary system needed include:

  - Earthing, Bonding and Lightning Protection Systems – Provides protection against extreme weather condition such as lightning. This applies specifically to the added electrical equipment for the wind power tie-in.

  - Station Control System - The Supervisory Control and Data Acquisition (SCADA) system is used to monitor all onboard equipment related to the wind power array as well as equipment in each individual offshore turbine. Interconnection between the wind power and FPSO control system is required for control and monitoring of the offshore wind power system.

- Mechanical systems such as cranes and HVAC systems are assumed to already be included in the FPSO.

- Fire and safety systems are assumed to already be included in the FPSO.

5.2.2 Power Interfaces and Tie-in

Interfaces to the facilities will be similar as in the brownfield approach described in Section 5.1.2. The interfaces in a greenfield approach will be preplanned and be integral to platform design. Dedicated pull tubes or swivels will be provided to accommodate subsea cables. Cables and cable trays from tie-ins to facility switchboard will be preinstalled at the construction yard.

5.2.3 Redundancy in Power Supply

The facility will have gas turbines sized to provide power supply to the platform at reduced rate. The total gas turbine generation capacity, for example, could cover half of the average wind generation (i.e. if the offshore wind array provides 50% of the host power on average, then 25% gas turbine capacity could be removed from the FPSO). The lowest risk option would be to retain all gas turbine generation capacity and only operate the required number of generators throughout the year. The process plant can be designed to scale down production or reduce power supply (load-shedding) to non-essential loads in the event of disruption of power from the wind array. During normal operation, wind power will be utilized to the maximum extent possible and the load on the facility gas turbines will be reduced. Battery storage on board the facility can also be evaluated for power fluctuations or disruption for short duration. A battery storage solution has the disadvantage of additional weight and CAPEX.

5.2.4 Real Estate Requirements

Larger facility layout space will be utilized to accommodate substation equipment described in Section 5.2.1. There would be a space and weight penalty on the platform, but this design will eliminate the need for separate platform for the wind array substation equipment. Facility deck space can be further optimized by reducing the sparing of the facility gas turbines.

5.3 Additional Upcoming Power Transmission Optimization (Subsea Substations)

In recent years, the industry has started moving toward the marinization of offshore substations. One of the most revolutionary subsea technological developments implemented in the last decade has been the subsea compression system installed at the Åsgard field, located offshore Norway. The project has been in continuous operation since September 2015. This has proven the feasibility of installing a large compression station on the seabed, but more importantly for offshore wind, proven the feasibility of the associated power distribution equipment and control system equipment being installed subsea. This includes large subsea transformers, power cables and terminations and high voltage wet-mate connectors, all of which are essential technologies for subsea substations for offshore wind application (Figure 5-2).

Subsea substations would be installed on the seabed in deeper water or in an excavated pit in shallower water (if required due to the presence of ice). Although marinized power equipment can be significantly more expensive, it is expected that there is significant cost savings and increased reliability associated with eliminating the full topsides substation in favor of a much more compact subsea substation. Benefits of subsea substations are as follows;

- HSE / safety is improved with this equipment on the seabed
- Less complex, lower cost installation and commissioning
- Increased lifetime and availability (cooler subsea environment)
- Lower Levelized Cost of Energy (LCOE)

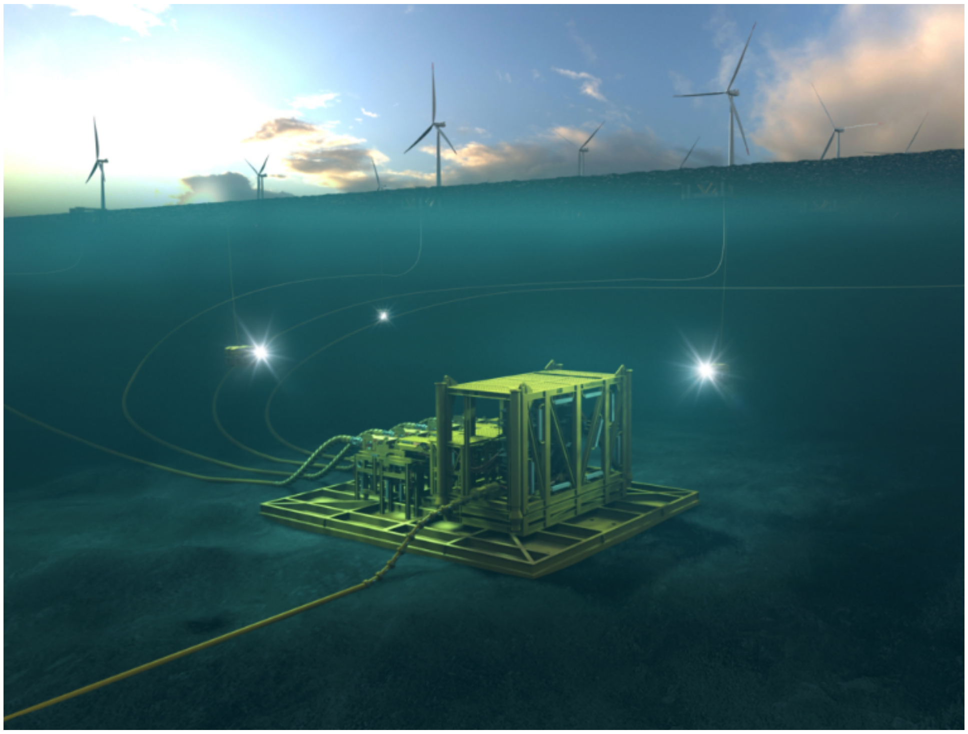


Figure 5-2: Offshore Subsea Substation Concept (Credit: Aker Solutions)

Regarding the technical readiness status of the required components, the primary substation equipment for 66kV applications is currently TRL 4 (qualified but not field proven). The primary components in question are the 66kV, high capacity subsea connector technologies. These connectors need further development in order for subsea substations to be realized. ABB and Siemens are currently outlining development of connectors that could satisfy the requirements of smaller subsea substations.

6 SUMMARY OF THE DIFFERENCES BETWEEN FIXED AND FLOATING WIND DESIGN

6.1 Fixed vs. Floating Systems

6.1.1 Fixed Foundation Wind Turbine System

Almost all currently operating offshore wind farms employ fixed foundation turbines, except for a few pilot projects which are using floating foundations. Fixed foundation offshore wind turbines have fixed foundations underwater and are installed in relatively shallow waters of up to 50–60 m depth.

Types of underwater structures of fixed wind turbines include monopile, tripod, and jacketed, with various foundations at the sea floor including monopile or multiple piles, gravity base, and caissons. Offshore turbines require different types of bases for stability, according to the depth of water and soil characteristics.

Most of the fixed foundation wind turbines use monopile (Figure 6-1) as the foundation type. Monopiles up to 11 m diameter at 2,000 tonnes can be constructed, but the largest so far are 1,300 tons which is below the 1,500 tonnes limit of some crane vessels.

The tripod pile (Figure 6-2) substructure system is a new concept developed to reach deeper waters than with the shallow water systems, up to 60 m. This technology consists of three monopiles linked together through a joint piece at the top. The main advantage of this solution is the simplicity of the installation, which is done by installing three monopiles and then adding the upper joint.

A steel jacket structure comes from an adaptation of concepts that have been in use in the oil and gas industry for decades. Their main advantage lies in the possibility of reaching higher water depths (up to 80m). Their main limitations are high construction and installation costs.

Gravity-based foundations (Figure 6-3) are used in Tahkoluoto wind farm, which is the only offshore wind farm with foundation designed for icy conditions. The main advantages of the GBS are: good performance of similar structures in the oil and gas and port engineering industries; suitability as a foundation in rocky or sandy soils, with its high bearing capacity, where pile driving can be complicated; and being an alternative that can enrich market competitiveness and therefore reduce costs in any industry. The main disadvantages of the GBS are: it has not had great acceptance in the wind industry up to now; it needs soil with specific geotechnical properties, such as high bearing capacity; in general, previous soil preparation is needed for correct support of the structure; the larger footprint area on the seabed, with its associated environmental impact; and the necessary means of manufacture, transport, and installation.

Figure 6-1: Monopile Foundations (Credit: ALE-Giant)

Figure 6-2: Tri-pod Foundations Ready to be Transported (Credit: Mandelsloh)

Figure 6-3: Gravity-based Foundation for Tahkoluoto Wind Farm (Credit: Offshorewind.biz)

6.1.2 Floating Foundation Wind Turbine System

For locations with water depths over about 60–80 m, fixed foundations are uneconomical or technically unfeasible, and floating wind turbines anchored to the ocean floor are needed. Till now, globally there has been only a few pilot projects with floating foundation wind turbines. The basic principles of floating foundations are from the offshore oil and gas industry. There are many kinds of floating foundations under development, but in general they can be separated into four types: SPAR type; semi-submersible type; barge type; and TLP type.

A SPAR type floating wind turbine is based on the SPAR type platform. It uses one long cylinder to provide buoyancy. The bottom part of SPAR type foundation is usually filled with fixed ballast to bring its center of gravity below its center of buoyancy, hence providing stability to the whole floating system. The SPAR type wind turbine will be moored by a few mooring lines to the seabed. The Hywind series wind turbines are SPAR type (Figure 4-1, Figure 4-3).

A semi-submersible type floating wind turbine is based on the semi-submersible platform. It has a few columns to provide buoyancy and stability through separated water plane area distanced from the platform center. The turbine can sit in the middle of the columns or on top of one of the columns. The semi-submersible type wind turbine will also be moored by mooring lines to the seabed. The WindFloat type wind turbines are semi-submersible type (Figure 4-2).

A barge type floating wind turbine uses a barge type of structure to provide buoyancy and stability mainly by large enough water plane area and distance from the structure center. Ideol type wind turbine is barge type (Figure 4-4).

A TLP type floating wind turbine is still in the concept stage. The floating foundation has a few columns to provide buoyancy. It is connected to the seabed by a few rigid tendons. The buoyancy of the foundation is much larger than the system's weight, so it can constantly maintain tensions in tendons to ensure the stability of the floating system. Tension leg mooring systems have vertical and/or slanted tethers under tension providing large restoring moments in pitch and roll. The GICON-SOF type wind turbine is TLP type (see Figure 4-7).

The advantages of floating foundations for wind turbines include:

- Elimination of the water depth limitation; wind farm can be deployed further away from the shore and benefit from greater wind resource in deeper water.
- Due to the further distance, visibility from the shore is dramatically reduced.
- The further distance can reduce the usage conflicts with other activities (fishing, coastal navigation, and recreation).
- Floating foundations and wind turbines are built on land then towed offshore to be anchored at the selected site. This provides for easier installation and decommissioning.
- A floating wind turbine platform can be towed out to sea fully constructed. This could potentially be much simpler and less costly than the specialized ships required to deploy fixed foundation wind farms.
- If a fixed foundation wind turbine needs to be replaced, it's an incredibly complex project. Floating platforms, by contrast, can be quickly and easily towed into place or removed.

At the same time, the floating foundations for wind turbines have disadvantages such as:

- Fixed offshore wind technology gets more mature every year, lowering total costs with each new innovation.
- A few floating-platform systems are in the water, but not enough to provide a clear picture of the optimum platform. A standard platform that can be manufactured at scale will be required to produce the economies that make offshore platforms viable.
- Floating platforms require anchors on the seabed and connecting cables or chains that can disrupt offshore ecosystems. Though most biomes can adapt to the temporary construction disruption, there's always the potential of creating artificial reefs that invite invasive species. The effects on migratory animals like whales and birds also are unknown.

- Floating foundations move in the ocean. The movement from foundations can impact the functionality and safety of the turbine components. Special control system in turbine needs to be designed to take the motion caused by the floating foundations into account to improve the power generating quality. The foundation movements could increase the accelerations at the turbine significantly and they will increase the cost for turbine components design and construction.

6.2 Foundation Installation Differences

The foundation installations methods are varied based on different foundation types and installation conditions, such as water depth, sea floor condition, wind/wave/current conditions, installation equipment availability, schedule, etc. In this section, only typical installation methods are described.

6.2.1 Fixed Foundation Installation

6.2.1.1 Monopiles Installation

The monopiles are normally taken to the site on a floating vessel and then picked up and upended by a crane. the pile driving operation requires a support exhibiting little or ideally no motion while holding the pile in its correct location and inclination. Hence, normally, jack-up vessels are preferred to be used since they are bottom supported platforms.

The monopiles are usually driven into the seabed but, sometimes, drilling may be required in harder ground soils. While it is impossible to drive the pile absolutely vertically, the installation tolerance is normally up to 0.5 degrees out of vertical.

The process of installation starts with the construction of the scour protection, then the pile is driven between the middle of the scour protection circumference into the seabed, using vibration and hammering techniques.

Once the pile is in position, the larger diameter transition piece is fitted with a grouting connection over the top of the smaller diameter of the monopile, leaving an annulus for the grout connection to fill. This connection is obtained by the static friction due to the surface roughness of the contact areas. The annulus allows some tolerance that enables verticality correction through hydraulic jacks inside the transition piece.

The monopile and transition piece are fabricated with a small cone angle in the grouted section. Additional mechanical interlocks in terms of weld beads, so-called shear keys, are adjusted in circumferential direction on the facing surfaces of outer and inner steel tube to increase the load bearing behavior. This connection was used already in the offshore oil and gas industry, giving the possibility to compensate the inclinations induced by the installation of the driven piles.

After the monopile foundation and the transition piece are in place, the assembly of the wind turbine begins with the installation of the tower above the transition piece platform, which is fitted and bolted into position being assembled in phases.

In order to allow a quick installation offshore, the wind turbine components must be pre-assembled onshore. The most important components to be pre-assembled are the tower segments and the blades connected to the hub, then it is easier to attach them to the nacelle.

Vessels with high cranes are needed to install the nacelle and the blades. The installation process can only be done in good weather conditions and with low wind speeds, due to the high level of precision that is required.

6.2.1.2 Gravity-based Foundation installation (Tahkoluoto)

The gravity-based foundation installation process is based on Tahkoluoto project. Before the foundation installation, the seabed needed to be dredged and levelled to make it suitable for the gravity-based foundation. After that, the gravity-based foundations were transported on *Vole au vent* offshore jack-up installation vessel to the installation site. Then the jack-up vessel lifted the foundations up and lowered them into the water at the target location. Finally, the jack-up vessel lifted the turbine towers and mated them with the foundations.

Figure 6-4: Gravity-based Foundations Transported on Vole au vent Offshore Jack-up Installation Vessel (Credit: Jan De Nul Group)

6.2.2 Floating Foundation Installation

Different from the fixed foundations, the floating foundations are connected to the seabed through their mooring systems. Therefore, the typical installation processes for floating foundation could be divided into three parts: mooring/anchor system installation; floating foundation installation and hook up; turbine installation and mate.

The Hywind Scotland Pilot Park wind farm uses spar type floating foundations. Each turbine system consists of one turbine tower, one Hywind type floating foundation, three mooring lines and three suction piles.

The suction anchors are first installed at the target locations. The marine works were carried out by the offshore construction vessel, Deep Explorer. Suction piles (also called suction caissons or suction anchors) are a long steel cylinder topped with a pile top or cap. The cap comprises valves to assist with embedment as well as connections that differ depending on the use of the pile. The typical installation process includes deployment, self-penetration, and remainder of embedment. The suction anchors can be deployed from an offshore construction vessel or from an anchor handling vessel, with or without an A-frame. The suction pile is lowered to the seabed. Loads are resisted through the structure with mooring padeyes or pile top footings to the soil via direct bearing and skin friction. Large steel cylinders with an open bottom, the suction pile penetrates up to 60% of its length under its own weight, depending on soil conditions and the pile properties. The remainder of embedment is achieved through suction; a remote-operated vehicle (ROV) pumps water out of the top suction port after sealing pile top valves. Pile top and ROV instrumentation contribute to a precise installation.

After that, the mooring lines are connected to the anchors and pre-laid on the seabed.

For the Hywind Scotland project, the wind turbine and its tower were fully assembled and commissioned onshore, and then transported to the site as one complete assembly. Saipem used Saipem 7000 for Hywind Scotland Pilot Park wind turbine transportation to site and installation. A stability frame, which looks like “twin forks”, is specially designed and fabricated. The stability frame is used to hold the wind turbine and keep it stable during the installation. The “twin forks" extended from transportation vessel picked up the assembly, transported it to the offshore site, and held it in position while the preinstalled SPAR is pulled up between the twin forks and connected to the tower. Later, the combined structure was towed to the installation site. Finally, the pre-installed mooring lines were hooked up.

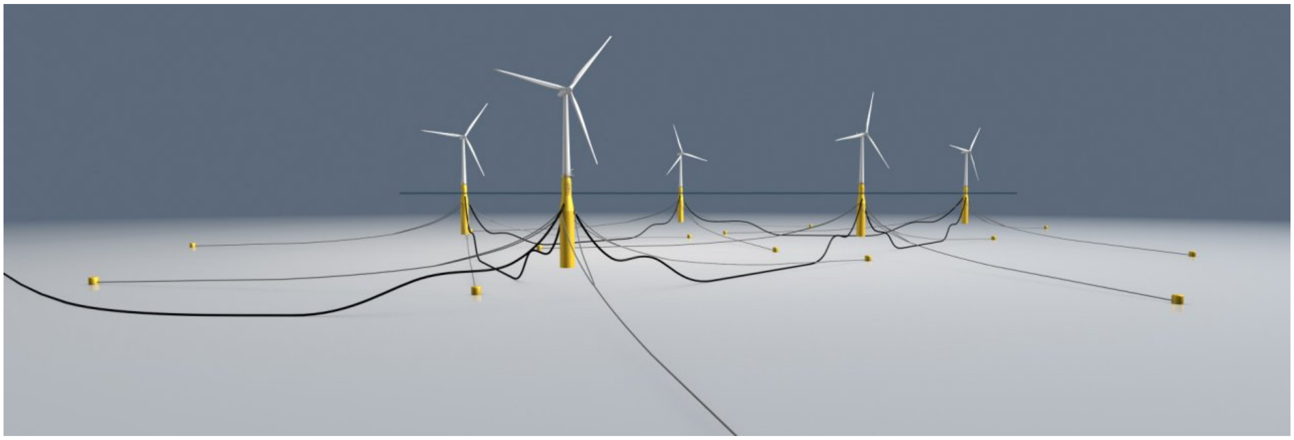


Figure 6-5: Hywind Scotland Pilot Park Mooring System (Credit: Equinor)

Figure 6-6: Hywind Scotland Pilot Park Installation (Credit: Equinor)

6.3 Cable Design and Installation Differences

For the purpose of this study, Medium Voltage Alternating Current (MVAC) and High Voltage Alternating Current (HVAC) are the primary focus due to the high CAPEX and significant real estate required for use of the more electrically efficient Direct Current (DC) systems. DC export power systems are generally used on high capacity offshore wind farms in excess of 300MW with significant tie-back distances and require AC to DC (and the reverse) conversion stations. Energization of greater than 300MW with long step-out distances is considered outside of the scope of this study.

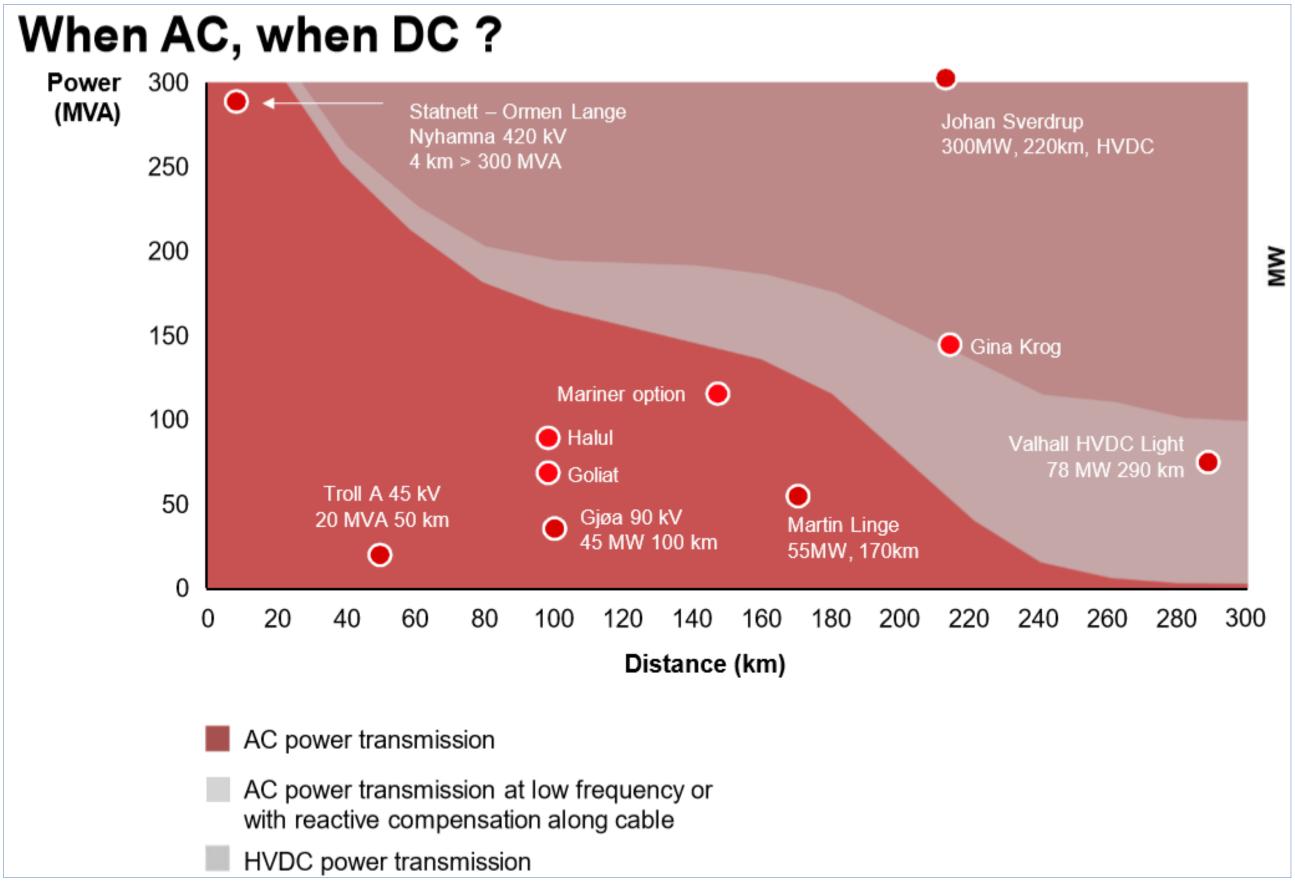


Figure 6-7: Subsea Power Transmission Project Comparison (Credit: ABB)

There has been investigation in recent years regarding the use of DC arrays, using medium voltage DC (MVDC) array cables rather than conventional 66 kV or 33 kV AC array cables. This has been a subject of ongoing research by academic and industry bodies looking at cost reduction opportunities for offshore renewables. The Offshore Wind Accelerator executed a DC Array project in 2011 [Ref. 18]. The TNEI (Tamil Nadu Electrical Inspectorate) ‘refresh study’ considered the advancements in DC technology in the intervening years [Ref. 19].

