FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

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FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

DC07 PROJECT

GIGAWATT SCALE CABLE AND MOORING INSTALLATION

PUBLIC SUMMARY REPORT

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PREFACE

Offshore Renewable Energy Catapult (ORE Catapult) has established the Floating Offshore Wind Centre of Excellence (FOW CoE). The FOW CoE is a collaborative programme with industry, academic and stakeholder partners.

The vision of the FOW CoE is to establish an internationally recognised centre of excellence in floating offshore wind which will work towards reducing the Levelised Cost of Energy (LCOE) from floating wind to a commercially manageable rate, cut back development time for FOW farms and develop opportunities for the local supply chain, driving innovation in manufacturing, installation and Operations and Maintenance (O&M) methodologies in floating wind.

More details on the FOW CoE can be found on: https://fowcoe.co.uk/

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- JDR Cables — Independent Advisor to project team
- Principle Power — Independent Advisor to project team
- ORE Catapult's Cables Strategic Programme Focus Group
- ORE Catapult's Moorings and Anchoring Strategic Programme Focus Group

The following organisations provided inputs on mooring equipment mobilisation:

- InterMoor — Mooring equipment mobilisation input
- Montrose Port Authority — Mooring equipment mobilisation input
- Global Energy Group — Mooring equipment mobilisation input

1 EXECUTIVE SUMMARY

This is a summary report showcasing the work carried out within the DC07 project identifying the benefits and drawbacks of potential Gigawatt scale floating wind installation methods. The work will inform decision-making around how the critical installation schedule and cost bottlenecks can be addressed.

Focusing on the requirements of the UK sector, the study explores methodologies, schedule and cost implications for a representative 100m water depth, 900 MW ScotWind site. Typical vessels and port facilities are assumed in an investigation of how to pre-install the mooring components, tow-out the commissioned FOWTs, connect the moorings and install the dynamic cables. Current and emerging technologies are applied in detail for selected cases, with the wider technology landscape explored through sensitivity analysis and qualitative review.

For Gigawatt scale floating wind, an optimal solution is likely to combine current methodologies and technology with new ideas and methods. The focus of this work is on installation step changes, which have the potential to address the critical installation bottlenecks. A 'base case' installation method was developed, by scaling up current practice for demonstrator floating wind arrays, which itself is built on oil and gas and fixed wind experience. An alternative mooring 'sensitivity case' was also detailed to allow for key uncertainties in the choice of mooring configuration. Looking to emerging solutions, a 'future case' was also detailed to explore their potential impact. Other technology options were either considered as variations to these set examples, or through general discussion.

Base case configuration

In the base case, shared suction piles are first installed by a construction vessel. Catenary mooring lines of large diameter chain are then connected to the suction piles and pre-laid using a high-capacity anchor handler. The 15MW semi-submersible FOWT is towed to location and hooked-up to the mooring lines using three anchor handlers. Finally, the tethered wave dynamic cable sections are installed from one FOWT to the next using a construction vessel with a cable lay spread. A team deployed from a W2W vessel supports cable pull-in on the FOWT.

The base case installation schedule is outlined below.