TNEI's previous assessment of DC technology identified barrier technologies which required development to enable the implementation of DC arrays. Based on the findings of the research the technology areas requiring the most technical development include integration with wind turbines and platform scale DC/DC conversion.

The main obstacle to implementing DC arrays currently is from the commercial side. Primarily, the greatest risk is uncertainty in the cost and cost reduction potential of key equipment, handling and installation. Another obstacle is the cost per MWh of AC array systems is falling at a rapid rate, estimated €63.28/MWh (CAN $98.30) for the delivery year 2022/23 compared to €125.90/MWh for 2015 (CAN $195.57). This has stifled investigation into DC array systems.

For the reasons outlined above, inclusion of DC array systems will not be considered in this study.

6.3.1 Static Cables

Traditional subsea cables are manufactured to meet the requirements of a static offshore system. This is generally associated with shallow water, fixed offshore wind farms. Static cables were designed for service in environments wholly different to those experienced by cables for floating offshore wind.

The standard arrangement of both array (MVAC) and export (HVAC) submarine cables is three core (3C). The layering of a 3C HVAC submarine power cable can be found in Figure 6-8 and shows a general structure of a static submarine power cable along with the individual cores. The MVAC cables have a similar configuration with some differences explained in this section below. The 3C cable also includes integrated optical fibers and the PVC/PE added as filling to create and maintain a circular cross-section.

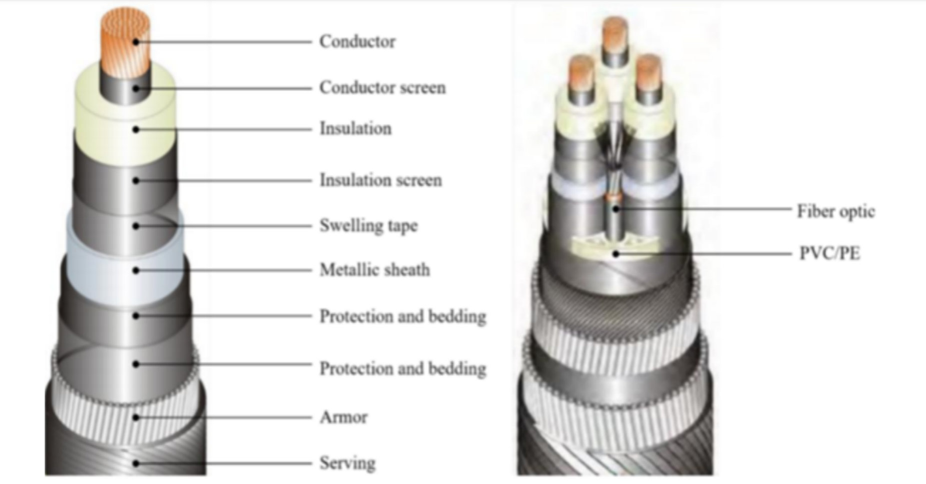


Figure 6-8: Three-Core HVAC Submarine Cable (Credit: [Ref. 6])

HVAC export cables are generally used for large power capacities across long distances and would only be used in the case of electrification of an FPSO if significant distance between the windfarm and FPSO existed.

- **Conductor Core -** The conductor is the core of each submarine power cable. The conductor conducts the electrical current from one point to the other. The conductor is made from either copper or aluminum depending on the application, but in subsea power transmission cables. Although copper is more expensive than aluminum, copper is traditionally used in submarine power cables due to a better current-carrying capacity, resulting in less material needed for the outer layers. Submarine cable cores usually use stranded round cross-section configurations.

- **Dielectric System -** The dielectric system comprises of the conductor screen, insulation and insulation screen. The insulation is the most important layer as it is a barrier for potential differences to prevent electrical leakage in the cable through fields. Most commonly, cross-linked polyethylene (XLPE) is the most dominant material for the insulation in submarine power cables. XLPE consists of cross-linked long molecular chains of LDPE forming a three-dimensional network. The cross-linking is irreversible and enables the insulation to withstand high temperatures. Due to the rough stranded conductor surface, local stresses can develop between the conductor and insulation, resulting in dielectric strength losses. To prevent local stresses on the insulation a semi-conductive XLPE conductor screen is added as layer between the conductor and insulation. The conductor screen removes these local stresses as it adds a smooth surface for the insulation. Also, a semi-conductive XLPE insulation screen is included as a layer between the insulation and swelling tape to protect the insulation from outer layers and to preserve its stable dielectric surface. The three layers of the dielectric system are generally manufactured simultaneously by triple-extrusion resulting in a long lasting, high quality insulation system.

- **Swelling Tape -** Swelling tape is placed between the insulation screen and metallic (watertight) sheath. Swelling tapes may be added to the submarine power cable to counteract the moisture which diffuses into the cable because of longitudinal welding seams. Also, swelling agents can also be applied between conductor core strands themselves to absorb moisture in the core and provide longitudinal water tightness.

- **Water Blocking Sheath -** A water-blocking sheath is added to the submarine cable to prevent water ingression into the dielectric system and conductor. MV submarine power cables have a polymeric sheath with a water absorbing agent underneath (semi-wet) or no sheath at all. The water absorbing agent is added since water vapor may diffuse through the polymeric sheath. A submarine power cable without an impermeable metallic sheath is called a “wet” cable design. HV submarine power cables have a metallic sheath to prevent water ingression which is called a “dry” design. Static HV submarine power cables generally have a smooth sheath. Furthermore, a metallic sheath provides protection against Teredo which are considered the “Termites of the sea”.

Often, high voltage submarine power cables utilize lead sheaths, which are manufactured by extrusion. The benefits of a lead sheath are the contribution to the submarine power cable stability on the seabed due to its high density, impermeability for water ingress and diffusion of humidity. Lead sheaths also have weak points like fatigue sensitivity and thermal cycling sensitivity which can initiate micro-cracks. In addition, the lead sheath's softness causes problems during manufacturing, transport and installation and therefore careful thought needs to be put into design and protection.

- **Armoring -** The armor is the second last outer layer of a submarine power cable and is laid after the protection and bedding. The armor provides structural integrity to the cable. In addition, the armor protects the cable from mechanical loading, such as crush and takes care of the tension stability. Types of mechanical loading that the cable must deal with are installation tensioners and tooling, fishing gear and anchors. The armor consists of metal (generally steel) wires wrapped around the cable. Common guidelines for armor designs are as follows;
    - More steel provides better protection
    - Harder wires provide a better protection
    - Double wire armoring is tougher than single wire armoring
    - Short-lay, where the length of armor wire needed to fully circle the cable in the helix lay is shorter, provides better protection against lateral impacts at the expense of tensional force protection.
- **Outer Serving -** The last layer of the submarine power cable is the outer serving. This outer serving provides protection to the armor from external stresses and corrosion during loading, installation and burying of the submarine power cable. Polymer materials are generally used as outer serving.
- **Fiber Cable –** Common to MVAC and HVAC cables, optical fiber cables are incorporated into the three-phase cable. Generally, optical fibers are added for the following purposes:
    - Fault detection and fault location
    - Data transmission for control and monitoring of wind tower generators or substations: Rotor speed, braking, rotor pitch, temperatures, liquid levels, vibration etc.
    - Measurements of cable temperature (DTS), strain (DSS), insulation (PDM), etc.
    - Detection of local movements of the submarine power cable

Installation of cables on traditional fixed wind power arrays involves running a guideline down through the j-tube (a tube from the cable interface point on the wind tower to the seabed) of the first wind tower to the floating cable installation vessel. The cable installation vessel utilizes a rotating carousel that is utilized to store and feed out the submarine cable.

Figure 6-9: Cable Installation Vessel Carousel (Credit: Offshorewind.biz)

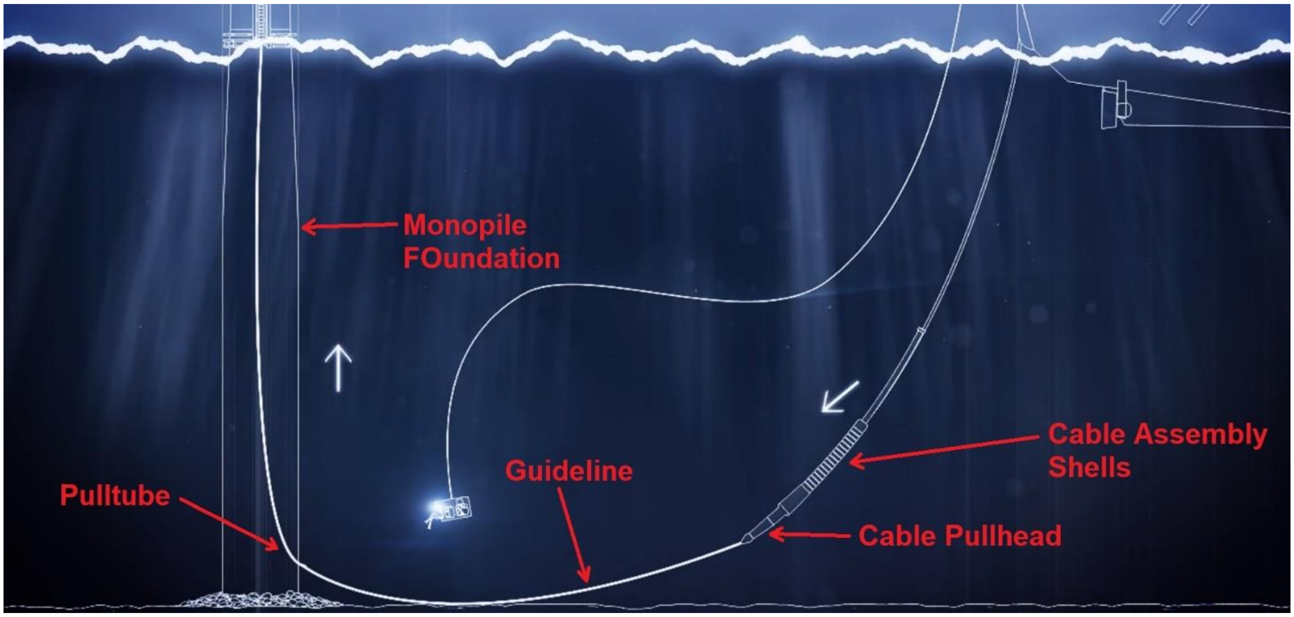


Figure 6-10: Cable Pull-in to Wind Tower Base (Credit: CADPeople, SIEM Offshore Contractors)

Once the installation vessel has the guideline on deck, the line is attached to the pullhead of the cable itself. The cable is fed out from the carousel through the vessel's onboard tensioner while simultaneously being slowly pulled in using a winch on the offshore wind tower. The cable pullhead is lowered to the seabed and guided through the j-tube with the guideline into position.

Once the cable is in place at the first wind tower, the cable vessel installs the cable along the seabed to the next wind tower using the rotating carousel and tensioner. From here, the guideline is again lowered through the tower J-tube and brought up to installation vessel to interface with the opposite side of the cable's pullhead. Before pulling towards the J-tube, the cable center is laid across a midway cable quadrant, which allows for the cable to be lowered to the seabed while being pulled towards and through the J-tube. These actions are repeated for each array cable and wind tower until the substation location is reached.

For array cables, burial can be achieved in multiple ways. A common way is the use a subsea cable vessel capable of ploughing and laying cable at the same time. The cable is run through the plough system, whether it be mechanical or jetting, which is towed by the vessel. The trench is simultaneously ploughed while the cable is laid. Another method is laying the cable on the seabed first and using an ROV equipped with a jet plough to bury the cable after it has been laid.

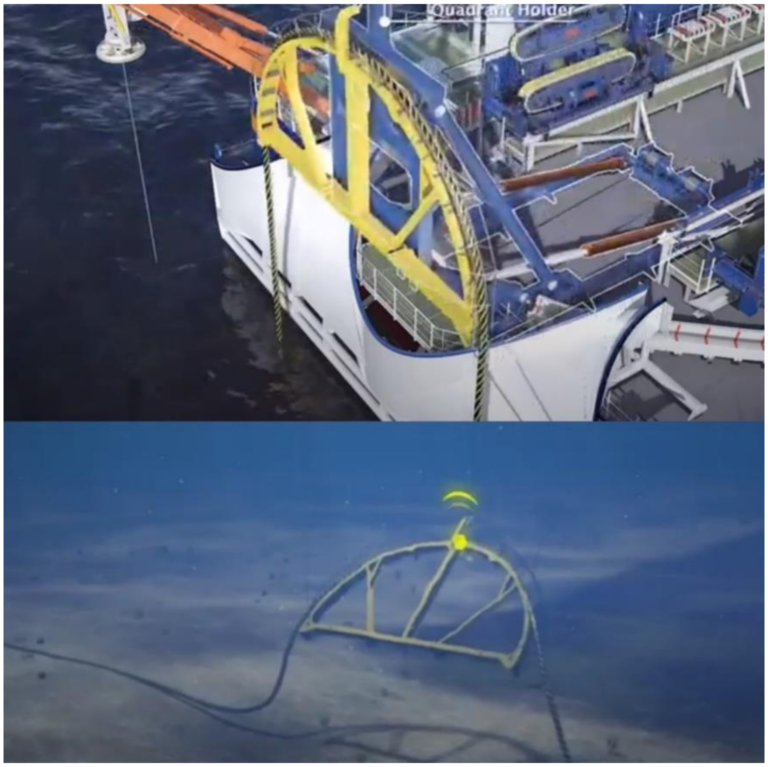


Figure 6-11: Cable installation Vessel Cable Lowering Quadrant (Credit: Nexus)

6.3.2 Differences Associated with Dynamic Cables

Dynamic cables used in floating offshore wind farms are exposed to sea currents, wave action and the movement of the floating turbine and substation themselves. Operating in a more dynamic environment will expose the cables to greater mechanical stresses and strain. Therefore, the cables themselves need to be designed to account for this. For example, they are often designed with greater levels of armoring for protection, traditional sheaths may need to be replaced with copper or plastic and bending stiffness and weight may need to be redesigned for dynamic applications. Furthermore, as offshore cables are already failing unexpectedly in service in static applications, a more dynamic environment will also have unexpected failures, if not more than in a static environment. This all must be accounted for during the cable design.

Offshore submarine HVAC dynamic power cables are at a relatively immature stage compared to that of HVAC static cables. This is the primary reason why all floating offshore wind projects to date have only utilized MV (33-66 kV) dynamic cables. Fortunately, this is a very viable option in the case of energization of FPSOs using wind power, as most often, tie-back distances and power capacities warranting HV cables can be avoided.

This provides the significant opportunity to use “wet” (no water barrier sheath) or “semi-wet” (polymeric sheath) submarine cables. For high voltage cables (>66 kV), the dry cable requirements are primarily related to water treeing (in insulation) and the associated accelerated electrical aging which is far exacerbated at higher voltage levels.

Due to the ability to use “wet” or “semi-wet” design and the smaller size of the MVAC dynamic power cable, less design challenges have to be faced compared to the HVAC dynamic cable. The primary difference between the design elements of MV submarine static and dynamic power cables is that the MV dynamic power cable requires double armoring to increase torsional and axial stiffness due to over-tension and fatigue mitigation. Another difference is the cross-sectional area of the conductor is larger to prevent high temperatures due to the thermal limitations at the bend stiffener. Increasing the cross-sectional area of the conductors reduces the induced heat. An example of a dynamic MV cable is shown in Figure 6-12.

For both MVAC and HVAC dynamic power cables, an additional friction reducing layer can be introduced between the sheath / insulation screen and adjacent layers to reduce the friction force between these layers [Ref. 10]. When the friction coefficient between the layers is too high, and therefore staying in the stick regime, the cable has a too high bending stiffness resulting in high local stresses in the cable and sheath. By adding a friction reducing layer, the bending resistance is improved and the risk of cracks on the sheath surface is reduced substantially. The friction reducing layer consists of either a polymer or a liquid like oil, graphite, grease or wax.

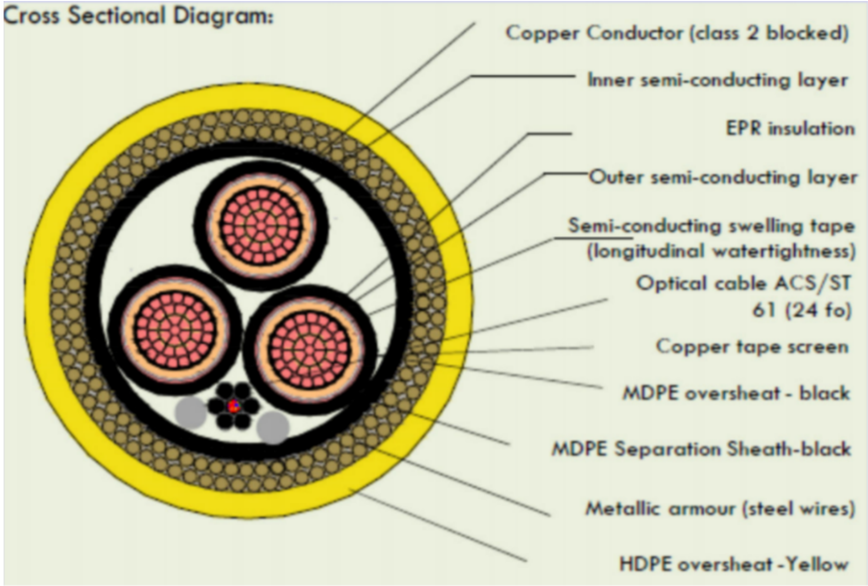


Figure 6-12: MVAC Dynamic Submarine Cable (Wet) Example Cross-Section (Credit: [Ref. 8])

In addition to the differences (static vs. dynamic) explained for the MVAC dynamic cable, the HVAC dynamic power cable has an additional difference with respect to the MV dynamic power cable due to the requirement of ’dry’ design. This additional difference is the corrugated copper sheath instead of lead sheath around each cable core. This corrugated copper sheath is double armored and used because of its excellent fatigue property and is crucial due to the dynamical loading. The benefits of a corrugated shape compared to a common smooth tubular sheath is that the corrugated shape can endure large deformations without exceeding its yield point and losing its strength. Smooth tubular sheaths do not have the capability of enduring such deformations and are therefore not suitable. Figure 6-13 shows the results of dynamic testing on a smooth lead sheath.

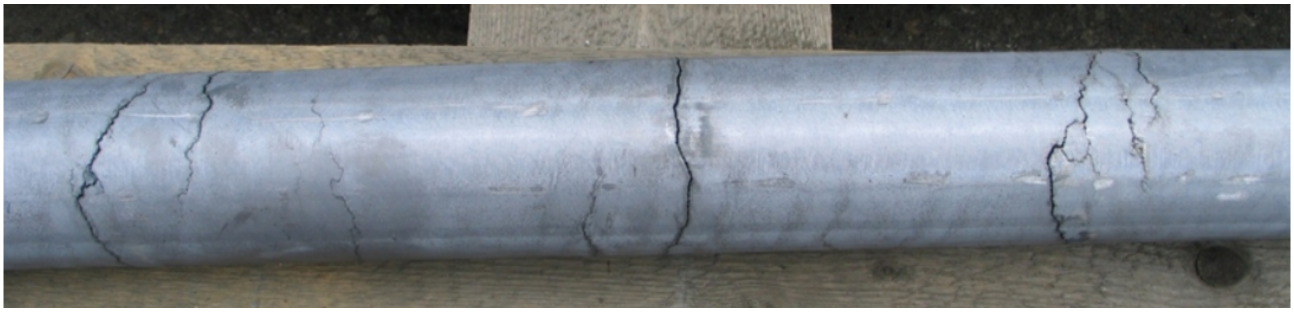


Figure 6-13: Lead Sheath Cracking from Fatigue Testing (Credit: ResearchGate - Björn Sonerud)

Bend stiffeners are attached to the top part and bottom part of the dynamic cable. At the top part, a dynamic bending stiffener is mounted to cope with heavy axial loads and curvatures to avoid over bending and fatigue failure. A dynamic bend stiffener has a conical body with an axial opening for the cable inlet. Internal steel work is mounted to the stiffener to transfer the induced loads to the floating structure.