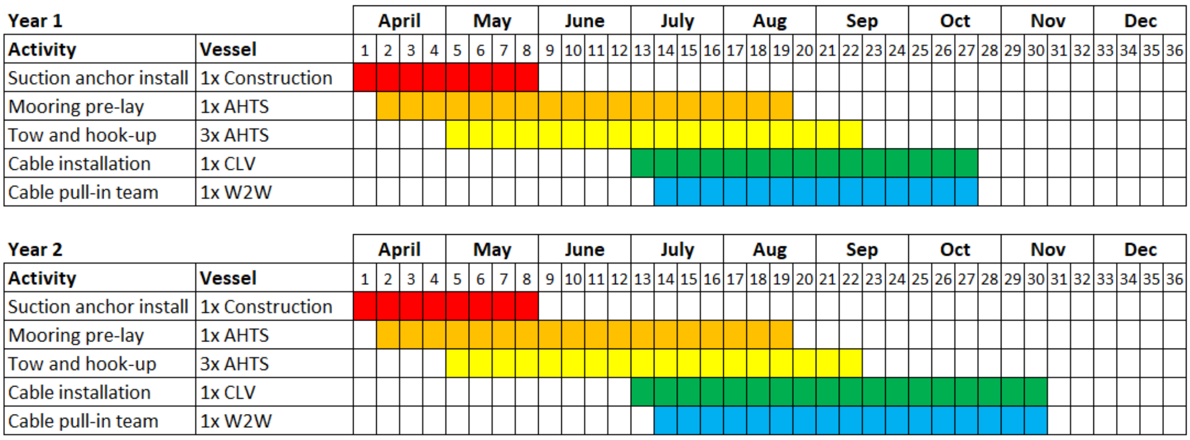

Figure 1 – Base case schedule overview

One major installation bottleneck is schedules running into the winter season, which drives project risk and installation cost. A rough approximation of seasonal weather downtime and cumulative delays is presented below for the first year of the installation schedule.

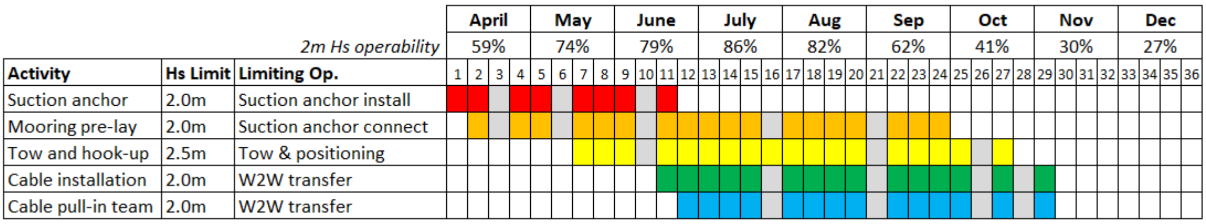

Figure 2 – Base case schedule overview with feasible weather delays shown as grey cells

Achievement of a two-year installation campaign depends on favourable weather and no major unplanned delays to any of the operations. Delays to one installation activity can impact the next, which can bring the mooring and cable connection operations into mid-winter, with in turn results in spiralling weather downtime. Options to accelerate the schedule are more likely to preserve the schedule against emergent delays and avoid a prolonged winter or third installation season.

For mooring pre-lay, tow, and hook-up operations AHTS capable of capable of handling 175mm chain are required. The available fleet of such vessels is highly constrained; only six vessels worldwide could feasibly handle 175mm chain. UK floating wind construction alone is expected to require an average of four such vessels continuously between 2030 and 2040, with a further four potentially required for two to port operations. Oil and gas and international floating wind demand will further squeeze the market and raise vessel hire day rates. Unless the global fleet of highly capable AHTS vessels grows substantially in the next decade, it may prove impossible to source vessels to handle the required construction and tow to port demand at acceptable cost.

Mooring installation comparison

To address some of the bottlenecks found in installing the base case mooring system, a detailed study has been performed for two alternative mooring solutions – a six line drag anchor system, termed the 'sensitivity case', and a taut mooring system, termed the 'future case'.

The base case mooring uses very large chain, which restricts installation to modern high specification anchor handling vessels. The sensitivity case system uses six lines per FOWT and drag embedment anchors. Using more mooring lines offers the opportunity to reduce chain size.

A taut nylon mooring has been selected as a promising technology to replace the large diameter chain with short lengths of lightweight synthetic rope. Nylon offers the elasticity required to keep peak mooring tensions within manageable levels in harsh environments. The taut system is coupled with an anchor-mounted tensioning system to reduce wear, corrosion, and fatigue issues associated with top chain connections.

A summary of comparative installation times and costs are presented below for the different mooring systems.