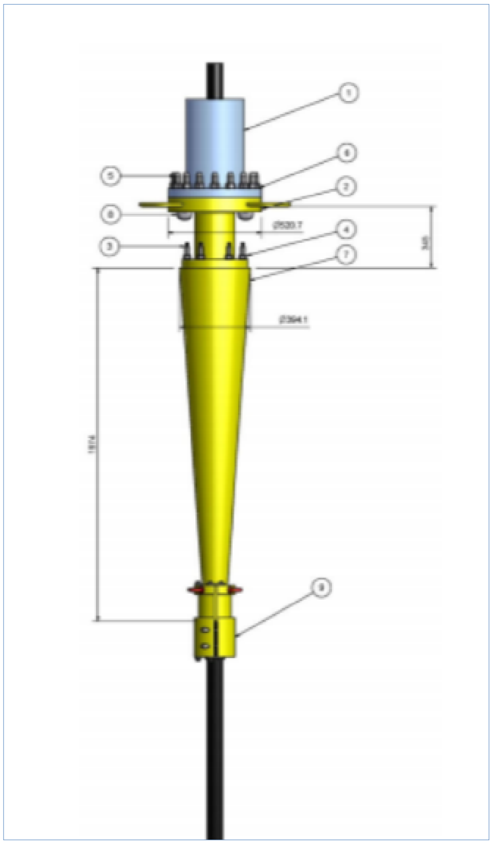


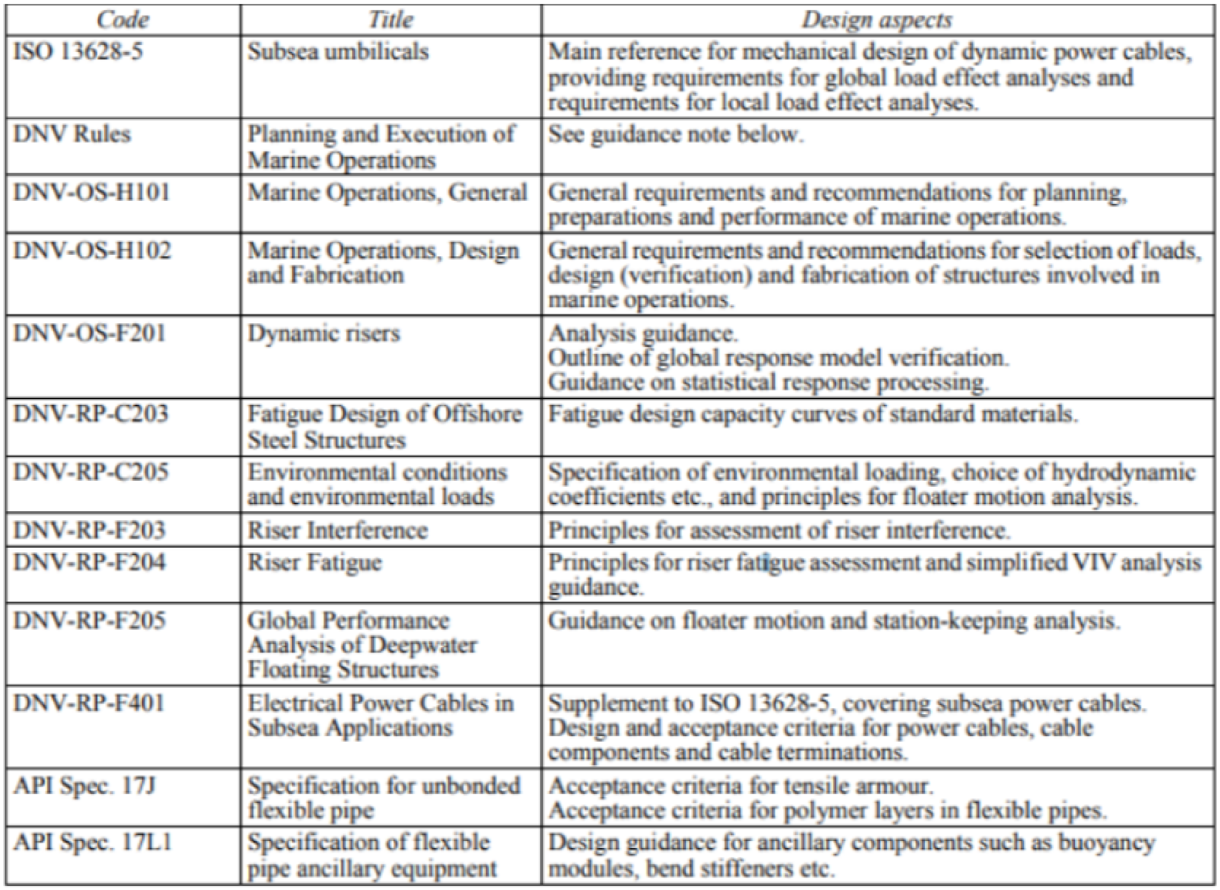
Figure 6-14: Dynamic Power Cable Bend Stiffener

While relatively straightforward for MVAC cables, the bend stiffeners used for HVAC dynamic power cables have a design and qualification gap. Currently, dynamic bend stiffeners have been used in smaller sizes, while for HVAC dynamic power cables, larger dynamic bend stiffeners with higher stiffness are needed to cope with the larger cable as well as heavier fatigue loads. Further development of these stiffeners for HV dynamic power cables is necessary by suppliers and researchers if they are to be provided for future HVAC export cables.

Another benefit to using MVAC dynamic cables versus HVAC is that there are a significant number of suppliers that can provide qualified MVAC dynamic submarine cable but very few that have qualified and supplied dynamic HVAC cables.

While design codes for dynamic submarine cables are still in their infancy, odes from other dynamic disciplines have been used the supplement the requirements for power cables. DNV-OS-J103 [Ref. 7], which covers the design of floating wind turbine structures, includes a section that is devoted to power cable design for the floating wind industry exposed to dynamic loading. The section provides criteria, requirements and guidance for the design and analysis of a dynamic power cable used for floating wind energy. Table 6-1 shows a list of codes that DNV-OS-J103 refers to for guidance to increase dynamic power cable integrity.

Table 6-1: Codes Referenced for Dynamic Guidance in DNV-OS-J103



Code	*Title*	*Design aspects*
ISO 13628-5	Subsea umbilicals	Main reference for mechanical design of dynamic power cables, providing requirements for global load effect analyses and requirements for local load effect analyses.
DNV Rules	Planning and Execution of Marine Operations	See guidance note below.
DNV-OS-H101	Marine Operations, General	General requirements and recommendations for planning, preparations and performance of marine operations.
DNV-OS-H102	Marine Operations, Design and Fabrication	General requirements and recommendations for selection of loads, design (verification) and fabrication of structures involved in marine operations.
DNV-OS-F201	Dynamic risers	Analysis guidance. Outline of global response model verification. Guidance on statistical response processing.
DNV-RP-C203	Fatigue Design of Offshore Steel Structures	Fatigue design capacity curves of standard materials.
DNV-RP-C205	Environmental conditions and environmental loads	Specification of environmental loading, choice of hydrodynamic coefficients etc., and principles for floater motion analysis.
DNV-RP-F203	Riser Interference	Principles for assessment of riser interference.
DNV-RP-F204	Riser Fatigue	Principles for riser fatigue assessment and simplified VIV analysis guidance.
DNV-RP-F205	Global Performance Analysis of Deepwater Floating Structures	Guidance on floater motion and station-keeping analysis.
DNV-RP-F401	Electrical Power Cables in Subsea Applications	Supplement to ISO 13628-5, covering subsea power cables. Design and acceptance criteria for power cables, cable components and cable terminations.
API Spec. 17J	Specification for unbonded flexible pipe	Acceptance criteria for tensile armour. Acceptance criteria for polymer layers in flexible pipes.
API Spec. 17L1	Specification of flexible pipe ancillary equipment	Design guidance for ancillary components such as buoyancy modules, bend stiffeners etc.

Cable Arrangement – Cable configurations for offshore floating wind differ from fixed facilities and include three primary options which depend on water depth and cable limitations. These configurations are free hanging, lazy wave, and W-shaped.

Hydrostatic analyses of the cable shapes have revealed that the lazy wave shape is technically superior to the catenary shape for a water depth range from 70 to 200+ m. For significant water depths, W-shaped can provide cable cost reduction due to reduced lengths of cable required. Each project must perform dynamic analysis to determine the best cable configuration for the project.

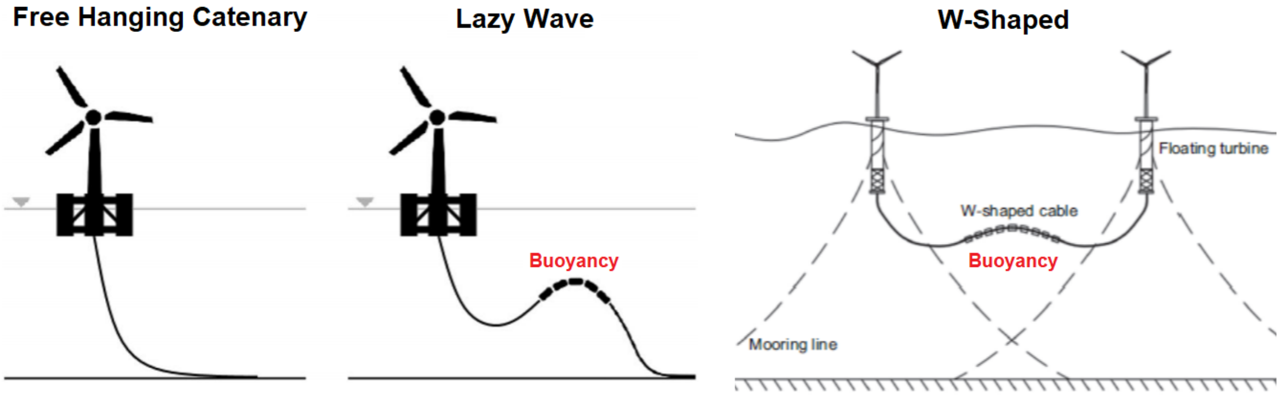


Figure 6-15: Cable Arrangements for Offshore Floating Wind Arrays

Installation of Dynamic Cables – Installation is one of the most critical phases of the dynamic cable lifecycle, as it is the leading cause of cable failures. The greatest potential for damage to the dynamic cable will occur during significant vessel motions because of adverse weather conditions or when cable installation needs to be stopped due to an equipment failure. This can lead to the cable being in a suspended state for substantial periods, with vessel motions subjecting the cable to continuous bending. However, these failure modes are relatively well understood.

Installation of **a** dynamic cable is performed similarly to a static cable, but more options can be considered.

- The first method is pull-in of the dynamic cable in a pre-installed floating turbine tower. A cable lay vessel performs the pull-in directly after laying of the dynamic cable towards the floating turbine (much like on a standard static cable installation), with the tether supporting the dynamic cable configuration being installed afterwards.

- The second method is a post-lay pull-in of the dynamic cable into the floating turbine tower with aid of the cable lay vessel.

- The third method is a post-lay pull-in of the dynamic cable from the floating turbine only.

In the last two methods, the dynamic cable is picked after wet storage on the seabed. The difference between these methods lies in the shape in which the dynamic cable is wet-stored. The distributed buoyancy modules (DBMs) and tether are already installed during the wet storage period of methods two and three. In the first two pull-in methods, the dynamic cable transfers from the cable lay vessel towards the floating wind turbine tower using a winch control system. The system controls the pay-out and pull-in rates of the carousel on the cable lay vessel and the winch on the floating turbine. The system ensures a minimum seabed clearance and keeps the cable configuration from becoming too tight.

The third pull-in method has the least amount of dynamic motion due to the cable pull-in being performed by using the floating turbine only. Only the floating turbine influences the cable motions; whereas in the other methods the cable lay vessel also adds to the dynamic cable behavior. The floating turbine has a more stable motion behavior in environmental conditions compared to the cable lay vessel, so the interaction of the cable with the seabed is reduced and a higher workability is obtained.

Cable compression is a limitation which is a common issue in cable installation. Compression in the two post-lay methods is caused by interaction with the seabed during recovery of the cable.

7 ASSESSING THE BEST ARRANGEMENT FOR A FLOATING WIND POWER ARRAY

7.1 Generator Capacity

A variety of generator capacity philosophies can be applied to offshore wind arrays but generally, the larger capacity per generator the better as it reduces total cable length required and installation time. There are some limitations regarding certain support structures (i.e. semi-submersible TLP and barge) as a larger generator increases the weight of the complete nacelle and rotors. Overall, the result of this is a higher center of gravity which needs to be considered during selection of the foundation.

7.2 Array Cable Layout and Strategy

A topic that must be considered for the collector system is the configuration of the wind power plant itself. Multiple wind turbines are generally connected into a “string” or “feeder” that feeds into the collector substation, and wind farms consist of multiple strings based on the capacity of the given array cable system. For example, a single 33kV array cable system will support fewer generators than a comparable 66kV array cable). These strings may be arranged in a number of configurations, such as radial connections, single-sided rings with a secondary cable connected between the last turbine in a string and the collector station, double-sided rings that connect the far ends of two strings together, or star patterns, where the cables of multiple turbines come to a central turbine from which the energy of the entire group is shipped to the collector substation. The design selected for a given development will seek to balance costs of the equipment and the desired reliability.

Significant cost savings can be achieved using more simple connection methods (such as the single collector radial configuration), but the more expensive methods (such as the ring configurations) offer more redundancy and higher reliability.

The methods configurations that offer more redundancy don’t just include additional cable. In the case of a double-sided ring configuration the additional cable is minimal, but common practice is to oversize the cable to allow for most of the power to be transmitted to the hub if a fault occurs on the loop (amount of oversize is generally based on cable size). For example, the worst-case failure on a double-sided ring would be in the instance in which the cable failure was incurred in the cable nearest to the substation, in which case the single circuit would be required to carry the total capacity of the two strings.

Location and availability of maintenance or repair vessels can have a large impact on evaluating options for the array collector configuration (affecting mean time to repair). If support is readily available to assist in a cable fault repair, operators often accept the lower cost, but higher risk of a single collector radial configuration over that of a ring configuration.

The assumed failure rate of the array cables vs. mean time to repair must be balance vs. CAPEX expenditure. Depending on access to cable repair vessels, a ring design may be the optimal solution for floating wind power electrification of FPSOs offshore Newfoundland and Labrador.

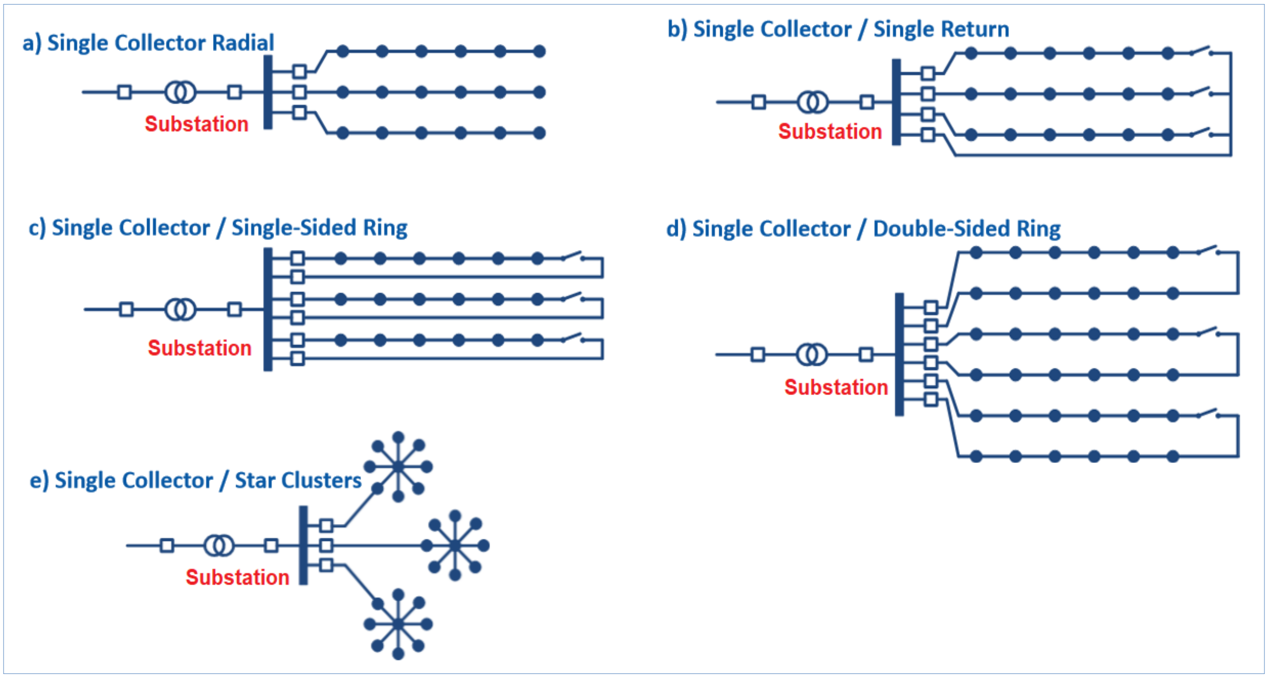


Figure 7-1: Offshore Wind Farm Array System Options

7.3 Tower Separation and Best Practices

On average, wind turbines require a separation of at least 7 complete rotor diameters for offshore wind turbines.

In recent research, it has been hypothesized that wind turbines might even need a little bit more space between them, exceeding previous limits for minimum spacing requirements. A study that was conducted at Johns Hopkins University proposed that for maximum efficiency, each wind turbine will require much more space to collect and convert energy as freely as possible [Ref. 20].

The total space required will include a variety of factors, including efficient space for the concrete foundation underneath the towers that work to keep them standing upright into the wind. This should be a stage in the initial planning of the wind project, and the foundations of each turbine should not interfere with any others to create adequate space.

The distance between the field of wind turbines and nearby power substations should be properly planned. The results of the research by the Max-Planck Institute [Ref. 21] confirmed that there should be an average of 4 megawatts per square kilometre expected when planning a wind farm project.

The 8 MW wind turbine has around a 167m rotor diameter. Therefore, the expected minimum distance between each turbine should be around 1,169m.

The water depth for Hywind Tampen is between 260m to 300m. However, for NL Offshore Block 401 (target brownfield), the water depth ranges from 75m and 125m. The shallower water depth could reduce the cost of mooring lines, but it will also reduce the radius of mooring lines as well. Due to the constraint of a minimum distance between each turbine, it may not be able to use the concept of "shared anchors" as the Hywind Tampen.

7.4 Maintenance Concerns

For standard small repairs and inspection, floating offshore wind towers are maintained the same as fixed offshore wind, where the turbine will be boarded directly by the maintenance crews through service operation vessels. The designs have been developed for effective access to wind installations offshore, and to ensure safe operations as well as serving comfortable accommodation for onboard personnel. personnel. These vessels generally have "Walk-to-Work" capability where an elevated, compensated walkway can be deployed to the wind tower.

Figure 7-2: Offshore Wind SOV Performing Maintenance Activities (Credit: Ulstein)

A primary concern regarding maintenance is with heavy maintenance. Heavy maintenance includes replacement and/or repair of large components in the rotor and nacelle assembly (RNA) of an offshore wind turbine. Examples of heavy maintenance components are rotors, rotor blades, hubs, rotor blade pitch bearings, main bearings, generators, gearboxes and transformers. Jack-up vessels are most often used for this purpose in the fixed offshore wind industry today.

It is expected that it will not be possible to use jack-up vessels for performing heavy maintenance for many of the floating wind farm developments due to water depth limitations. To date, large floating crane vessels, such as the Saipem S7000, have been used for heavy maintenance on floating wind turbines. This solution is neither practical nor economic due to long mobilization time, large day rates and very short weather windows of these large vessels.

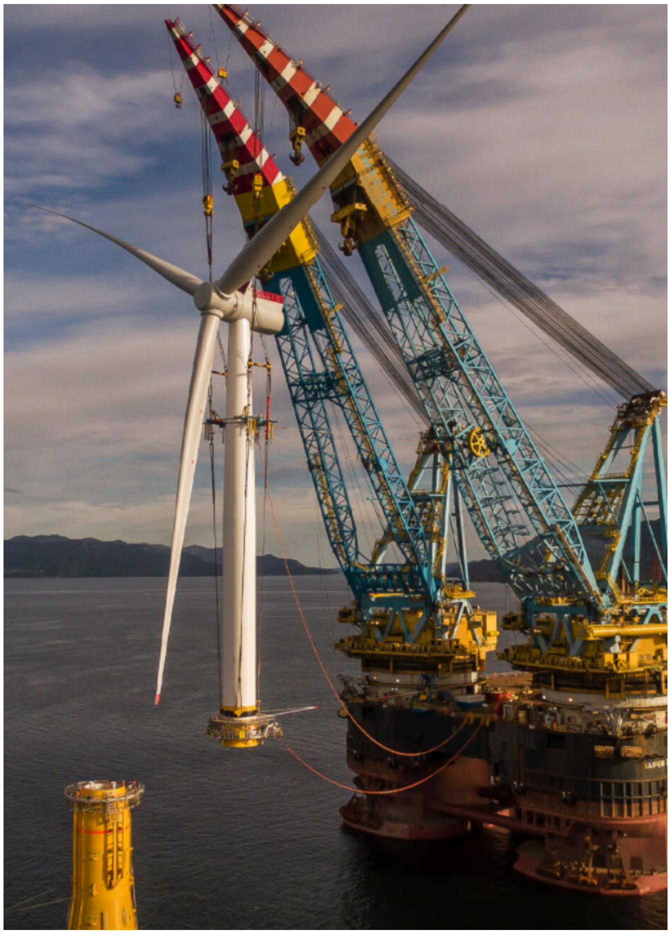


Figure 7-3: Installation of Hywind Scotland Turbine by Floating Semisubmersible Crane Vessel Saipem S7000 (Credit: Saipem)

Most floating offshore wind turbines are designed to be disconnected and towed back to port for major interventions, or to sheltered waters in the case of SPAR designs, such as Hywind Scotland's. How easy and costly this depends on the type of floater, the disconnection and reconnection process, how sensitive it is to metocean conditions, and the distance to shore or shallow waters.