Table 1 Mooring installation vessel cost comparison

Installation Cost Element	Base Case		Sensitivity Case		Future Case	
	Hire Duration (months)	Cost (% of base case total)	Hire Duration (months)	Cost (% of base case total)	Hire Duration (months)	Cost (% of base case total)
Suction anchor install	3.5	15%	-	-	5.9	26%
Mooring pre-lay	9.1	31%	10.3	64%	5.3	18%
Tow & hook-up	9.1	55%	10.5	63%	8.8	53%
Total	-	**100%**	-	**127%**	-	**97%**

The drag anchor sensitivity case is found to be 22% more expensive. The installation cost for the six-line system is driven by the complexity of test tensioning the anchors to high loads using two vessels in tandem. There are clear opportunities to follow a smarter risk-based approach to anchor tensioning requirements. Following such an approach could accelerate the pre-lay schedule by 6 weeks per year and reduce the mooring installation cost by 15%.

The taut mooring design, which uses shorter lengths of more transportable synthetic rope, reduces the need for frequent mooring chain loadouts, and therefore accelerates pre-lay. This time saving is partially offset by a four week longer suction anchor installation campaign. Synthetic ropes can stretch over time after initial installation. Whilst this can be managed via re-tensioning the system after the first year of operation, risks associated with synthetic rope creep require further study. The risk associated with long term wet storage of nylon rope also requires further qualification.

Cable installation comparison

The base case cables are installed in a continuous operation between two FOWTs. This requires a two-day weather window, and dual operations between a W2W and cable lay vessel. A 'future case' array installation scenario has been studied using wet stored dynamic cables, which are pre-terminated and pre-laid. The more efficient cable connection process allows the cable pull-in time to be halved, with installation completed earlier in the year. The overall installation costs and schedules for the future case cable system are outlined below.

Table 2 Cable installation vessel duration and cost comparison

Installation Cost Element	Vessels Required	Base Case		Future Case	
		Hire Duration (months)	Cost (% of base case total)	Hire Duration (months)	Cost (% of base case total)
Cable installation	1 x CLV	8.1	58%	5.7	41%
Cable pull-in	1 x W2W	7.3 (Note 1)	42%	3.2	19%
Total	-	-	**100%**	-	**59%**
Note 1: W2W vessel is available to support other transfer operations. This is not considered in the study.					

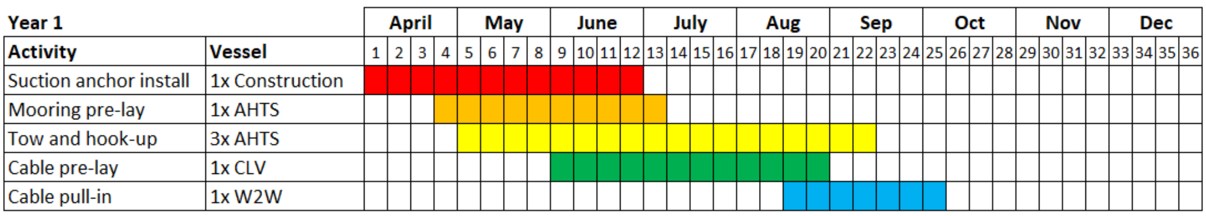

Figure 3 – Future case mooring and cable installation schedule

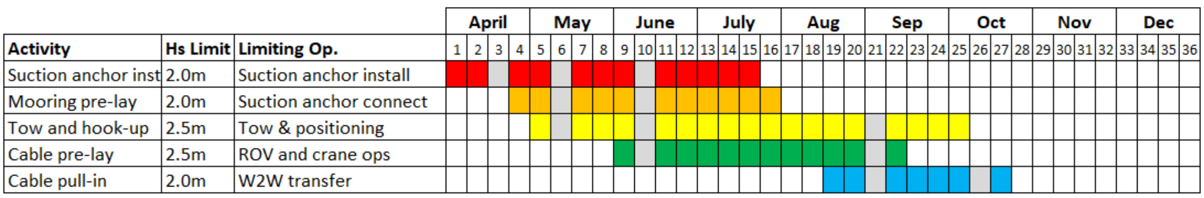

Figure 4 – Future case schedule overview with feasible weather delays shown as grey cells

An important change for the future case cable system is that the maximum weather window for the cable pull-in operation has reduced from 49 hours to 12 hours. This is expected to significantly reduce the weather downtime associated with the cable pull-in taking place later in the installation year.

The technology challenges associated with long term wet store of cables needs further qualification to mitigate the risk of water ingress and other degradation. Cable stability when subject to wet store in harsh conditions also required further assessment, depending on the specific project parameters.

Other Technology Options

High potential technology that is in an earlier stage of development has also been studied in this report. The installation costs for different cable connection scenarios are summarised in the table below.

Table 3 Cable installation technology variation cost comparison

Cable installation scenario	Vessel hire cost (% of total base case cost)		
	Cable & infrastructure pre-lay	Cable pull-in	Total
Base case	58%	42%	**100%**
Future case	41%	19%	**59%**
Reel lay optimisation	36%	19%	**55%**
Wet mate subsea hub	49%	13%	**62%**
Dry mate subsea hub	71%	13%	**84%**
Cable quick connection	69%	2%	**70%**

Most of the base and future case cables are installed via carousel loadouts. A reel-focussed lay spread, which could be enabled by hosting up to 8 reels on a construction vessel deck, could save 10% of the future case vessel hire cost. The saving is gained from reduced carousel transpooling time and optimised loadouts.

The total wet mate hub installation costs were estimated to be 5% greater than the future case. The cost savings on pre-lay and hook-up vessel time are balanced against the additional subsea hub installation time. Dry mate subsea hubs are substantially more complex to install and are estimated to cost 41% more than the future case.

Cable quick connection to the FOWT is explored in combination with a subsea hub. Installation costs were expected to be 20% more than the future case. However, cable pull-in costs and duration were only a tenth of the future case, which represents an opportunity to optimise tow to port operations. The influence of cable system design on tow to port costs also requires further study.

CONTENTS

NOMENCLATURE

AHTS	Anchor Handling Tug Supply Vessel (e.g. the Skandi Iceman or Skandi Skansen)
CoE	Centre of Excellence
CLV	Cable Lay Vessel (e.g. the Skandi Acergy with suitable cable lay spread)
CSA	Cross Section Area (area of copper conductor wire in each of the 3 cable cores)
CSV	Construction Support Vessel (e.g. the Skandi Acergy or Skandi Seven)
FEED	Front End Engineering Design
FOW	Floating Offshore Wind
FOWT	Floating Offshore Wind Turbine
HLS	Horizontal Lay Spread
ORE	Offshore Renewable Energy
OSS	Offshore Substation
O&G	Oil and Gas
O&M	Operations and Maintenance
PALM	Pull and Lock Marine
QCS	Quick Connect System (used to connect a cable to a FOWT)
ROV	Remotely Operated Vehicle
W2W	Walk to Work (personnel transfer from an accommodation vessel to the FOWT)
WROV	Work class ROV (suitable for subsea mooring and cable component handling operations)
SIMOPS	Simultaneous Operations
SKV	Station Keeping Vessel (a lower capacity AHTS e.g. the Skandi Emerald)
TRL	Technology Readiness Level
ULS	Ultimate Limit State
VLS	Vertical Lay Spread

2 INTRODUCTION

2.1 Study background

In the coming decade (towards 2035), commercial floating wind projects are expected to be built at gigawatt scale, an order of magnitude greater than current 10MW to 100MW demonstrator projects.

This study has been commissioned to showcase likely installation methods for Gigawatt scale Floating Offshore Wind. The study starts with a 'base case', which explores in detail how to pre-install the mooring components, tow out the commissioned FOWTs, connect the moorings, and install the cables. The base case installation methodology has been developed by scaling up current practice for demonstrator floating wind arrays, which itself is built on oil and gas and fixed wind experience.