In many cases, the process requires generally available tugs and anchor handling vessels, which cost approximately €15,000/day (CAD $23,320) and €35,000/day (CAD $54,420).

For example, to disconnect or reconnect Principle Power’s WindFloat semi-submersible platform takes less than 24 hours and can be achieved at significant wave heights up to 1.5-2 metres. Towing to port progresses at about three knots. Once docked or in shallow water, maintenance teams will require space at the quayside and suitable cranes or a jack-up vessel nearby to provide the required height for maintenance. If multiple turbines require service, wet storage also must be provided.

Many industry subject matter experts claim that workarounds for performing heavy maintenance of floating wind towers at location (such as barges with large onshore cranes parked onboard) exist while others claim that tow in is the best solution.

7.5 Tie-back Distance to Host Facility

As stated in Section 6.3.2, it is in the best interest of an electrification development to utilize only cables in the MVAC (33-66kV) range as this allows access to well qualified, available dynamic cable systems. The result of this is that it will restrict tie-back distance from the floating wind power array to the oil and gas host facility. Determining the exact tie-back distance capability depends on the number of MVAC export cables used. The expected tie-back limit for an array with a 100MW capacity and two export cables is approximately 20 km.

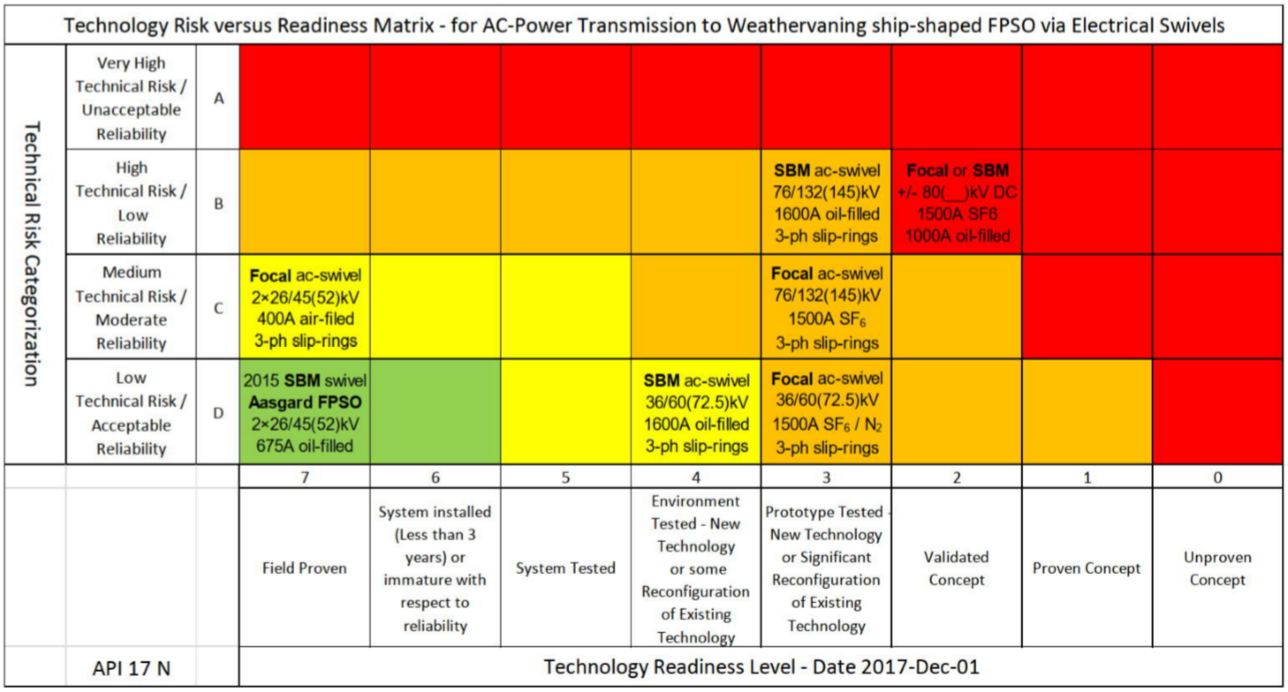
However, there is always the option of significantly increasing tie-back distance if the voltage is stepped up to HVAC, but this adds significant cost and comes with the qualification gaps of current dynamic HVAC submarine cable suppliers as well as disconnectability issues for the cable in the FPSO turret. In the future, these dynamic, disconnectable HVAC systems will become increasingly available for future electrification projects.

8 DYNAMIC, DISCONNECTABLE CABLE INVESTIGATION

The primary technical challenge for cable interface on disconnectable FPSO turrets is currently the swivel. The swivel ensures that power is transferred safely from the wind array to the rotating vessel and its processing plant under all environmental conditions.

The highest power disconnectable cables and swivels installed to date are on the Asgard project. These cables/swivels are rated for 45kV and 675A and are designed for up to 30MW of power transmission each. They currently provide power to a large subsea compression station. The power transmission system was installed and began operation in 2015.

Figure 8-1 reflects the technical readiness of AC power transmission to weathervaning FPSOs as of 2017. However, SBM offshore currently has power transmission swivels qualified to 66kV and 2000A (or 132MW). The API 17N Technical Readiness Level of the 66kV SBM swivel is currently TRL 4 (environment tested - qualified) and is ready for purchase.



Technology Risk versus Readiness Matrix - for AC-Power Transmission to Weathervaning ship-shaped FPSO via Electrical Swivels

Technical Risk Categorization										
	Very High Technical Risk / Unacceptable Reliability	A	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	High Technical Risk / Low Reliability	B	🟧	🟧	🟧	🟧	🟧 **SBM** ac-swivel 76/132(145)kV 1600A oil-filled 3-ph slip-rings	🟥 **Focal** or **SBM** +/- 80(__)kV DC 1500A SF6 1000A oil-filled	🟥	🟥
	Medium Technical Risk / Moderate Reliability	C	🟨 **Focal** ac-swivel 2×26/45(52)kV 400A air-filed 3-ph slip-rings	🟨	🟨	🟧	🟧 **Focal** ac-swivel 76/132(145)kV 1500A SF_6 3-ph slip-rings	🟧	🟥	🟥
	Low Technical Risk / Acceptable Reliability	D	🟩 2015 **SBM** swivel **Aasgard FPSO** 2×26/45(52)kV 675A oil-filled	🟩	🟨	🟨 **SBM** ac-swivel 36/60(72.5)kV 1600A oil-filled 3-ph slip-rings	🟧 **Focal** ac-swivel 36/60(72.5)kV 1500A SF_6 / N_2 3-ph slip-rings	🟧	🟧	🟥
			7	6	5	4	3	2	1	0
			Field Proven	System installed (Less than 3 years) or immature with respect to reliability	System Tested	Environment Tested - New Technology or some Reconfiguration of Existing Technology	Prototype Tested - New Technology or Significant Reconfiguration of Existing Technology	Validated Concept	Proven Concept	Unproven Concept
	API 17 N		Technology Readiness Level - Date 2017-Dec-01							

Figure 8-1: Technical Risk Matrix for AC Power Transmission to Weathervaning FPSOs (Credit: ABB)

Other development work is being performed by SMB and Focal on high voltage swivels to meet the demands of high-power fields in the future. These high voltage swivels are currently TRL 3 (Concept validation) or below.

The result of the current qualification status is that a disconnectable cable with swivel currently requires the dynamic system to operate at 66kV or below (or at array voltage). However, there are currently available qualified methods to facilitate the use of HVAC export cables to FPSOs, such as using a subsea transformer/reactor combination to step down HVAC to MVAC, so the dynamic section of the cable and turret interface remain in MVAC. ABB confirmed that this technology is qualified with very few technical challenges to this solution.

It is important to note that swivel technology limitations are not the only reason to opt for this type of configuration, as it also allows for the elimination of the HVAC dynamic cable (discussed previously).

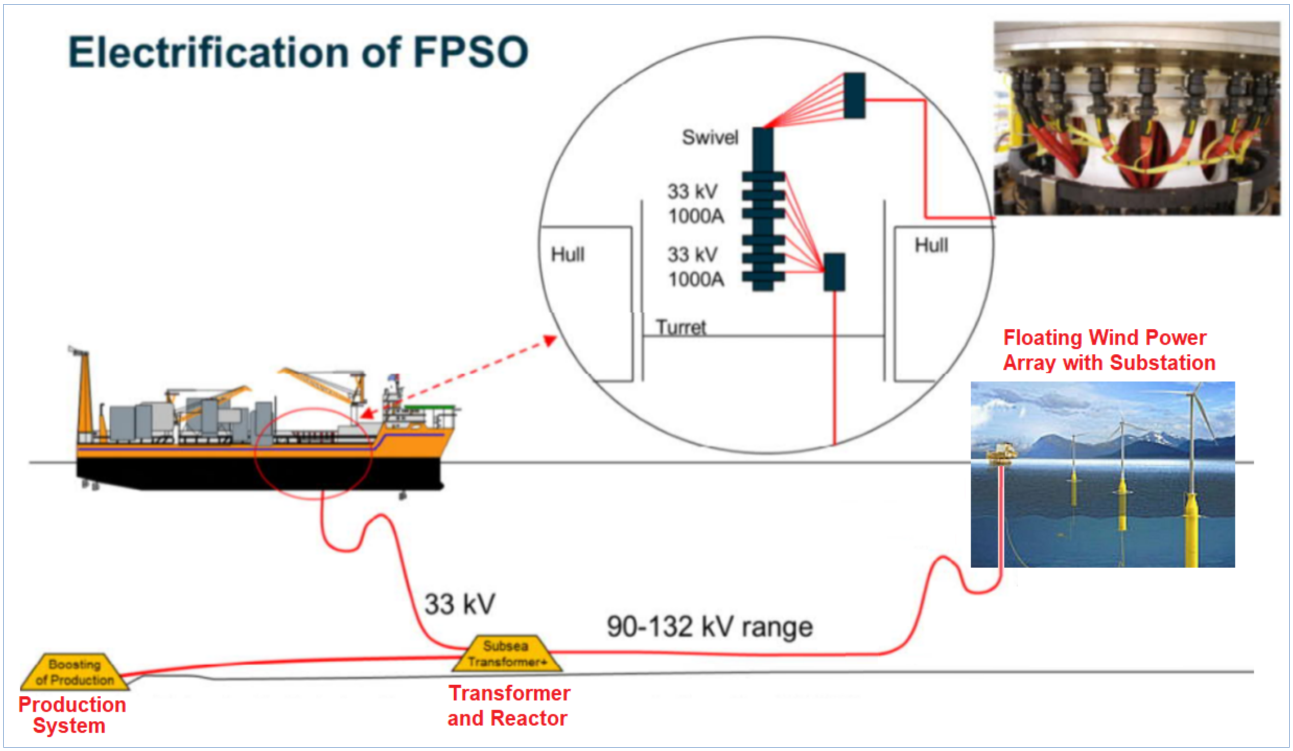


Figure 8-2: Enablement of HVAC Tie-back using MV Turret Interface (Credit: ABB)

9 GHG EMISSIONS

There are multiple sources of emissions on offshore platforms and various types of air pollutants are released into atmosphere during operation. The following are major sources of emission considered for this study:

- Power generation
- Gas compression (if compressors are driven by turbines)
- Water Injection (if water injection pumps are driven by gas turbines)
- Flaring
- Crude oil storage tank venting (applicable to FPSO)
- Fugitive emissions (leaks from valves, flanges, glands and seals)
- Support vessels and helicopter operations

The primary source of emissions on an offshore platform are the gas turbine generators. The emissions include Nitrogen oxides (NOx), Carbon monoxide (CO), Sulphur dioxide (SO2), total suspended particulate matter (TSP) and volatile organic compounds (VOC)

Carbon dioxide, Methane and Nitrous oxide are considered as part of greenhouse gases due to their greenhouse warming potential. Typically, these gases and other gases are quantified for reporting emissions.

A study and air dispersion modeling were conducted by Stantec [Ref. 9] to evaluate the GHG emissions from the Hebron development. The study results show the quantities of the GHG emitted from various point sources in Hebron platform. The GHG emission quantities estimated from the study are tabulated below. The quantities are listed as tonnes per year. For point source comparison, the GHG weights are expressed in CO2 equivalent.

Table 9-1: GHG Emissions on Hebron Project, tonnes per year (Source: Environment Canada 2009c, US EPA 2000, Sikorsky 2007, Rolls-Royce Marine 1991, ExxonMobil Canada Properties (EMCP)).

SOURCES	CO2	N2O	CH4	TOTAL (CO2 Equivalent)
Power Generation	269,024	19.9	5	275,298
Gas Compression	174,612	6.7	3.3	176,758
Flaring	92,849	0.17	484	103,067
Ships	12,589	-	-	12,589

SOURCES	CO2	N2O	CH4	TOTAL (CO2 Equivalent)
Helicopters	491	-	-	491
Fugitive Emissions	-	-	1346	28,266
Total	549,565	26.8	1838.3	596,469

Notes: Power generation based on three turbines. Gas compression based on two turbine-driven compressors.

Power generation and gas compression are two major sources of GHG emission and points of discussion in this study. To achieve reduction in GHG emission, both power generation and gas compression can incorporate electrification. The gas compression drive would need to be changed to motor driven. This may pose a challenge in brownfield projects due to layout restrictions.

It can be noted from the table above that approximately 75% of the GHG of the platform is contributed by the power generation and the gas compression. Reduction in usage of the gas turbines with electrification of the platform will significantly reduce the GHG emissions during operations. The GHG emissions will vary with type of platform and different operations being undertaken.

9.1 Inputs and Assumptions

The following are the inputs and assumptions made for GHG estimation:

- Electrical load demand varies during the field life of the platform. A constant load is assumed to calculate the GHG emission. The estimated electrical load is during peak production phase.
- Gas turbine emission composition is not similar when running on natural gas and distillate liquid fuel. Natural gas use is considered.
- Unavailability or reduced power availability from wind array is not factored into estimation of power demand.
- Existing platform with gas compression driven by turbines may not be converted to electric motor driven due to CAPEX or layout restrictions. In such cases reduction in GHG emissions will be less.

9.2 Reduction in Emissions

In a greenfield scenario, the design concept of the process plant can be selected to maximize the use of power supply from the windmills. Selection of motor driven equipment for compression and water injection or any other large rotating equipment can be made in the early stage of the design. A major portion of the electrical power demand can be met with wind energy supplemented by the gas turbines or reciprocating engines onboard. Gas turbine exhaust is used for waste heat recovery units to provide heat source for the process plant. Electrical heaters can be provided to reduce the operation of gas turbines.

Multiple projects in the Norwegian sector of North Sea have similar concepts. However, the electrification of the platforms is achieved with power supply from the onshore power grid. The Goliat FPSO project in the Barents Sea is one such example.

10 STUDY LOCATION

The brownfield project considered in this study is the Hebron offshore platform. The Hebron Project is an oil development project located in the NL offshore, approximately 340 km east of St. John's (See Section 11.1). The Hebron oil field has been developed using a concrete gravity-based structure (GBS) situated in roughly 92 metres of water.

The greenfield site presented to the study team was in the west Orphan Basin at approximately Lat 50 20N, Long 49 45W. This is in Block 1147 as shown approximately in Figure 10-1.

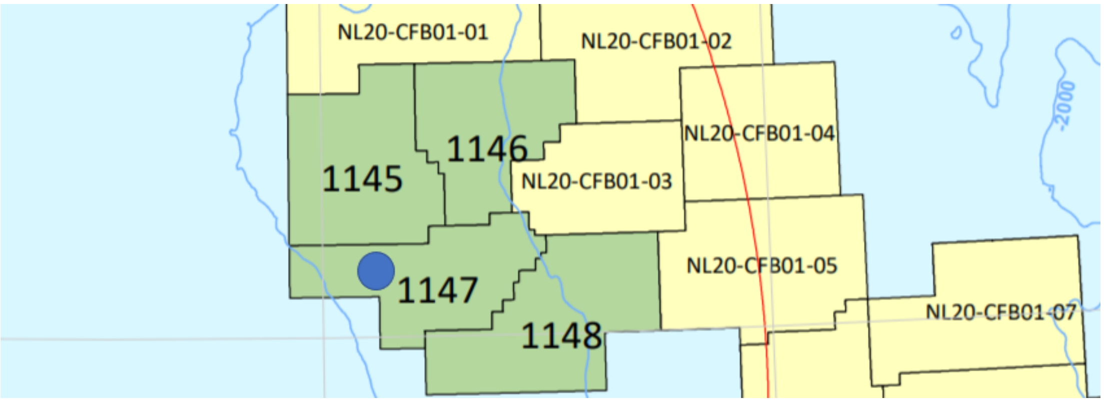


Figure 10-1: Greenfield Project Location

10.1 Offshore Newfoundland and Labrador Ice Environment Considerations

While not in an Arctic environment, offshore Newfoundland and Labrador is a region that can be frequented by sea ice and icebergs during spring and summer months. Fixed platforms in the region have been designed to withstand loads and impact from ice. Floating platforms have been designed to disconnect and move off station if ice loads become too great or if the threat from an iceberg is high.

Any floating structure offshore Newfoundland and Labrador will have potential risk from sea ice and icebergs. This will include floating wind farms. These floating wind turbines are currently not designed to be disconnectable and additional work would need to be done to check ice loads that might be sustained by a typical (or re-engineered) mooring system. Ice detection and monitoring would need to be a part of the operation of any offshore wind farm, and an ice management program implemented to ensure the integrity of the facilities. Ice management might include the breaking of pack ice into smaller floes or the towing (deflection) of icebergs in an impact trajectory with wind facilities. Ice management on the Grand banks has been very successful. Ice detection, monitoring, and management for offshore wind facilities would most likely be combined with the same activities being carried out for the host facility.

Subsea cables located in ice environments and in a certain range of water depths may need to be protected from potential ice gouging (also known as ice scouring) created when a moving ice keel interacts with the seabed. The integrity and operability of the cable can be affected by direct contact between the ice keel and the cable, or from loading imposed on a buried cable through soil deformation caused by ice gouging. Subsea cables may also be subjected to 3rd party risks from fishing activities depending on location and water depth. Depending on the risk, cables may need to be buried for safety and protection. The typical method considered for protecting against the risk of damage caused by ice gouging or 3rd party activity is through cable burial. Conventional methods of cable burial use equipment such as dredges, ploughs, mechanical trenchers, and jetters.

An assessment of the risks to wind facilities and cables due to the presence of ice or fishing activity is beyond the scope of this study and would be a study unto itself. If further work is carried out to more fully evaluate the feasibility of wind energy to electrify oil and gas production facilities, then this topic warrants further study.

10.2 Ice Resistant Floating Platform Concepts

It is unlikely that wind farms using fixed foundation turbines would be economical for offshore Newfoundland and Labrador given the risks from and need to design for ice (sea ice and icebergs). Certainly, one could envision gravity-based structures (such as those proposed for ice resistant wellhead platforms) being used to support wind turbines, albeit an expensive solution that would likely make such a concept uneconomical except for shallow waters. This then suggests that a concept needs to be a less expensive floating solution.

In the Newfoundland and Labrador offshore, operators have in place ice management plans which outline how operators will detect, monitor and manage sea ice and/or icebergs before they pose a threat to facilities. Floating Production Storage and Offloading Vessels are strengthened to withstand sea ice loads but not iceberg impact. In the event of a situation where sea ice loads become too high or icebergs pose a threat, these FPSOs have a quick-disconnect feature, allowing them to safely disconnect and leave the area in the event of unmanageable ice.

As mentioned above, floating wind turbines are currently not designed to be quickly disconnectable; none so far have been designed for ice environments.

It is anticipated that those same ice management activities would cover the wind energy facilities. However, even with regional ice management, the wind facilities would need to be able to withstand some level of ice loading and/or have the ability to disconnect in the event of an unmanageable threat. The risk would need to be assessed and the cost to mitigate that risk to an acceptable level calculated and evaluated.

While floaters are being considered for offshore areas, the presence of ice offshore Newfoundland and Labrador brings additional challenges. FPSO’s offshore NL are ice-class, are protected somewhat through ice management, and are designed to disconnect. Any floating wind turbines being considered for offshore ice environments will likely follow a similar philosophy. However, the economics must be such that the project is feasible; adding rapid disconnectability to a floating wind turbine will significantly increase the cost. A risk assessment would need to be carried out on specific structures in specific locations to determine if disconnectability could be avoided, if the risk was deemed to be small.

As an example of floater concept for offshore Newfoundland and Labrador, work has been done by Technip ([Ref. 25]) to develop a Disconnectable Concrete Spar FPSO for offshore Eastern Canada which can withstand iceberg loads and/or be disconnected and towed away if required if faced with a significant iceberg threat, leaving the mooring lines and risers in-place (Figure 10-2). The mooring system can be used to provide offset to the platform, allowing it to move laterally roughly 10% of water depth. The developers believe the platform should provide low motion response to storm and ice loads and could be constructed locally in Eastern Canada.