Next, different options for mooring and cable installation are compared with the base case benchmark to explore the wider technology landscape. If there are unresolved bottlenecks, these need to be flagged early to inform supply chain growth, project front end engineering design (FEED) scoping, and technology development support activities.

This report presents a public domain summary of more detailed reports prepared for the FOW CoE developer partners (references [2] and [3]).

2.2 Definition of the Gigawatt scale array

2.2.1 Nominal array location

To focus the study on a realistic use case for Gigawatt scale floating wind, the Marram Wind site was selected as the nominal array location. This is typical of a wide range of planned ScotWind and Celtic Sea Gigawatt scale sites. The array is approximately 20km x 25km in plan area (Figure 5).

The study focusses on a 100m water depth applicable to the case study site. Shallower water is likely to require more or larger mooring chains in harsh environment conditions. Wet storage of cables in shallower waters will also be more challenging. Deeper waters require longer components, higher static loads, and further qualification of cable end terminations against water ingress.

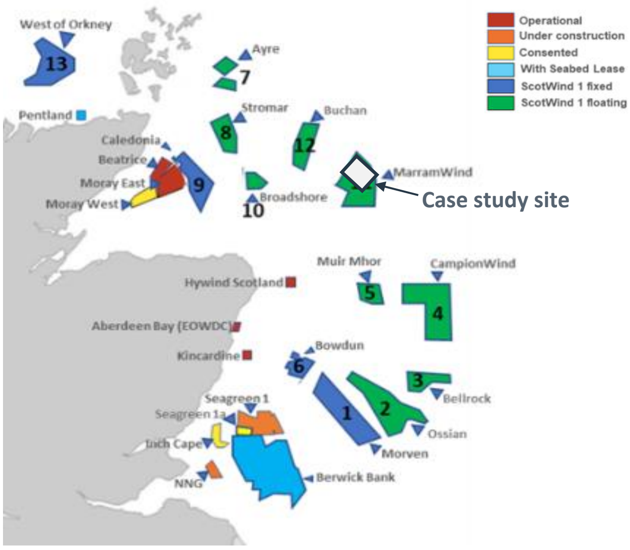

Figure 5 – ScotWind floating lease areas and case study site location (adapted from Ref. [1])

2.2.2 Array layout

At present there is no accepted optimum field layout for such a large multi-foundation farm. A layout consisting of five clusters of FOWTs sharing suction anchors was adopted as a representative base case.

Each individual cluster consists of twelve FOWTs - two strings of six FOWTs. Five clusters are strung together to give a nominal Gigawatt scale array of 60 FOWTs (900MW). Figure 6 shows the whole field layout assumed in the base case study.

In theory the 1km gap between the individual clusters could be closed and additional sharing of suction anchors would be possible. However, the gap has been maintained for the following reasons:

- Logistics and planning are easier if operations are broken down into sub blocks or clusters.
- The gaps may provide improved vessel access for vessel operations – inspection, maintenance, fishing, and other potential shared use.
- The gaps provide possibilities for alternative cable routing, cable topologies such as subsea hubs, and alternative substation positioning.
- The gaps enables optimisation of the array dimensions with respect to wind blockage – for example, the turbine spacing can be stretched in the prevailing wind direction by increasing the gap distance.
- Shared anchors may not be viable at all sites. A clustered array represents a compromise between shared anchor optimisation and allowing gaps between anchors.

The collector cables export electricity to an Offshore Substation (OSS). The fixed OSS is assumed to be located in a pocket of shallow water, 25km from the furthest cable and 5km from the nearest.

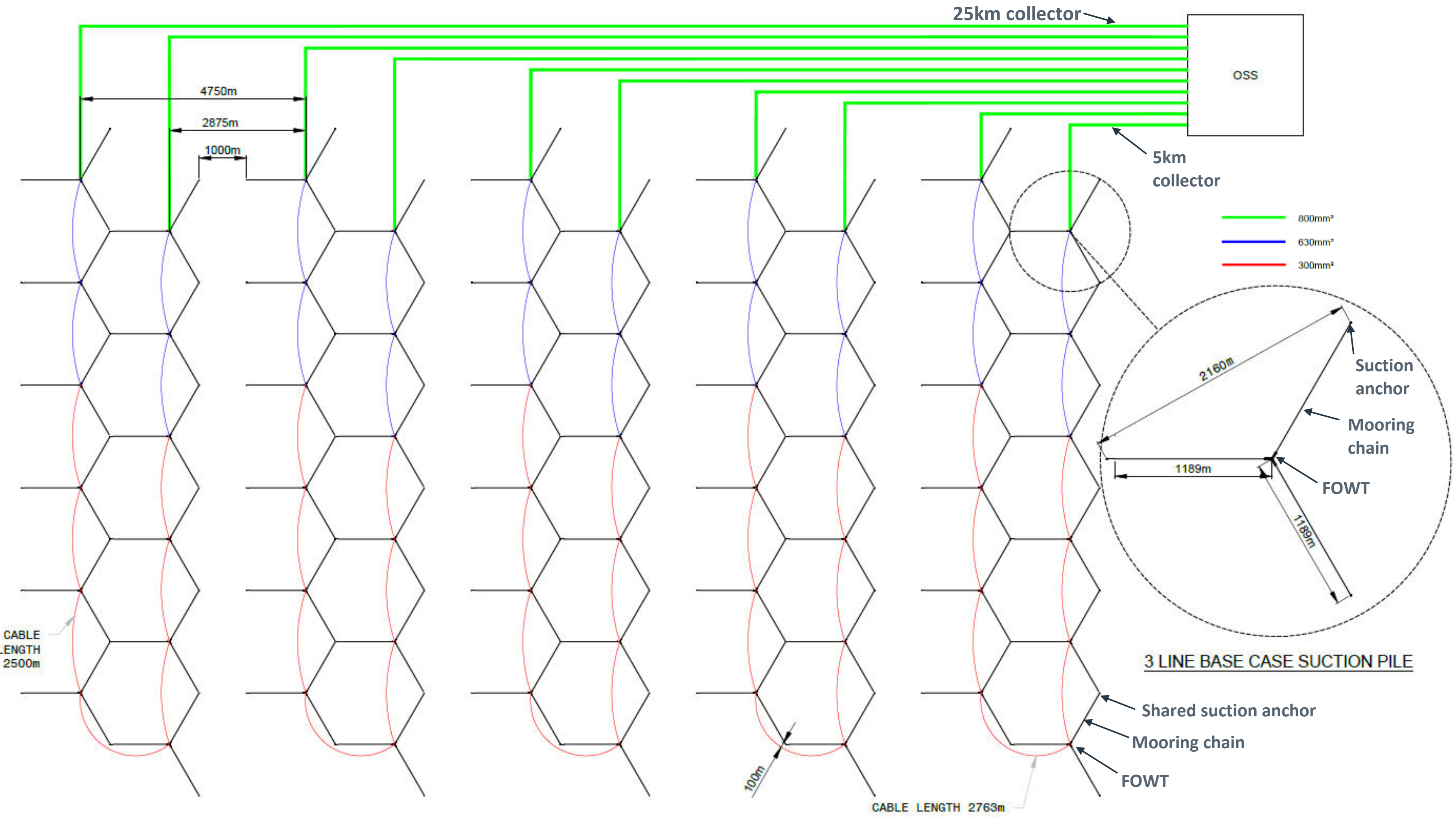

Figure 6 – Base case five cluster field comprising of 60 FOWTs (900MW)

2.3 FOWT Turbine

The base case foundation for this study is the University of Maine VolturnUS steel semi-submersible 15 MW offshore turbine [14]. The FOWT hull displacement is 21000 Tonnes with 3900 Tonnes of steel mass. The scale and main dimensions of the FOWT are shown in Figure 7.