Figure 10-2: Disconnectable SPAR Concept (Credit: [Ref. 27])

The Rigid Artic Tension Leg Platform (RATLP) is another example of a potential concept and is the result of efforts to develop solutions and concepts to meet the challenges of exploration and production in ice infested waters of the east coast of Canada ([Ref. 26]). The RATLP has been developed for use in first-year ice and iceberg environments. This concept is not disconnectable but combines the tensioning principles of a conventional TLP with the properties of a buoy (Figure 10-3). This concept can move laterally through manipulation of its morning system. This concept could also be constructed in Eastern Canada.

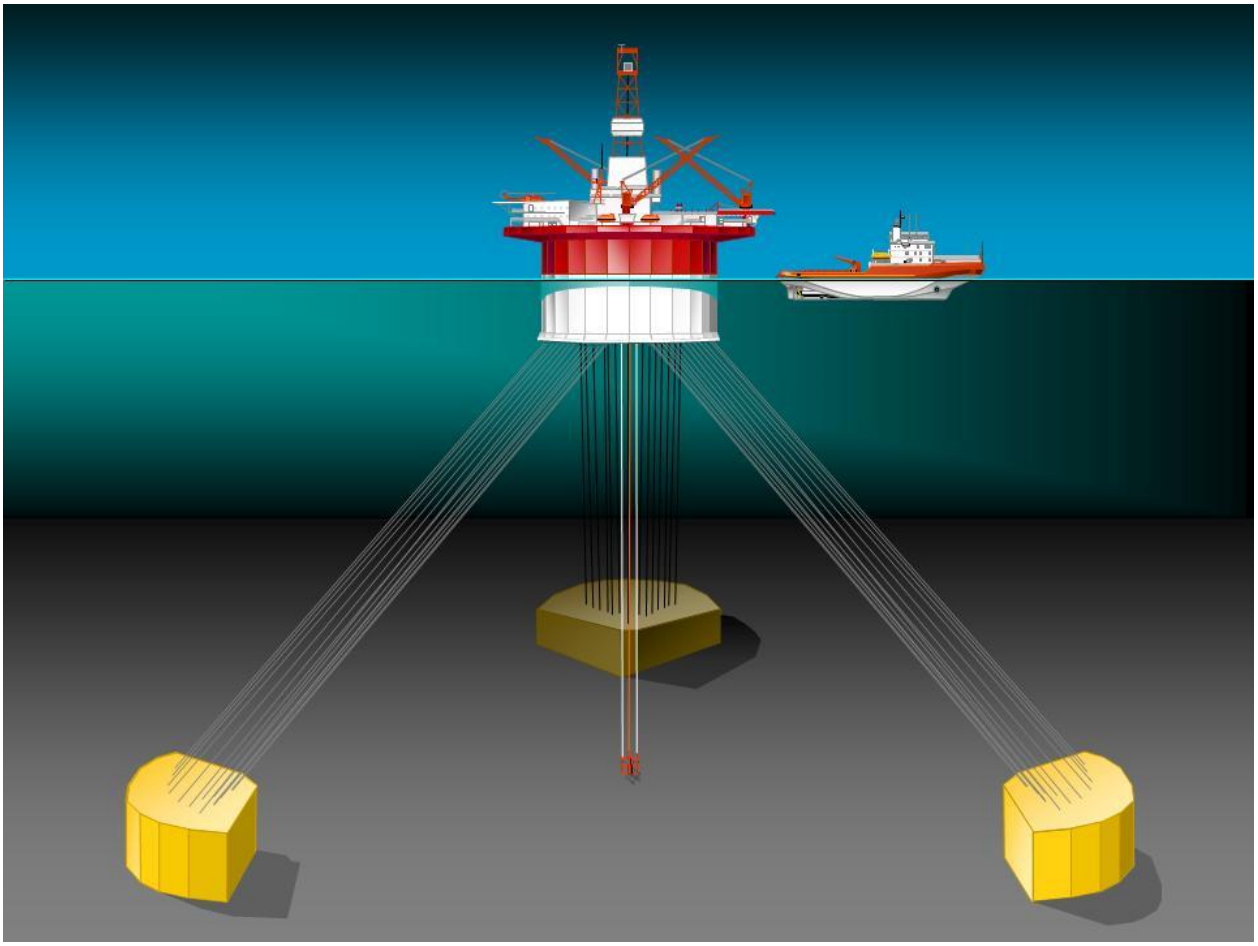


Figure 10-3: Rigid Artic Tension Leg Platform (RATLP) (Credit: [Ref. 26])

11 PROJECT STUDIES

The following subsections present the brownfield and greenfield scenarios evaluated as part of this study. The scope of work had requested that the study look at wind farm configurations (wind turbine size, number of wind turbines, etc.) that would be optimal for the existing power requirements of oil producing facilities in the Jeanne d'Arc Basin. The studies also included estimation of cost and reduction of GHG emissions for each scenario. The Hebron project was selected on the brownfield study for a number of reasons including information in the public domain, the perceived ability to be able to tie in wind generated power, and the availability of a previous preliminary emissions study which had been conducted for the project [Ref. 9].

While Hebron was selected for the brownfield study case, any of the existing Jean D’Arc projects could have been chosen or a combination of multiple existing projects. The criteria which might be applied to these cases would be the same: minimize tieback distances; location provides good source of wind; floating wind turbine placement not to interfere with existing or planned future operations; placement such that ice management requirements for wind facilities take advantage of current ongoing ice management activities; the area is suitable for installation within the annual installation window of the area; and the expected CAPEX and OPEX is economical enough for execution.

Tieback to existing FPSO’s will be more complex given the modifications required to the turret/swivel to accommodate power transfer onboard the vessel.

11.1 Hebron Project Brownfield Study

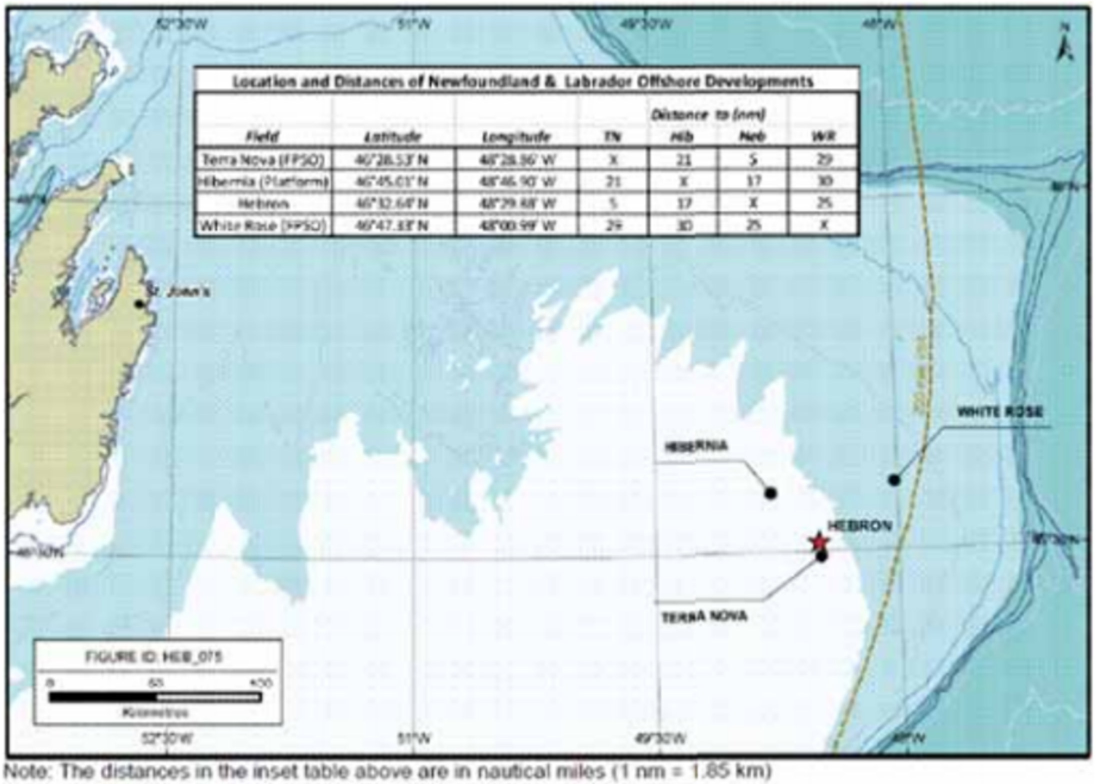
The Hebron Project is an oil development project located in the NL offshore, approximately 340 km east of St. John’s (Figure 11-1). The project is a partnership of ExxonMobil, Chevron, Suncor Energy, Statoil, and Nalcor. The Hebron oil field has been developed using a concrete gravity-based structure (GBS) similar to that employed in the province’s first offshore development at Hibernia. The Hebron platform is situated in roughly 92 metres of water approximately 32 km southeast of Hibernia, 9 km north of the Terra Nova Field, and 46 km southwest of White Rose [Ref. 12].

The Hebron asset contains separate oil accumulations in at least four reservoirs, the largest of which is the Ben Nevis Reservoir. This reservoir, which has been designated as Pool 1, is the anchor resource of the Hebron project and is expected to produce approximately 70 % of the recoverable crude oil based on the current knowledge of the asset. The current best estimate of total oil in place is 2,620 million barrels of oil (MBO) of which close to 800 MBO is considered recoverable at this time. The GBS for the Hebron Project is a reinforced concrete structure designed to withstand impacts from sea ice and icebergs and the meteorological and oceanographic conditions at the Hebron Field. It can accommodate up to 52 well slots with J-tubes inside the central shaft connected to the base of the GBS for potential future expansion.

The GBS is designed to store approximately 1.2 million barrels of crude oil in segregated storage compartments. The offshore loading system (OLS) consists of two main offshore pipelines running from the GBS to separate but interconnected pipeline manifolds. The notional offloading rate of the system is 5400 cubic metres of oil per hour.

An integrated array of topsides structures weighing 65,000 tonnes (operating) is mounted on top of the gravity base. The topsides includes a drilling support module, derrick equipment set, utilities and production module, flare boom and living quarters, including helideck and lifeboat stations. The GBS has accommodations for approximately 150 personnel under normal circumstances and up to 220 during intensive operations including the initial drilling phase.

The Hebron production facilities has the capacity to handle the predicted life-of-field production stream for 30 plus years. In the initial development phase, it is expected the facility has been designed to accommodate a nominal production rate of 150 thousand barrels of oil per day. First oil was achieved in November 2017.



Location and Distances of Newfoundland & Labrador Offshore Developments

Field	*Latitude*	*Longitude*	*Distance to (nm)* *TN*	*Hib*	*Heb*	*WR*
Terra Nova (FPSO)	46°28.53' N	48°28.56' W	X	21	5	29
Hibernia (Platform)	46°45.01' N	48°46.90' W	21	X	17	30
Hebron	46°32.64' N	48°29.88' W	5	17	X	25
White Rose (FPSO)	46°47.33' N	48°00.99' W	29	30	25	X

Note: The distances in the inset table above are in nautical miles (1 nm = 1.85 km)

Figure 11-1: Hebron Project Location (Credit: [Ref. 12])

11.1.1 Study Outline

The brownfield study incorporates wind power electrification of the Hebron Project. The wind farm is located near the Hebron GBS with the goal of providing 45% of the platform power requirements. The sitemap near Hebron GBS is shown in Figure 11-2. The red box is the expected wind farm location. The average distance from the wind farm to the Hebron GBS is about 15 km.

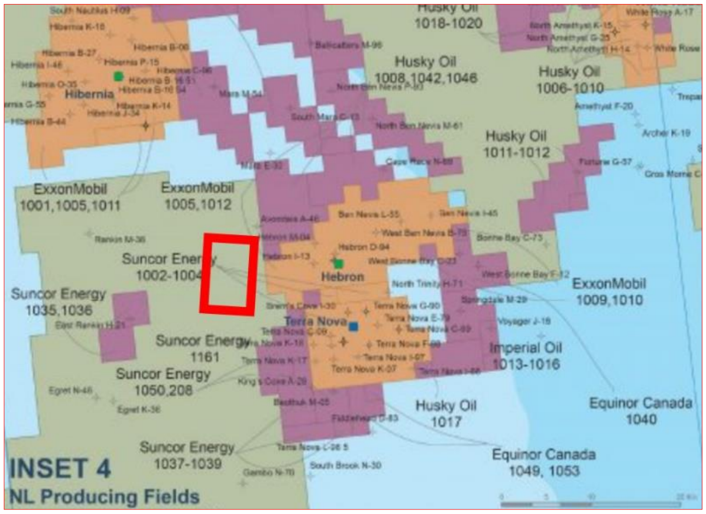


Figure 11-2: Sitemap near Hebron GBS

11.1.2 Wind Power Electrification (inputs and assumptions)

The expected wind farm location is at the south side of cell 401 from “MetOcean Climate Study Phase II, Offshore Newfoundland & Labrador” ([Ref 15]), as shown in Figure 11-3. The water depth for this area is around 75m. The wind summary for the cell 401 is listed in Table 11-1.

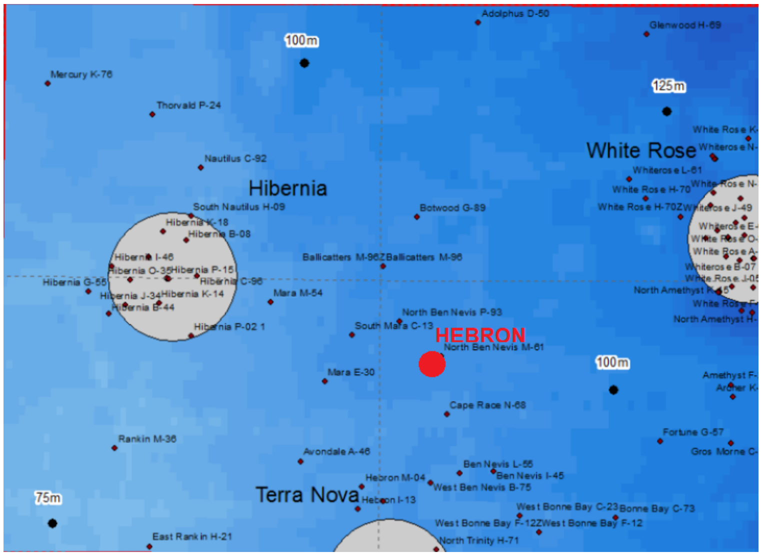


Figure 11-3: Water Depth for Cell 401

Table 11-1: Wind Speed Summary for Hebron Project Wind Farm Location

	Wind Speed (m/s)				
	Median	**Dom. Dir.***	**10yr**	**100yr**	**Median Wind Speed at Hub***
Jan	11.5	285	27.1	30.4	14.9
Feb	11.4	275	27.9	32.1	14.8
Mar	10.4	285	25.3	29.5	13.5
Apr	8.7	235	23.4	29.1	11.3
May	7.4	235	19.9	24	9.6
Jun	6.9	225	18.5	21.5	8.9
Jul	6.6	225	17.7	21.3	8.5
Aug	6.7	225	21.5	30.6	8.7
Sep	7.8	225	23.8	31.5	10.1
Oct	9.2	225	25.3	33.8	11.9
Nov	9.9	275	24.7	28.6	12.8
Dec	11.1	275	26.9	31	14.4

*The wind direction is “blowing from, clockwise from north in degrees”.

** Assume the Hub height is 105m above still water level.

Based on the Siemens-8MW wind turbine specification, the rated wind speed is 12m/s. The rated wind speed is defined as the wind speed at which the rated power (the maximum output power) of the electrical generator is reached. Based on the wind industry practical experience, the wind turbine work efficiency is about 0.55 (working time vs. total time). Consider the turbine power curve as cubic function of wind speed before the rated wind speed and constant after. The monthly and annual estimated wind capacity factors (the average power generated, divided by the rated peak power) are listed below. The annual average wind capacity factor is about 42%, which is within the common existing offshore industry experience (35% ~ 45%).

Table 11-2: Wind Capacity Factors for Brownfield Case

	Median Wind Speed at Hub*	**Wind Capacity Factor**
Jan	14.9	55%
Feb	14.8	55%
Mar	13.5	55%
Apr	11.3	46%
May	9.6	28%
Jun	8.9	23%
Jul	8.5	20%
Aug	8.7	21%
Sep	10.1	33%
Oct	11.9	54%

Nov	12.8	55%
Dec	14.4	55%
Annual Average		**42%**

11.1.3 Brownfield Study Wind Turbines Array Determination

The maximum continuous load of the Hebron GBS is about 90 MW. It is expected to replace 45% of the annual power supply by wind power. Therefore, the required total wind power is about:

90 MW x 45% ≈ 41 MW

The estimated amount of GHG reduction per year with average utilization of 41 MW power is 139,197 tonnes.

Based on the 42% annual average wind capacity factor, the wind farm rated power should be at least:

41 MW / 42% ≈ 98 MW

An 8MW wind turbine is adopted in this study. So, the total number of wind turbines required is:

98 MW / 8 MW ≈ 13

The general practice in the wind power industry is to allow a separation of at least 7 times the rotor diameter between each turbine. The Siemens-8MW wind turbine has 167m rotor diameter. Therefore, each turbine should be at least 1169 m away from each other.

The mooring system is expected to be taut mooring system to control the turbines' offset. The mooring line horizontal span is estimated to be 120m, which is 1.6 times water depth for this location, based on industry experience. Each turbine has three mooring lines and three anchors.

Considering the dominant wind direction for the largest wind speed (275 deg ~ 285 deg), the wind turbines' spacing is 1200m and the array is preliminary designed as shown in Figure 11-4.

Array cabling is assumed to be dynamic 66kV, 3-phase cable in a lazy-wave configuration to protect cables from the dynamics and axial forces involved at this water depth.

11.1.4 Subsea Power Tie-back

The single export cable is assumed to be identical with the 66kV MVAC dynamic array cables to facilitate qualified tie-in to the FPSO.

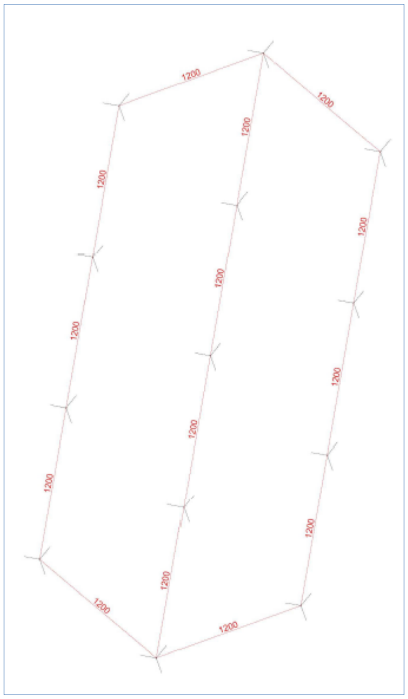


Figure 11-4: Wind Turbine Array for Brownfield Case

11.1.5 CAPEX and OPEX Study

The costs associated with the offshore wind electrification are estimated based on the cost of the offshore substation (with required additions to the GBS, submarine cables and wind power array).

Technically, all costs associated with offshore wind are scalable costs. Number of wind turbines, generator capacity, and size of tower are all scalable costs. For substations, higher capacity power generation requires higher capacity transformers, reactors and power storage (increasing the size of the hull). Submarine power cables are generally scalable costs, but longer lengths of cable are often lower cost per metre for similar cables due to cost savings with large quantity purchases.

OPEX

Operation and Maintenance (O&M) is a significant cost when it comes to offshore wind power, with an average annual cost of CAD $169/kW year [Ref.17] of energy capacity (or CAD $169,000 per MW year). Assuming an array of thirteen 8MW floating offshore wind turbines with associated cabling and substation equipment for the brownfield scenario, the annual O&M cost for the wind power generation facilities would be CAD $17,576,000/year.

Floating offshore wind may potentially offer a much lower O&M cost than the bottom-fixed offshore wind. For major inspections and repairs, the individual FOW structure can be disconnected from the mooring lines and towed back to a deepwater dock facility, if required. The O&M activities associated with floating offshore wind carried out dockside is also less influenced by the weather conditions than that of bottom-fixed wind farm (this potential for savings was not included in the O&M cost presented). The cost assumes an offshore maintenance contract with the equipment supplier as purchase of a dedicated Service Operation Vessel (SOV) would be economically inefficient with a field of this size. This annual cost does not include the cost of intervention and repair resulting from catastrophic equipment failure or cable faults.

No specific costs have been included in this study for ice management for the floating substation platform or floating wind turbines. Ice management plans are required offshore Newfoundland and Labrador which outline how operators will detect, monitor and manage sea ice and/or icebergs before they pose a threat to facilities. It is anticipated that those same ice management activities would cover the wind energy facilities; the incremental cost increase to do so has not been determined.

Table 11-3: Offshore Substation Equipment Cost - Brownfield Study

Offshore Substation + Host Facility Equipment Cost – Costs Include Installation

Outside Plant Electrical Construction

ITEM	DESCRIPTION	QTY	UNIT	TOTAL LABOUR & MATERIAL $CAD	COMMENTS
1	98MW Offshore Substation Platform	1	EA	$53,707,000	• Cost estimates are based on historic rate information available in-house from a previous similar project. No new Vendor Quotes were requested. • Cost of topside utilities such as crane, emergency generator, fire protection system, facility lighting, navigational aids, PA system, CCTV, deck drains, safety equipment, water and sewage system, temporary refuge/rest room, HVAC are included. • Topside will be designed, fabricated, loaded out, transported and installed as a single lift unit. • Floating foundation is included in this cost • Fabrication yard is assumed located in the Newfoundland and Labrador area. • Offshore Installation spread duration is 22 days, including 10 days for mobilization/transit. • No weather delays are included during the transportation/installation phases.