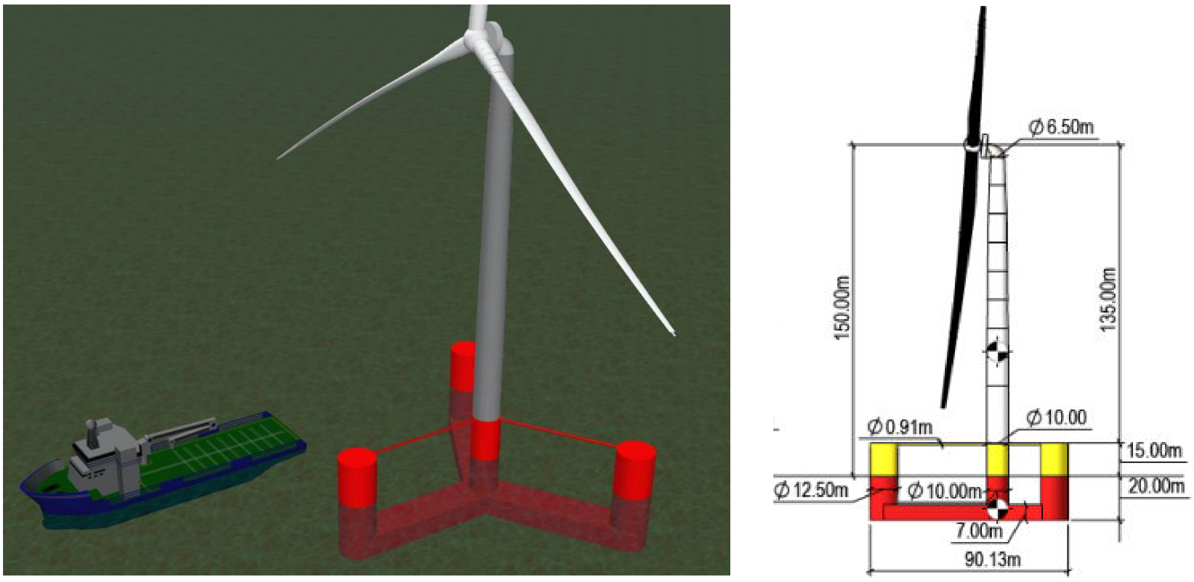

Figure 7 – 15MW FOWT alongside a 90m long installation vessel (left) and main dimensions (right)

2.4 Mooring design

The base case mooring design is shown below. Note that 'base case' denotes the system design that is the main focus of the study. Other variations are considered, which are discussed later in the report.