Offshore Substation + Host Facility Equipment Cost – Costs Include Installation					
Outside Plant Electrical Construction					
ITEM	**DESCRIPTION**	**QTY**	**UNIT**	**TOTAL LABOUR & MATERIAL $CAD**	**COMMENTS**
2	Cost of Modifications to the Offshore Platform	1	EA	12,000,000	• Cost include topsides modifications to accommodate cable, switchboard and changes to power management.
3	Testing & Commissioning	1	EA	$2,600,000	
4	Control House (66kV)	1	EA	$3,640,000	
5	3-phase 66kV/13.8kV Transformer	1	EA	$1,147,000	
6	3-phase 13.8kV/480v Transformer	2	EA	$104,000	
7	Control House (13.8kV)	1	EA	$1,242,000	
8	Diesel Emergency Generator	2	EA	$1,210,000	
9	Shunt Reactors (3 - Single Phase)	3	EA	$764,000	• Single Phase, 24.5 MVAR
10	Switchgear 13.8kV	1	EA	$471,000	
11	Switchgear 480V	1	EA	$179,000	
12	MVAC and LVAC Cables and Bus Duct Systems	1	Lot	$2,438,000	
13	Battery System (Including Associated Rectifier)	1	Lot	$19,676,000	• Assumes total storage can accommodate wind array at average power output of 41MW for 2 hours.
14	Harmonic Filters	1	Lot	$813,000	
	TOTAL			**$99,178,000**	

Notes:

1. Some equipment will be located on the host Facility to enable tie-in of the wind power supply to the GBS grid. The items on this list will be split between the substation and the host facility

Table 11-4: Submarine Cable Cost - Brownfield Study

Submarine Cables					
Submarine Cable Construction and Installation					
ITEM	**DESCRIPTION**	**QTY**	**UNIT**	**TOTAL LABOUR & MATERIAL CAD $**	**COMMENTS**
1	66kV Dynamic Submarine Cable, 1200mm^2 Conductors	38.6	km	$65,234,000	• Cost of Dynamic Cable: CAD $1,690,000/km 1200mm2 conductor x-section assumed as ampacity requirement is 857A • Cable length between array towers = 1.8km Assumed export cable length = 17km • Cables are assumed to be unburied, laid on seabed
2	Installation of Tri-core Submarine Cables to each Tower and to Substation	1	EA	$4,760,000	• Installation Lay Rate: 3km / day (unburied) Installation Vessel Rate: $300,000 / Day 3 days Mobilization
	Total			**$69,994,000**	

Table 11-5: Turbine, Floating Foundation, Mooring and Piles Cost - Brownfield Study

NO.	**ITEM**	**CAPEX COST (CAD)**	**COMMENTS**
1	Turbine	$184,548,000	• The "Turbine" sheet cost is estimated based on "Annual Technology Baseline: Electricity (2019)". Unit price is $1.3 million/MW. • Assume de-icing system cost is 5% of unit price (turbine blades).
2	Floater	$208,654,000	• It is assumed that the floating foundation material is steel. • The structural weight of the floater is scaled from reference project.

NO.	ITEM	CAPEX COST (CAD)	COMMENTS
3	Floater Appurtenance	$10,433,000	• Assume the appurtenance price is 5% of the floater structure price.
4	Chain	$11,268,000	• The mooring system is chain only. • The mooring length is scaled from reference project based on water depth. • The mooring chain size is scaled from reference project based on rated power.
5	Mooring Accessories	$2,254,000	• The mooring accessories price is assumed to be 20% of the mooring chain price.
6	Piles	$8,872,000	• The pile size is scaled from reference project.
7	Mooring/Pile Transportation and Installation	$19,408,000	• The mooring chains and piles are assumed to be fabricated in Europe and transported to Canada offshore. • The mooring chains and piles are assumed to be transported to Canada by ocean barges, each with three tow tugs.
8	Turbine and Floater Transportation and Installation	$75,222,000	• The turbines are assumed to be fabricated in Europe and transported to Canada offshore. • The floating foundation is assumed to be fabricated in Eastern Canada. • The turbine towers are assumed to be fabricated in Eastern Canada. • The turbines and blades are assumed to be transported to Canada by ship.
	Total	**$520,659,000**	

Cost Summary

The estimated total cost for all Hebron project brownfield study additions for offshore wind electrification is CAD $689,831,000. There will also be an additional O&M cost for the floating wind power equipment of CAD $17,576,000 per year.

Cost saving of fuel gas for operating gas turbine is not considered as gas is currently not saleable from the Hebron platform. If the gas could be sold, the reduction in fuel gas consumption on the platform would equate to approximately CAD $7,583,000 based on current gas prices. The associated reduction in costs associated with gas turbine maintenance, spares, and applicable carbon tax has not been quantified for this study.

Estimated costs shown in this report should be considered a snapshot in time. It is important to understand the market fluctuations when it comes to offshore wind equipment and equipment costs have significantly decreased over the past several years [Ref. 22]. Additionally, due to the infancy of offshore wind in North America, local supply chain infrastructure is under significant development and costs are expected to decrease more rapidly. Many additional offshore wind installation (wind towers, submarine cables, and substations) and O&M vessels will be available in the coming years due to the rapidly expanding interest and government solicitation in offshore wind.

11.1.6 Study Results

The brownfield scenario study shows that floating wind power electrification of a brownfield host facility is a feasible concept in offshore Newfoundland and Labrador. Additional CAPEX is required compared to a greenfield application due to the requirements for a separate floating wind power substation to accommodate equipment.

11.2 Greenfield Study 1

11.2.1 Study Outline

The first greenfield study includes one disconnectable turret moored FPSO with a dedicated wind array nearby. The wind array provides a targeted 45% of the total load capacity of the FPSO.

The location of the disconnectable FPSO is assumed to be in Offshore Block 1147, shown as the blue dot in Figure 11-5. The wind farm is located near the FPSO to provide power. The red box is the expected wind farm location. The average distance from the wind farm to the FPSO is about 15 km.

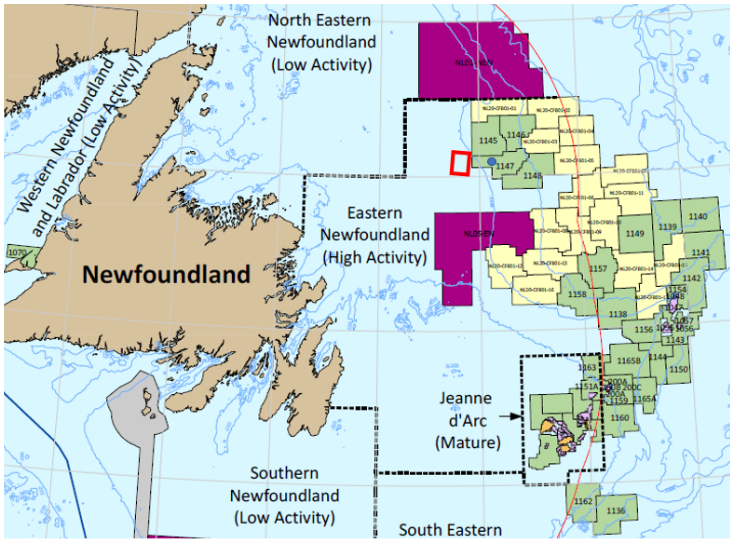


Figure 11-5: Sitemap for Greenfield Study 1

11.2.2 Wind Power Electrification (Inputs and Assumptions)

The expected wind farm location is at the north east corner of the cell 292 from "MetOcean Climate Study Phase II, Offshore Newfoundland & Labrador" ([Ref 16]), as shown below. The water depth for this area is around 1200m. The wind summary for cell 292 is listed in Table 11-6.

Figure 11-6: Location of Cell 292

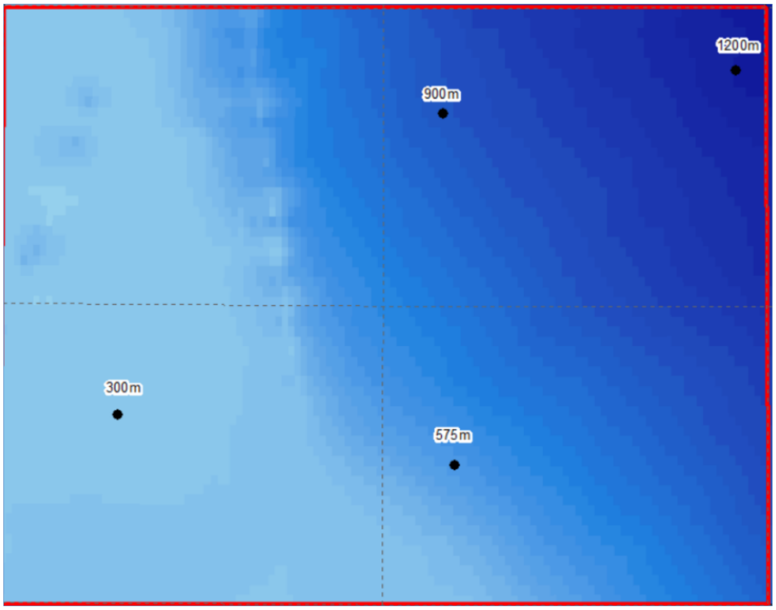


Figure 11-7: Water Depth for Cell 292

Table 11-6: Wind Speed Summary for Greenfield Study 1

	Wind Speed (m/s)				
	Median	Dom. Dir.*	10yr	100yr	Median Wind Speed at Hub**
Jan	12.3	285	27.5	31.3	15.9
Feb	11.6	275	28	32.4	15.0
Mar	10.6	285	25.4	29.8	13.7
Apr	9.2	215	23.3	26.8	11.9
May	7.7	215	20.9	24.7	10.0
Jun	6.8	215	18.7	21.9	8.8
Jul	6.4	215	16.8	19.2	8.3
Aug	6.9	215	19.1	24.5	8.9
Sep	8.4	235	23.6	29.8	10.9
Oct	9.8	275	24.7	29.9	12.7
Nov	10.9	285	25.5	29.2	14.1
Dec	11.9	285	27.5	31.5	15.4

*The wind direction is “blowing from, clockwise from north in degrees”.

** Assume the hub height is 105m above still water level.

Based on the Siemens-8MW wind turbine specification, the rated wind speed is 12m/s. Based on the wind industry practical experience, the wind turbine work efficiency is about 0.55 (working time vs. total time). Consider the turbine power curve as cubic function of wind speed before the rated wind speed and constant after. The monthly and annual estimated wind capacity factors (the average power generated, divided by the rated peak power) are listed below. The annual average wind capacity factor is about 44%, which is within the common existing offshore industry experience (35% ~ 45%).

Table 11-7: Wind Capacity Factors for Greenfield Study 1

	Median Wind Speed at Hub*	Wind Capacity Factor
Jan	15.9	55%
Feb	15.0	55%
Mar	13.7	55%
Apr	11.9	54%
May	10.0	32%
Jun	8.8	22%
Jul	8.3	18%
Aug	8.9	23%
Sep	10.9	41%
Oct	12.7	55%
Nov	14.1	55%
Dec	15.4	55%
Annual Average		**44%**

11.2.3 Greenfield Study 1 Wind Turbines Array Determination

The maximum continuous load of the FPSO is assumed to be about 65 MW. It is expected to replace 45% of the annual power supply by wind power. Therefore, the required total wind power is about:

65 MW x 45% ≈ 29 MW

The estimated amount of GHG reduction per year with average utilization of 29 MW power is 98,456 tonnes.

Based on the 44% annual average wind capacity factor, the wind farm rated power should be at least:

29 MW / 44% ≈ 66 MW

An 8MW wind turbine is adopted in this study. So, the total number of wind turbines required is:

66 MW / 8 MW ≈ 9

The turbines are again placed with greater than 7 times the rotor diameter between each turbine. The Siemens-8MW wind turbine has 167m rotor diameter. Therefore, each turbine should be at least 1,169 m away from each other.

The mooring system is expected to be a taut mooring system to control the turbines’ offset. The mooring line horizontal span is estimated to be 1,920m, which is 1.6 times water depth for this location, based on industry experience. Each turbine has three mooring lines. Anchors are shared between mooring lines. A total of 16 anchors would be deployed.

In this study, the wind turbines are separated 3,334m from adjacent turbines due to the significant water depth. Considering the dominant wind direction for the largest wind speed (275 deg ~ 285 deg), the preliminary wind turbine array is shown in Figure 11-8.

Array cabling is assumed to be dynamic 66kV, 3-phase cable in a W-shaped configuration between turbines to protect cables from the dynamics and forces involved at this extreme water depth as well as limiting cable lengths required between each turbine.

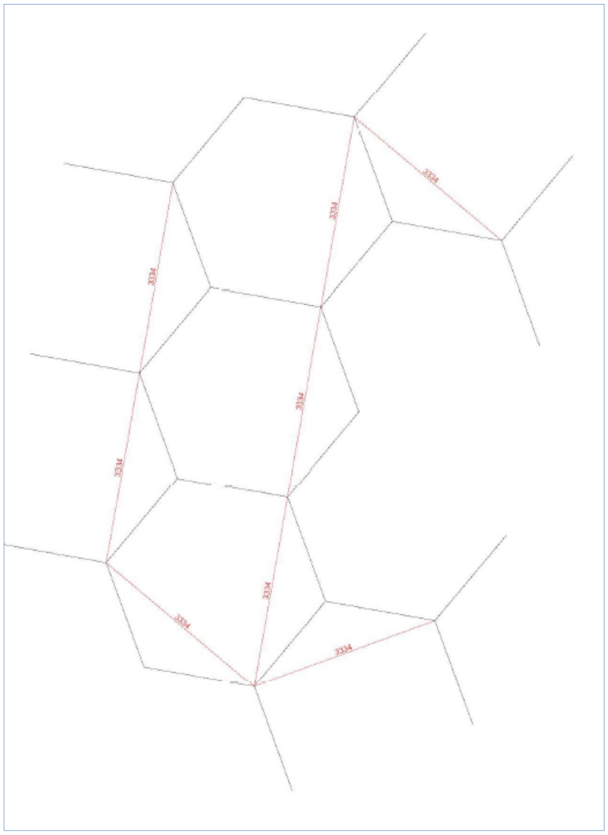


Figure 11-8: Wind Turbine Array for Greenfield Study 1

11.2.4 Subsea Power Tie-back

The single export cable is assumed to be identical with the 66kV MVAC dynamic array cables to facilitate qualified tie-in to the FPSO microgrid.

11.2.5 CAPEX and OPEX Study

CAPEX

The costs associated with the offshore wind electrification are estimated based on the cost of the substation equipment included on the FPSO, submarine cables and wind power array.

Table 11-8: Offshore Substation Equipment Cost – Greenfield Study 1

<table>
<tr><th colspan="6">Offshore Substation Equipment Cost for Greenfield FPSO – Greenfield Study 1</th></tr>
<tr><th colspan="6">Outside Plant Electrical Construction</th></tr>
<tr><th>ITEM</th><th>DESCRIPTION</th><th>QTY</th><th>UNIT</th><th>TOTAL LABOUR & MATERIAL $CAD</th><th>COMMENTS</th></tr>
<tr><td>1</td><td>Additions to Greenfield FPSO system to Accommodate Electrification via Wind Power</td><td>1</td><td>EA</td><td>$11,700,000</td><td>• Cost estimates are based on historic rate information available in-house from a previous similar project. No new Vendor Quotes were requested.
• Cost of additions to traditional FPSO to accommodate electrification equipment. The costs include cable pull tube, turret swivels, trays, Larger switch gear and switch gear room. Structural steel for accommodating additional equipment on process deck.
• No weather delays are included during the transportation/installation phases.</td></tr>
<tr><td>2</td><td>Testing & Commissioning</td><td>1</td><td>EA</td><td>$2,600,000</td><td></td></tr>
<tr><td>3</td><td>Control House (66kV)</td><td>1</td><td>EA</td><td>$3,640,000</td><td></td></tr>
<tr><td>4</td><td>3-phase 66kV/13.8kV Transformer</td><td>1</td><td>EA</td><td>$772,000</td><td></td></tr>
<tr><td>5</td><td>3-phase 13.8kV/480v Transformer</td><td>2</td><td>EA</td><td>$70,000</td><td></td></tr>
<tr><td>6</td><td>Control House (13.8kV)</td><td>1</td><td>EA</td><td>$621,000</td><td>• Assumed as additional cost to FPSO control house.</td></tr>
<tr><td>7</td><td>Shunt Reactors (3 - Single Phase)</td><td>3</td><td>EA</td><td>$515,000</td><td>• Single Phase, 17.3 MVAR</td></tr>
<tr><td>8</td><td>Switchgear 13.8kV</td><td>1</td><td>EA</td><td>$317,000</td><td>• Assumed as addition to 13.8 kV switchgear</td></tr>
<tr><td>9</td><td>Switchgear 480V</td><td>1</td><td>EA</td><td>$120,000</td><td>• Assumed as additional cost to FPSO control house.</td></tr>
</table>

Offshore Substation Equipment Cost for Greenfield FPSO – Greenfield Study 1					
Outside Plant Electrical Construction					
ITEM	**DESCRIPTION**	**QTY**	**UNIT**	**TOTAL LABOUR & MATERIAL $CAD**	**COMMENTS**
10	MVAC and LVAC Cables and Bus Duct Systems	1	Lot	$1,642,000	
11	Battery System (Including Associated Rectifier)	1	Lot	$13,251,000	• Assumes total storage can accommodate wind array at average power output of 29MW for 2 hours.
12	Harmonic Filters	1	Lot	$547,000	
	TOTAL			**$35,795,000**	

Table 11-9: Submarine Cable Cost - Greenfield Study 1

Submarine Cables – Greenfield Study 1					
Submarine Cable Construction and Installation					
ITEM	**DESCRIPTION**	**QTY**	**UNIT**	**TOTAL LABOUR & MATERIAL CAD $**	**COMMENTS**
1	66kV Dynamic Submarine Cable, 1200mm^2 Conductors	49	km	$76,440,000	• Cost of Dynamic Cable: CAD $1,560,000/km • 1000mm2 conductor x-section assumed as ampacity requirement is 577A • Cable length between array towers = 4km • Assumed export cable length = 17km • Cables are assumed to be unburied, laid on seabed
2	Installation of Tri-core Submarine Cables to each Tower and to Substation	1	EA	$5,800,000	• Installation Lay Rate: 3km / day (unburied) • Installation Vessel Rate: $300,000 / Day

					• 3 days Mobilization
	Total			**$82,240,000**	

Table 11-10: Turbine, Floating Foundation, Mooring and Piles Cost - Greenfield Study 1

No.	Item	CAPEX COST (CAD)	COMMENT
1	Turbine	$127,764,000	• The "Turbine" sheet cost is estimated based on "Annual Technology Baseline: Electricity (2019)". Unit price is $1.3 million/MW. • Assume de-icing system cost is 5% of unit price (turbine blades).
2	Floater	$144,453,000	• It is assumed that the floating foundation material is steel. • The structural weight of the floater is scaled from reference project.
3	Floater Appurtenance	$7,223,000	• Assume the appurtenance price is 5% of the floater structure price.
4	Top Chain	$3,334,000	• The mooring system is chain-Polyester-chain only. • The mooring length is based on similar oil & gas project. Top chain 200m, Polyester 2100m, Anchor Chain 300m. • The mooring chain size is scaled from reference project based on rated power.
5	Polyester	$8,283,000	
6	Anchor Chain	$5,001,000	
7	Mooring Accessories	$3,323,000	• The mooring accessories price is assumed to be 20% of the mooring chain price.
8	Piles	$3,640,000	• The pile size is scaled from the reference project.

No.	Item	CAPEX COST (CAD)	COMMENT
9	Mooring/Pile Transportation and Installation	$22,304,000	• The mooring and piles are assumed to be fabricated in Europe and transported to Canada offshore. • The mooring and piles are assumed to be transported to Canada by ocean barges, each with three tow tugs.
10	Turbine and Floater Transportation and Installation	$72,217,000	• The turbines are assumed to be fabricated in Europe and transported to Canada offshore. • The floating foundation is assumed to be fabricated in Eastern Canada. • The turbine towers are assumed to be fabricated in Eastern Canada. • The turbines and blades are assumed to be transported to Canada by ship.
	Total	**$397,542,000**	

OPEX

Operation and Maintenance (O&M) is a significant cost when it comes to offshore wind power, with an average annual cost of CAD $169/kW year [Ref.17] of energy capacity (or CAD $169,000 per MW year). Assuming an array of nine 8MW floating offshore wind turbines with associated cabling and substation equipment for Greenfield Study 1, the annual O&M cost for the wind power generation facilities would be CAD $12,168,000/year.

Floating offshore wind may potentially offer a much lower O&M cost than the bottom-fixed offshore wind. For major inspections and repairs, the individual FOW structure can be disconnected from the mooring lines and towed back to a deepwater dock facility, if required. The O&M activities associated with floating offshore wind carried out dockside is also less influenced by the weather conditions than that of bottom-fixed wind farm (this potential for savings was not included in the O&M cost presented). The cost assumes an offshore maintenance contract with the equipment supplier as purchase of a dedicated Service Operation Vessel (SOV) would be economically inefficient with a field of this size. This annual cost does not include the cost of intervention and repair resulting from catastrophic equipment failure or cable faults.

No specific costs have been included in this study for ice management for the floating wind turbines. Ice management plans are required offshore Newfoundland and Labrador which outline how operators will detect, monitor and manage sea ice and/or icebergs before they pose a threat to facilities. It is anticipated that those same ice management activities would cover the wind energy facilities; the incremental cost increase to do so has not been determined.

Cost Summary

The estimated total cost for all Greenfield Study 1 additions for offshore wind electrification is CAD $515,577,000. There will also be an additional O&M cost for the floating wind power equipment of CAD $12,168,000 per year.

Cost saving of fuel gas for operating gas turbine is not considered as gas is currently not saleable from the Jeanne d'Arc Basin. If the gas could be sold, the reduction in fuel gas consumption on the platform would equate to approximately CAD $5,364,000 based on current gas prices. The associated reduction in costs associated with gas turbine maintenance, spares, and applicable carbon tax has not been quantified for this study.

As stated in Section 11.1.5, cost is rapidly decreasing as development of offshore wind power increases. Estimated costs shown in this report should be considered a snapshot in time.

11.2.6 Study Results

Greenfield Study 1 demonstrates that floating wind power electrification of an FPSO requires significantly lower CAPEX if electrification is accounted for in a greenfield application (or was enabled for on a brownfield application through weight capacity and host real estate). The elimination of the separate substation results in a greater than 50% reduction in costs related to substation equipment. If offshore oil and gas projects include wind power electrification in a greenfield application, the optimum design is to locate the substation equipment onboard the host facility itself.

The water depth in the greenfield scenario 1 study results in significant spacing of wind turbines which drives up the submarine cable length and cost but is likely beneficial regarding overall power generated by each turbine.

11.3 Greenfield Study 2

11.3.1 Study Outline

The Greenfield Study 2 scenario includes a shared wind array for two adjacent disconnectable FPSOs in the vicinity with wind power providing 50% of the power supply for both FPSOs. This case is targeted to demonstrate better optimization of CAPEX and generated power.

The Greenfield Study 2 scenario is based on the two FPSOs in Offshore Block 1147, as the blue dot in Figure 11-9. The wind farm is located near the FPSOs to provide power. The red box is the expected wind farm location. The average distance from the wind farm to the FPSOs is about 15 km. The target wind farm has the same location as in Greenfield Study 1.

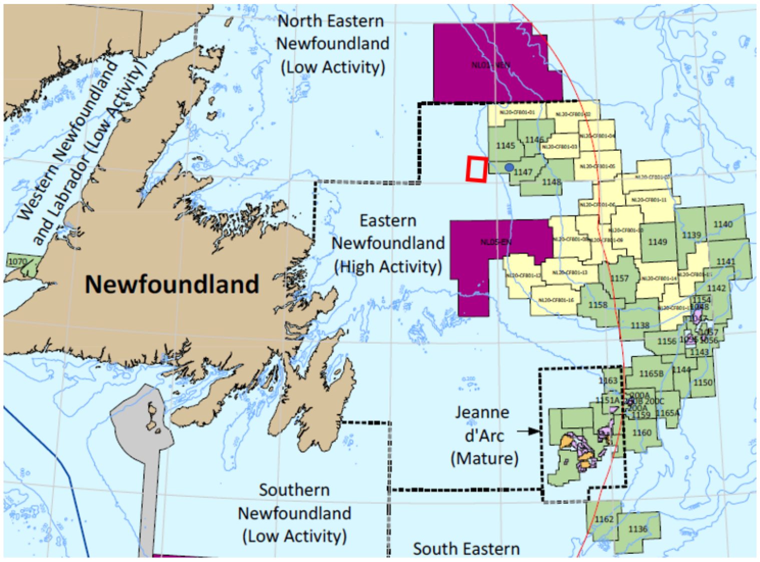


Figure 11-9: Sitemap for Greenfield Study 2

11.3.2 Wind Power Electrification (Inputs and Assumptions)

As discussed in Section 11.2, the water depth for this area is around 1200m. The annual average wind capacity factor is about 44%, which is within the common existing offshore industry experience (35% ~ 45%).

11.3.3 Greenfield Study 2 Wind Turbines Array Determination

The maximum continuous load of the FPSOs are assumed to be 65 MW and 45 MW. It is expected to replace 50% of the annual power supply by wind power. Therefore, the required total wind power is about:

(65 + 45) MW x 50% ≈ 55 MW

The estimated amount of GHG reduction per year with average utilization of 55 MW power is 186,728 tonnes.

Based on the 44% annual average wind capacity factor, the wind farm rated power should be at least:

55 MW / 44% ≈ 125 MW

An 8MW wind turbine is adopted in this study. So, the total number of wind turbines required is:

125 MW / 8 MW ≈ 16

The turbines are again placed with at least 7 times the rotor diameter between each turbine. The Siemens-8MW wind turbine has 167m rotor diameter. Therefore, each turbine should be at least 1,169 m away from each other.

The mooring system is expected to be taut mooring system to control the turbines' offset. The mooring line horizontal span is estimated to be 1,920m, which is 1.6 times water depth for this location, based on industry experience. Each turbine has three mooring lines. Anchors are shared between mooring lines. A total of 24 anchors would be deployed.

In this study, the wind turbines are separated 3,334m from adjacent turbines due to the significant water depth. Considering the dominant wind direction for the largest wind speed (275 deg ~ 285 deg), the preliminary wind turbine array is shown in Figure 11-10.

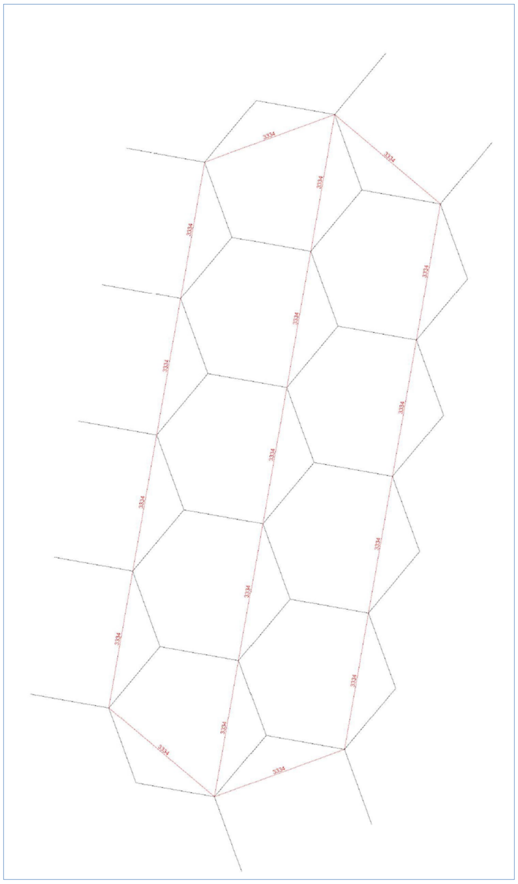


Figure 11-10: Wind Turbine Array for Greenfield Study 2

Array cabling is assumed to be dynamic 66kV, 3-phase cable in a W-shaped configuration between turbines to protect cables from the dynamics and forces involved at this extreme water depth as well as limiting cable lengths required between each turbine.

11.3.4 Subsea Power Tie-back

The single export cable is assumed to be identical with the 66kV MVAC dynamic array cables to facilitate qualified tie-in to the FPSO microgrid.

11.3.5 CAPEX and OPEX Study

CAPEX

The CAPEX costs associated with the offshore wind electrification are estimated based on the cost of the substation equipment included on the FPSO, submarine cables and wind power array.

Table 11-11: Offshore Substation Equipment Cost – Greenfield Study 2

Offshore Substation Equipment Cost for Greenfield FPSO – Greenfield Study 2					
Outside Plant Electrical Construction					
ITEM	**DESCRIPTION**	**QTY**	**UNIT**	**TOTAL LABOUR & MATERIAL $CAD**	**COMMENTS**
1	Additions to Greenfield FPSO system to Accommodate Electrification via Wind Power	1	EA	$13,000,000	• Cost estimates are based on historic rate information available in-house from a previous similar project. No new Vendor Quotes were requested. • Cost of additions to traditional FPSO to accommodate electrification equipment. The costs include cable pull tube, turret swivels, trays, Larger switch gear and switch gear room. Structural steel for accommodating additional equipment on process deck. • No weather delays are included during the transportation/installation phases.
2	Testing & Commissioning	1	EA	$2,600,000	
3	Control House (66kV)	1	EA	$3,640,000	
4	3-phase 66kV/13.8kV Transformer	1	EA	$1,463,000	
5	3-phase 13.8kV/480v Transformer	2	EA	$133,000	
6	Control House (13.8kV)	1	EA	$621,000	• Assumed as additional cost to FPSO control house.

Offshore Substation Equipment Cost for Greenfield FPSO – Greenfield Study 2					
Outside Plant Electrical Construction					
ITEM	**DESCRIPTION**	**QTY**	**UNIT**	**TOTAL LABOUR & MATERIAL $CAD**	**COMMENTS**
7	Shunt Reactors (3 - Single Phase)	3	EA	$975,000	• Single Phase, 32.8 MVAR
8	Switchgear 13.8kV	1	EA	$601,000	• Assumed as addition to 13.8 kV switchgear
9	Switchgear 480V	1	EA	$228,000	• Assumed as additional cost to FPSO control house.
10	MVAC and LVAC Cables and Bus Duct Systems	1	Lot	$3,109,000	
11	Battery System (Including Associated Rectifier)	1	Lot	$25,096,000	• Assumes total storage can accommodate wind array at average power output of 55MW for 2 hours.
12	Harmonic Filters	1	Lot	$1,036,000	
	TOTAL			**$52,502,000**	

Table 11-12: Submarine Cable Cost - Greenfield Study 2

Submarine Cables – Greenfield Study 2					
Submarine Cable Construction and Installation					
ITEM	**DESCRIPTION**	**QTY**	**UNIT**	**TOTAL LABOUR & MATERIAL CAD $**	**COMMENTS**
1	66kV Dynamic Submarine Cable, 1200mm2 Conductors	90	km	$140,400,000	• Cost of Dynamic Cable: CAD $1,560,000/km • Two cables are assumed (due to ampacity) with 8 wind towers to each FPSO • 2X1000mm2 conductor x-section assumed as ampacity requirement is 1093A

Submarine Cables – Greenfield Study 2

Submarine Cable Construction and Installation

ITEM	DESCRIPTION	QTY	UNIT	TOTAL LABOUR & MATERIAL CAD $	COMMENTS
					• Cable length between array towers = 4km • Assumed export cable length = 17km each • Cables are assumed to be unburied, laid on seabed
2	Installation of Tri-core Submarine Cables to each Tower and to Substation	1	EA	$9,900,000	• Installation Lay Rate: 3km / day (unburied) • Installation Vessel Rate: $300,000 / Day 3 days Mobilization
	Total			**$150,300,000**	

Table 11-13: Turbine, Floating Foundation, Mooring and Piles Cost - Greenfield Study 2

No.	Item	CAPEX COST (CAD)	COMMENT
1	Turbine	$227,136,000	• The "Turbine" sheet cost is estimated based on "Annual Technology Baseline: Electricity (2019)". Unit price is $1.3 million/MW. • Assume de-icing system cost is 5% of unit price (turbine blades).
2	Floater	$256,805,000	• 1. It is assumed that the floating foundation material is steel. • The structure weight of the floater is scaled from the reference project.
3	Floater Appurtenance	$12,840,000	• Assume the appurtenance price is 5% of the floater structure price.
4	Top Chain	$5,890,000	• The mooring system is chain-polyester-chain.
5	Polyester	$14,633,000	

No.	Item	CAPEX COST (CAD)	COMMENT
6	Anchor Chain	$8,835,000	• The mooring length is based on similar oil & gas project. • Top chain 200m, Polyester 2100m, Anchor Chain 300m. • The mooring chain size is scaled from reference project based on rated power.
7	Mooring Accessories	$5,871,000	• The mooring accessories price is assumed to be 20% of the mooring chain price.
8	Piles	$5,460,000	• The pile size is scaled from the reference project.
9	Mooring/Pile Transportation and Installation	$37,284,000	• The mooring and piles are assumed to be fabricated in Europe and transported to Canada offshore. • The mooring and piles are assumed to be transported to Canada by ocean barges, each with three tow tugs.
10	Turbine and Floater Transportation and Installation	$115,555,000	• The turbines are assumed to be fabricated in Europe and transported to Canada offshore. • The floating foundation is assumed to be fabricated in Eastern Canada. • The turbine towers are assumed to be fabricated in Eastern Canada. • The turbines and blades are assumed to be transported to Canada by ship.
	Total	**$690,309,000**	

OPEX

Operation and Maintenance (O&M) is a significant cost when it comes to offshore wind power, with an average annual cost of CAD $169/kW year [Ref.17] of energy capacity (or CAD $169,000 per MW year). Assuming an array of sixteen 8MW floating offshore wind turbines with associated cabling and substation equipment for Greenfield Study 2, the annual O&M cost for the wind power generation facilities would be CAD $21,632,000/year.

Floating offshore wind may potentially offer a much lower O&M cost than the bottom-fixed offshore wind. For major inspections and repairs, the individual FOW structure can be disconnected from the mooring lines and towed back to a deepwater dock facility, if required. The O&M activities associated with floating offshore wind carried out dockside is also less influenced by the weather conditions than that of bottom-fixed wind farm (this potential for savings was not included in the O&M cost presented). The cost assumes an offshore maintenance contract with the equipment supplier as purchase of a dedicated Service

Operation Vessel (SOV) would be economically inefficient with a field of this size. This annual cost does not include the cost of intervention and repair resulting from catastrophic equipment failure or cable faults.

No specific costs have been included in this study for ice management for the floating wind turbines. Ice management plans are required offshore Newfoundland and Labrador which outline how operators will detect, monitor and manage sea ice and/or icebergs before they pose a threat to facilities. It is anticipated that those same ice management activities would cover the wind energy facilities; the incremental cost increase to do so has not been determined.

Cost Summary

The estimated total cost for all Greenfield Study 2 additions for offshore wind electrification is CAD $893,111,000. There will also be an additional O&M cost for the floating wind power equipment of CAD $21,632,000 per year.

Cost saving of fuel gas for operating gas turbine is not considered as gas is currently not saleable from the Jeanne d'Arc Basin. If the gas could be sold, the reduction in fuel gas consumption on the platforms would equate to approximately CAD $10,172,000 based on current gas prices. The associated reduction in costs associated with gas turbine maintenance, spares, and applicable carbon tax has not been quantified for this study.

As stated in Section 11.1.5, cost is rapidly decreasing as development of offshore wind power increases. Estimated costs shown in this report should be considered a snapshot in time.

11.3.6 Study Results

Greenfield Study 2 shows that increase in the capacity of a wind array is scalable with CAPEX and OPEX. Although two separate export cables were required in this case, the additional wind turbine quantity would have required two MVAC cables even if the tie-back was to a single host facility.

The required swivel technology is qualified, but not field proven, as is the case in all the studies performed in this report.

11.4 Greenfield Study 3

11.4.1 Study Outline

Greenfield Study 3 includes a single disconnectable, turret moored FPSO with dedicated wind array at a shallower water depth location. The host in this case requires an HVAC export cable to enable the tie-back to the wind power array due to the distance.

The Greenfield Study 3 scenario again has the FPSO in Offshore Block 1147, as the blue dot in Figure 11-11. The wind farm is located near the FPSO to provide power. The red box is the expected wind farm location. The average distance from the wind farm to the FPSO is about 65 km.

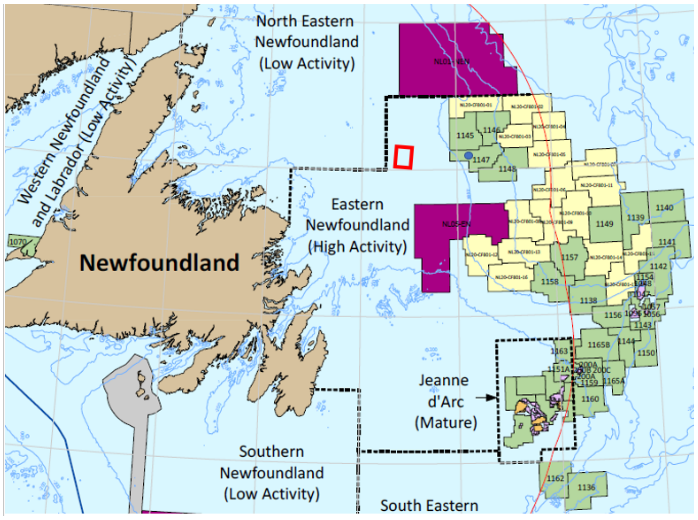


Figure 11-11: Sitemap for Greenfield Study 3

11.4.2 Wind Power Electrification (Inputs and Assumptions)

The expected wind farm location is at the southwest corner of the cell 292 from “MetOcean Climate Study Phase II, Offshore Newfoundland & Labrador” ([Ref 16]). The water depth for this area is around 300m. (Figure 11-7)

As discussed in Section 11.2, the annual average wind capacity factor for cell 292 is approximately 44%, which is within the common existing offshore industry experience (35% ~ 45%).

Table 11-14: Wind Capacity Factors for Greenfield Study 3

	Median Wind Speed at Hub*	Wind Capacity Factor
Jan	15.9	55%
Feb	15.0	55%
Mar	13.7	55%
Apr	11.9	54%
May	10.0	32%
Jun	8.8	22%
Jul	8.3	18%
Aug	8.9	23%
Sep	10.9	41%
Oct	12.7	55%

	Median Wind Speed at Hub*	Wind Capacity Factor
Nov	14.1	55%
Dec	15.4	55%
Annual Average		**44%**

11.4.3 Study 3 Wind Turbines Array Determination

The maximum continuous load of the FPSO is assumed to be about 65 MW. It is expected to replace 45% of the annual power supply by wind power. Therefore, the required total wind power is about:

65 MW x 45% ≈ 29 MW

The estimated amount of GHG reduction per year with average utilization of 29 MW power is 98,456 tonnes.

Based on the 44% annual average wind capacity factor, the wind farm rated power should be at least:

29 MW / 44% ≈ 66 MW

An 8MW wind turbine is adopted in this study. So, the total number of wind turbines required is:

66 MW / 8 MW ≈ 9

The turbines are again placed with greater than 7 times the rotor diameter between each turbine. The Siemens-8MW wind turbine has 167m rotor diameter. Therefore, each turbine should be at least 1,169m away from each other.

The mooring system is expected to be a taut mooring system to control the turbines' offset. The mooring line horizontal span is estimated to be 480m, which is 1.6 times water depth for this location, based on industry experience. Each turbine has three mooring lines and three anchors.

In this case, turbine's spacing is 1,200m. Considering the dominant wind direction for the largest wind speed (275 deg ~ 285 deg), the preliminary wind turbine array is shown in Figure 11-12.

Array cabling is assumed to be dynamic 66kV, 3-phase cable in a lazy-wave configuration to protect cables from the dynamics and axial forces involved at this water depth.

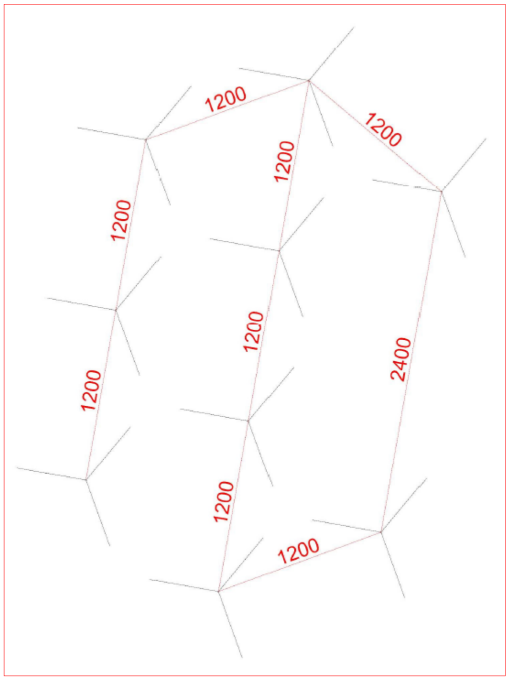


Figure 11-12: Wind Turbine Array for Greenfield Study 3

11.4.4 Subsea Power Tie-back

For Greenfield Study 3, a single 132kV, 3-phase HVAC export cable is assumed between the wind power array and the host facility location. A structure would be placed on the seabed near the FPSO and closest wind tower which includes a subsea transformer and reactor combination. This allows step-up and step-down from 132kV to 33kV or 66kV (or vice-versa for step-up) enabling use of an MVAC dynamic cables to facilitate qualified tie-in to the floating facilities.

11.4.5 CAPEX and OPEX Study

The costs associated with the offshore wind electrification are estimated based on the cost of the substation equipment included on the FPSO, submarine cables and wind power array.

Table 11-15: Offshore Substation Equipment Cost – Greenfield Study 3

Offshore Substation Equipment Cost for Greenfield FPSO – Greenfield Study 3					
Outside Plant Electrical Construction					
ITEM	**DESCRIPTION**	**QTY**	**UNIT**	**TOTAL LABOUR & MATERIAL $CAD**	**COMMENTS**
1	Additions to Greenfield FPSO system to Accommodate Electrification via Wind Power	1	EA	$11,700,000	• Cost estimates are based on historic rate information available in-house from a previous similar project. No new Vendor Quotes were requested. • Cost of additions to traditional FPSO to accommodate electrification equipment. The costs include cable pull tube, turret swivel, trays, Larger switch gear and switch gear room. Structural steel for accommodating additional equipment on process deck. • No weather delays are included during the transportation/installation phases.
s2	Testing & Commissioning	1	EA	$2,600,000	
3	Control House (66kV)	1	EA	$3,640,000	
4	3-phase 66kV/13.8kV Transformer	1	EA	$772,000	
5	3-phase 13.8kV/480v Transformer	2	EA	$70,000	
6	Control House (13.8kV)	1	EA	$621,000	• Assumed as additional cost to FPSO control house.
7	Switchgear 13.8kV	1	EA	$317,000	• Assumed as addition to 13.8 kV switchgear
8	Switchgear 480V	1	EA	$120,000	• Assumed as additional cost to FPSO control house.
9	MVAC and LVAC Cables and Bus Duct Systems	1	Lot	$1,642,000	

Offshore Substation Equipment Cost for Greenfield FPSO – Greenfield Study 3					
Outside Plant Electrical Construction					
ITEM	**DESCRIPTION**	**QTY**	**UNIT**	**TOTAL LABOUR & MATERIAL $CAD**	**COMMENTS**
10	Battery System (Including Associated Rectifier)	1	Lot	$13,251,000	• Assumes total storage can accommodate wind array at average power output of 29MW for 2 hours.
11	Harmonic Filters	1	Lot	$547,000	
	TOTAL			**$35,280,000**	

Table 11-16: Submarine Cable Cost - Greenfield Study 3

Submarine Cables + Subsea Transformer/Reactors - Greenfield Study 3					
Submarine Cable Construction and Installation					
ITEM	**DESCRIPTION**	**QTY**	**UNIT**	**TOTAL LABOUR & MATERIAL CAD $**	**COMMENTS**
1	66kV Dynamic Submarine Cable, 1000mm^2 Conductors	17.2	km	$26,832,000	• Cost of Dynamic Cable: CAD $1,560,000/km 1000mm2 conductor x-section assumed as ampacity requirement is 577A • Cable length between array towers = 1.8km • Assumed export cable dynamic section length (after subsea transformer) = 2km • Cables are assumed to be unburied, laid on seabed

Submarine Cables + Subsea Transformer/Reactors - Greenfield Study 3					
Submarine Cable Construction and Installation					
ITEM	**DESCRIPTION**	**QTY**	**UNIT**	**TOTAL LABOUR & MATERIAL CAD $**	**COMMENTS**
2	Subsea Transformer (138kV / 66kV and 66kV / 138kV) and Reactor with Foundation (one on each side of the HVAC export cable)	2	EA	$32,308,000	• Subsea Transformer + Reactor 159.2 MVAR reactors. Higher reactive power compensation required due to longer step-out and high voltage
3	125kV Static Submarine Cable, 500mm^2 Conductors	70	km	$91,700,000	• Cost of Dynamic Cable: CAD $1,510,000/km 500mm2 conductor x-section assumed as ampacity requirement is 276A • Cable length assumed 70km • Assumed static export cable dynamic section termination into subsea transformer on each end
4	Installation of Tri-core Submarine Cables to each Tower and to Substation	1	EA	$10,220,000	• Installation Lay Rate: 3km / day (unburied) • Installation Vessel Rate: $300,000 / Day • 3 days Mobilization • 2 days assumed for subsea transformer/reactor Installation
	Total			**$161,060,000**	

Table 11-17: Turbine, Floating Foundation, Mooring and Piles Cost - Greenfield Study 3

No.	Item	CAPEX COST (CAD)	COMMENT
1	Turbine	$127,764,000	• The "Turbine" sheet cost is estimated based on "Annual Technology Baseline: Electricity (2019)". Unit price is $1.3 million/MW.

No.	Item	CAPEX COST (CAD)	COMMENT
			• Assume de-icing system cost is 5% of unit price (turbine blades).
2	Floater	$144,453,000	• It is assumed that the floating foundation material is steel. • The structural weight of the floater is scaled from the reference project.
3	Floater Appurtenance	$7,223,000	• Assume the appurtenance price is 5% of the floater structure price.
4	Top Chain	$3,334,000	• The mooring system is chain-wire-chain. • The mooring length is based on similar oil & gas project. Top chain 200m, Polyester 400m, Anchor Chain 200m. • The mooring chain size is scaled from reference project based on rated power.
5	Wire	$1,578,000	
6	Anchor Chain	$5,001,000	
7	Mooring Accessories	$1,982,000	• The mooring accessories price assumed to be 20% of the mooring chain price.
8	Piles	$6,142,000	• The pile size is scaled from the reference project.
9	Mooring/Pile Transportation and Installation	$18,438,000	• The mooring and piles are assumed to be fabricated in Europe and transported to Canada offshore. • The mooring and piles are assumed to be transported to Canada by ocean barges, each with three tow tugs.
10	Turbine and Floater Transportation and Installation	$57,611,000	• The turbines are assumed to be fabricated in Europe and transported to Canada offshore. • The floating foundation is assumed to be fabricated in Eastern Canada. • The turbine towers are assumed to be fabricated in Eastern Canada. • The turbines and blades are assumed to be transported to Canada by ship.
	Total	**$373,526,000**	

OPEX

Operation and Maintenance (O&M) is a significant cost when it comes to offshore wind power, with an average annual cost of CAD $169/kW year [Ref.17] of energy capacity (or CAD $169,000 per MW year).

Assuming an array of nine 8MW floating offshore wind turbines with associated cabling and substation equipment for Greenfield Study 3, the annual O&M cost for the wind power generation facilities would be CAD $12,168,000/year.

Floating offshore wind may potentially offer a much lower O&M cost than the bottom-fixed offshore wind. For major inspections and repairs, the individual FOW structure can be disconnected from the mooring lines and towed back to a deepwater dock facility, if required. The O&M activities associated with floating offshore wind carried out dockside is also less influenced by the weather conditions than that of bottom-fixed wind farm (this potential for savings was not included in the O&M cost presented). The cost assumes an offshore maintenance contract with the equipment supplier as purchase of a dedicated Service Operation Vessel (SOV) would be economically inefficient with a field of this size. This annual cost does not include the cost of intervention and repair resulting from catastrophic equipment failure or cable faults.

No specific costs have been included in this study for ice management for the floating wind turbines. Ice management plans are required offshore Newfoundland and Labrador which outline how operators will detect, monitor and manage sea ice and/or icebergs before they pose a threat to facilities. It is anticipated that those same ice management activities would cover the wind energy facilities; the incremental cost increase to do so has not been determined.

Cost Summary

The estimated total cost for all Greenfield Study 3 additions for offshore wind electrification is CAD $569,866,000. There will also be an additional O&M cost for the floating wind power equipment of CAD $12,168,000 per year.

Cost saving of fuel gas for operating gas turbine is not considered as gas is currently not saleable from the Jeanne d'Arc Basin. If the gas could be sold, the reduction in fuel gas consumption on the platform would equate to approximately CAD $5,364,000 based on current gas prices. The associated reduction in costs associated with gas turbine maintenance, spares, and applicable carbon tax has not been quantified for this study.

As stated in Section 11.1.5, cost is rapidly decreasing as development of offshore wind power increases. Estimated costs shown in this report should be considered a snapshot in time.

11.4.6 Study Results

Greenfield Study 3 shows that wind power electrification of an FPSO is feasible using a long-distance tie-back with qualified equipment. Just like the other greenfield cases, the required swivel technology is qualified, but not field proven. If the tie-back can utilize HVAC power transmission, there is room for even greater power capacity tie-back using a single static HVAC cable.

However, if the comparison is made between the short step-out (Greenfield Study 1) and a long step-out (Greenfield Study 3) with identical electrification power capacities, the increase in cost of the additional 50 mile distance is approximately CAN $80 million for the additional submarine cabling and subsea equipment.

11.5 Installation Durations (All Studies)

Installation durations were estimated based on previous project experience with the assumed load out from Bull Arm. Substation and related equipment installation is assumed during floater and turbine installation.

Installation assumes all major components are assembled keyside at Bull Arm and towed (floated) to site. Weather downtime is not included in these estimates.

Table 11-18: Installation Durations (All Studies)

Installation Days				
Scenario	Mooring Lines and Anchor	Floater and Turbine	Submarine Cable	Total
	Days	Days	Days	Days
Brownfield	22	28	17	67
Greenfield 1	27	27	20	74
Greenfield 2	48	48	33	129
Greenfield 3	18	18	34	70

12 SUPPLY CHAIN AND FABRICATION FACILITIES

12.1 Supply Chain

Planning and developing offshore wind farm projects offer a number of supply chain opportunities, some of which might be provided by NL companies. The following table lists many of the components associated with the development of a floating offshore wind farm, and which have been broadly categorized as follows: Engineering; Procurement; Construction; Operations; and Decommissioning.

Some of these areas require specific experience/expertise with respect to offshore wind (e.g. some aspects of Engineering, Construction, Operations). The level of specific wind experience/expertise required might vary from item to item; this experience/expertise might have been gained (and be transferable) from NL's offshore oil industry or it might be gained through partnerships with companies in other parts of the world experienced in various aspects of the offshore wind industry.

Aspects of the work will require skilled trades, offshore survey vessels, access to technology, specialized facilities, offshore installation vessels, and industry-specific project management; which may or not be available in NL. The actual regional opportunities that might eventually be realized through offshore wind development will depend on the optimal solution determined for offshore NL. The expertise, infrastructure, facilities, and skilled trades that have been developed as part of the NL offshore and other industries are potential areas that could be tapped into for offshore wind developments.

Table 12-1: Summary of Supply Chain Capabilities and Competencies Required

Engineering	Procurement	Construction	Operations	Decommissioning
Planning and Economic Analysis	Procurement	Topsides Engineering or Modifications	Remote Sensing	Removal of Floating Wind Turbine
Feasibility Studies	Logistics	Floating Technology	Remote Operations	Removal of Seabed Foundations
Regulatory and Permitting	Storage	Wind Turbine Foundations	Inspections	Reeling of Power Cables
Environmental Studies	Customs Brokerage	Wind Turbine Generators	Modifications	Dismantling of Equipment
Metocean and Modelling	Transportation	Offshore Substation	Maintenance	Disposal
Geophysical & Geotechnical	Subsea Cables	Seabed Foundation / Anchor	Repair	
Site Assessment	Classification Society	Offshore Electrical Systems	Replacement	
Engineering	Fabrication	Subsea Cables		
Construction Planning	Installation	Classification Society		
Operations & Maintenance Planning	Commissioning	Fabrication		
Project Management		Installation		
		Commissioning		

12.2 Local Fabrication and Assembly Infrastructure Requirements

As discussed earlier in this report, it is unlikely that wind farms using fixed foundation turbines would be economical for offshore Newfoundland and Labrador given the risks from and need to design for ice (sea ice and icebergs). However, if found to be technically feasible at an acceptable cost, then foundations of fixed wind turbines utilizing monopile, tripod, and jacketed structures with various foundations at the sea floor including monopile or multiple piles, gravity base, and caissons, might be fabricated in NL (depending on economics associated with local fabrication). One could envision gravity-based structures (such as those proposed for ice resistant wellhead platforms) being used to support wind turbines and those could be fabricated in the Bull Arm or Argentia facilities, albeit an expensive solution.

For locations with water depths over about 60–80 m, fixed foundations are generally uneconomical or technically unfeasible, and floating wind turbines anchored to the ocean floor are needed. These structures will require a deepwater facility to assemble the completed wind turbine assemblies; Bull Arm or Argentia could be candidate sites for these activities. The proximity of other fabrication/construction infrastructure could also be used to assist in the construction of the floating foundation (whether concrete or steel), fabrication of seabed foundations, as a location for stockpiling other components (e.g. anchor chain/cables and power transmission cables), and as an installation base during offshore activity.

13 TECHNOLOGY GAPS AND GAP RESOLUTION

A primary benefit that the pilot projects related to floating wind and electrification have provided is the significant reduction in gaps for floating wind systems in the MVAC range. Technology gaps related to power transmission are primarily related to dynamic HVAC systems and include the dynamic HVAC cable, dynamic HVAC bend stiffener and HVAC connectors and swivels. While HVAC power cables and interfaces are not necessarily required for wind power electrification for offshore Newfoundland and Labrador, the study of the current and projected status of this equipment is of value.

The following are estimations of duration for gap resolution to a “ready for purchase” status.

Dynamic HVAC Cable - An international competition was launched on behalf of the floating wind Joint Industry Project (JIP) to aid cable manufacturers in the development and test of suitable dynamic HVAC cable designs. Five cable manufacturers are currently being supported by the JIP to make these designs available as products for future projects. The findings of the competition show that a number of design and manufacturing challenges must be overcome before HV dynamic export cables can be routinely produced. Handling techniques also need to be modified to safely manipulate HV dynamic export cables as they will be heavier and stiffer than traditional export cables. The suppliers have also used this opportunity to justify the use of more significant condition monitoring than just the DTS fibre systems (for temperature) as the dynamic environment opens the cable up to additional failure scenarios.

It is anticipated that the JIP results will significantly reduce the time to market and accelerate the development of commercial floating wind farms by ensuring that HV dynamic cables (230kV or below) are available for the first large-scale projects within the next 5-10 years.

Dynamic HVAC Bend Stiffener – The gap related to bend stiffeners is primarily based on large capacity dynamic export cables with significant weight and stiffness. Smaller, lower capacity export cables used for electrification could likely utilize bend stiffeners which would only require small modification of existing technology. The estimated time for having ready for purchase small capacity HVAC cable dynamic bend stiffeners is 2-3 years based on the current status of MVAC dynamic bend stiffeners.

HVAC Connectors and Swivels - Section 8 detailed the current status of MV and HV swivels (and associated connectors). It is anticipated that the HVAC interfaces require significant reconfiguration of the existing MVAC technology, with only preliminary prototype testing performed on few designs (such as 132kV swivels). It is expected that these connection systems will require at least 5 years to be in a ready for purchase state (could take as long as 10 years).

Ice Resistant Floating Wind Turbine Foundations - There are no existing projects with floating wind turbine foundations designed for an ice environment. As discussed earlier in this report, a floating wind turbine would need to be designed to accommodate some ice loading and perhaps to be rapidly disconnectable. Pack ice can increase the environmental loads on the turbine foundation and requires a special mooring system and foundation structure design. If icebergs are too large for turbine foundations and anchoring to withstand resulting impacts/loads, the turbines may need to be quickly disconnected and towed away. In order to develop an economical ice resistant and disconnectable floating wind turbine foundation, additional research, engineering, and proof of concept work would need to be carried out.

14 SUMMARY

Several floating offshore wind projects in operation have been reviewed. None are currently being used for electrification of offshore projects. The Hywind Scotland project was the first commercial floating wind project in the world to generate power to shore. The project was commissioned in October 2017 five 6MW turbines in water depths of up to 129m. WindFloat Atlantic is another floating wind farm which is providing power back to shore. Tahkoluoto is a fixed offshore wind farm and is located in a cold weather environment subject to sea ice and icing (offshore west coast of Finland). A number of smaller pilot projects exist in floating offshore wind consisting of single prototype floating towers to demonstrate a design concept. Among these, Hywind Demo (installed in 2009), FloatGen Demonstrator (installed May 2018), and WindFloat Demo (installed October 2011) are examples of development of floating wind test demonstration projects.

The integration of floating wind power into a brownfield development project offshore has not yet been undertaken. Two projects with some degree of similarity are the Goliat FPSO and Gjoa platform. Both projects were greenfield and power supply was from an onshore electrical grid. No operating greenfield projects have incorporated floating wind into their design.

Hywind Tampen is a floating wind pilot power project located approximately 140km off the Norwegian coast. It is intended to provide electricity for the Snorre and Gullfaks offshore field operations in the Norwegian North Sea and is under development by Equinor. It will be the world's first floating wind farm to electrify offshore oil and gas platforms. The field will include eleven 8MW floating wind turbines with 167m rotors. The turbines will be installed in water depths of 260-300m.

Each of the existing floating wind power projects have similarities to project challenges of electrification of an FPSO or platform. Key similarities of the associated challenges are: challenges associated with dynamic cabling at different water depths; determination of best cable configuration and array layout; determination of the best suited support structure (Floating Foundation); sizing of generator (can have a significant effect on the tower's performance); best anchoring solutions; optimization of power storage.

When considering the electrification of an offshore production facility, the modifications required on an existing facility or the design for a purpose-built facility will be driven by the type of the installation. The subsea cables must be interfaced with the platform electrical system. The solution for a geostationary platform or weathervaning ship-shaped FPSO will be significantly different. In a brownfield scenario, the required equipment may need to be located on a small floating structure separate from the production facility (but located close by). In a greenfield approach for electrification of an offshore development, the power supply from a wind array will be integral part of facility design. The process deck layout will be optimized to reduce the need for heavy equipment to be located in the wind farm; the equipment would be located on the production facility or on a separate nearby structure.

Several pilot projects are ongoing to further prove technology required for electrification of brownfield and greenfield oil and gas developments. In the case of weathervaning FPSO's, the required swivel technology is qualified, but not field proven.

A brownfield and three greenfield scenarios offshore Newfoundland and Labrador have been investigated. These are summarized in Table 14-1 below.

Table 14-1: Study Summaries

Scenario	Brownfield	Greenfield 1	Greenfield 2	Greenfield 3
Configuration	GBS	Single FPSO	Two FPSOs	Single FPSO
Water Depth at Host	93m	1,200m	1,200m	1,200m
Water Depth at Wind Farm	75m	1,200m	1,200m	300m
Distance to Host	15km	15km	15km	65km
Wind Array Power Requirements	41MW Average 98MW Max Capacity	29MW Average 66MW Max Capacity	55MW Average 125MW Max Capacity	29MW Average 66MW Max Capacity
Number of Floating Offshore Wind Turbines	13	9	16	9
Wind Array Voltage	MVAC (66kV)	MVAC (66kV)	MVAC (66kV)	MVAC (66kV)
Export Voltage	MVAC (66kV)	MVAC (66kV)	MVAC (66kV)	HVAC (138kV)
CAPEX	$689,831,000	$515,577,000	$893,111,000	$569,866,000
OPEX (per year)	$17,576,000	$12,168,000	$21,632,000	$12,168,000
Avoided GHG Emissions Estimate	Average 139,197 tonnes/year	Average 98,456 tonnes/year	Average 186,728 tonnes/year	Average 98,456 tonnes/year

The brownfield scenario study shows that floating wind power electrification of a brownfield host facility is a feasible concept for offshore Newfoundland and Labrador. Additional CAPEX is required compared to a greenfield application due to the requirements for a separate floating wind power substation to accommodate equipment.

Greenfield Study 1 indicates that floating wind power electrification of an FPSO requires significantly lower CAPEX if electrification can be incorporated in a greenfield development (or was enabled for on a brownfield application through weight capacity and host real estate). The elimination of the separate substation results in a greater than 50% reduction in costs related to substation equipment. If offshore oil and gas projects include wind power electrification in a greenfield application, the optimum design is to locate the substation equipment onboard the host facility itself. The water depth in the greenfield scenario 1 study results in significant spacing of wind turbines which drives up the submarine cable length and cost but is likely beneficial regarding overall power generated by each turbine.

Greenfield Study 2 shows that increase in the capacity of a wind array is scalable with CAPEX and OPEX. Although two separate export cables were required in this case, the additional wind turbine quantity would have required two MVAC cables even if the tie-back was to a single host facility.

Greenfield Study 3 shows that wind power electrification of an FPSO is feasible using a long-distance tie-back with qualified equipment. If the tie-back can utilize HVAC power transmission, there is room for even greater power capacity tie-back using a single static HVAC cable.

Cost saving of fuel gas for operating gas turbine has not been considered as gas is currently not saleable from the Jeanne d’Arc Basin. If the gas could be sold, the reduction in fuel gas consumption on the platform would equate to several million dollars per year. The associated reduction in operating costs associated with gas turbine maintenance, spares, and applicable carbon tax has not been quantified for this study. The avoided GHG emissions should result in a reduction in carbon tax; the quantification of such was beyond the scope of this study.

Planning and developing offshore wind farm projects offer a number of supply chain opportunities. The actual regional opportunities that might be realized through offshore wind development will depend on the optimal solution determined for offshore NL. The expertise, infrastructure, facilities, and skilled trades that have been developed as part of the Newfoundland and Labrador offshore and other industries are potential areas that could be tapped into for offshore wind developments.

15 RECOMMENDATIONS FOR FURTHER WORK

In order to move this initiative forward, and further investigate the development of an offshore wind power support industry in Newfoundland and Labrador, there are several additional studies that might be carried out.

- Floater Concepts - In order to develop an economical ice resistant and disconnectable (if required) floating wind turbine foundation specific to the Newfoundland and Labrador offshore, additional research, engineering, and proof of concept work would need to be carried out.

- Site Specific Alternatives Screening – Further work to determine best suited floating structures specific to offshore NL could be carried out. Not only technically best options but those most beneficial to NL supply chain. This would include looking at tradeoffs between shallower water depths and longer cable lengths (to the extent feasible).

- Detailed Technology Development Assessment – Based on potential options for offshore wind in NL, determine what detailed work would need to be done to move an offshore wind concept technically forward. Concept selection, compilation of environmental data, model testing, etc.

- Supply Chain Opportunities and Capabilities – This study has briefly touched on the supply chain for an offshore wind development. A more detailed assessment of local/regional facilities and capabilities which could support such a project could be carried out.

- Cold Region Implications - An assessment of the risk to wind facilities and cables due to the presence of ice or 3rd party activity is beyond the scope of this study. If further work is carried out to more fully evaluate the feasibility of wind energy to electrify oil and gas production facilities, then this topic warrants further study. The need for a de-icing system on wind turbine blades for the local offshore environment also needs to be investigated.

- Floating Wind Turbine Generator Limitations – Additional study is required to determine the maximum size vs. cost benefits of larger floating wind turbines (i.e. 14MW vs. 8MW).

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