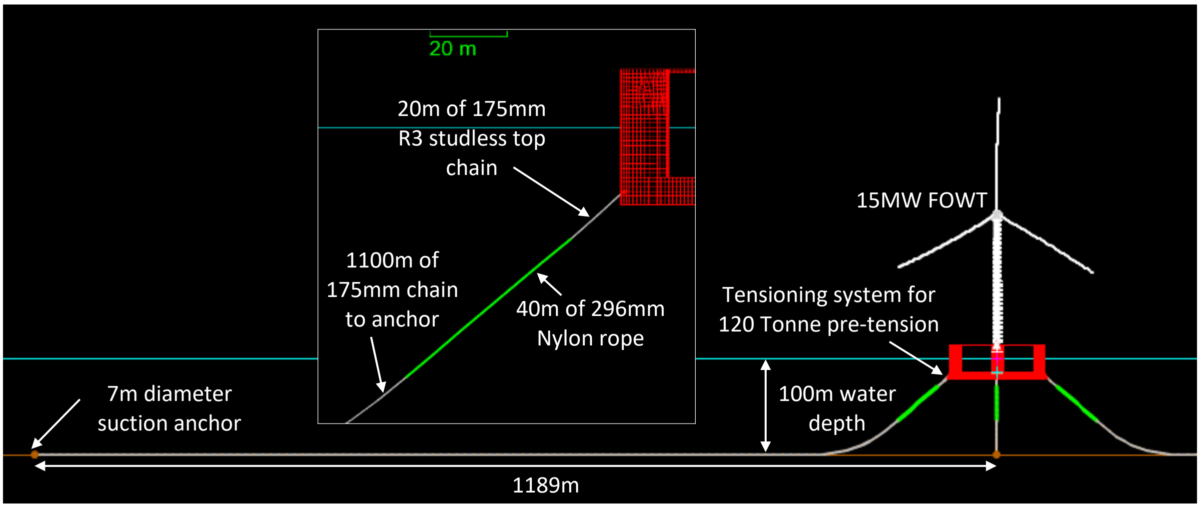

Figure 8 – Base case three line mooring system arrangement

2.5 Cable design

The array definition is based on the 132kV ring design specified in the ORE Catapult report on dynamic cable topologies [7], with a maximum 800 mm^2 copper conductor size. The array cable design is illustrated in Figure 6.

The cable system is composed of buoyancy modules, tether clamps, hold back anchor and bend stiffeners, shown in Figure 9.

For the base case cable installation, an inter-array cable string is installed in a continuous operation between two FOWTs. In parallel, a W2W vessel transfers the pull-in team personnel to the FOWT at the first and then second end of each cable string. Variations in cable system installation method are discussed later in the report.

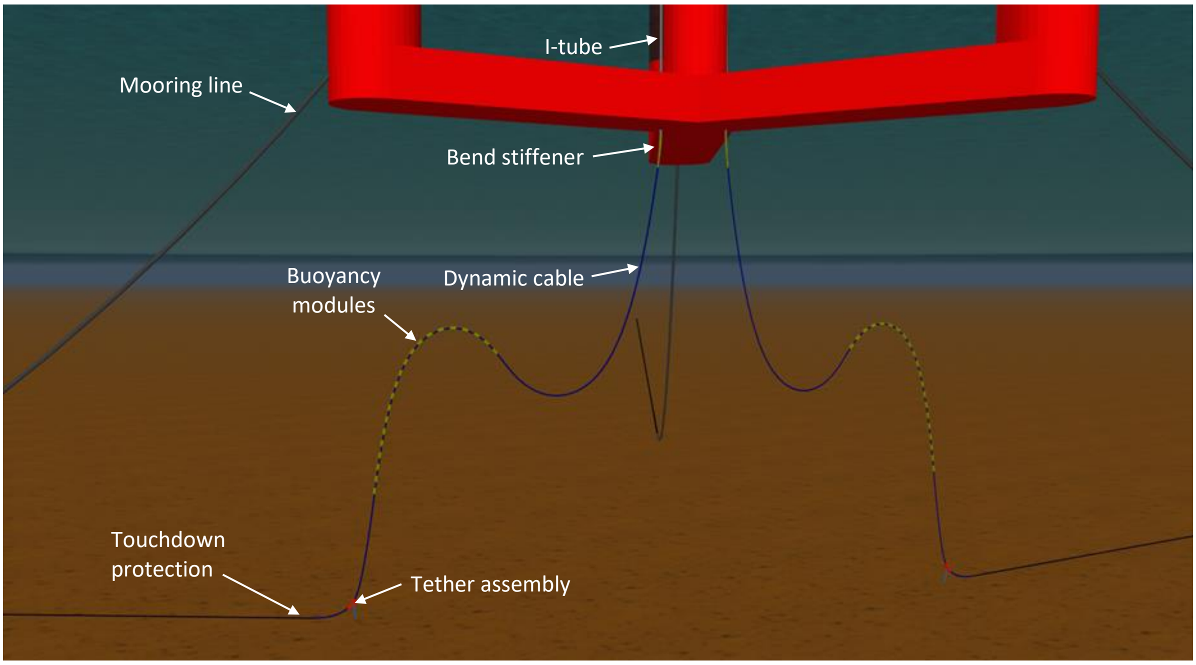

Figure 9 – Dynamic tethered cable lazy wave configuration

3 VESSELS AND MOBILISATION PORTS

The overall base case installation strategy follows the main phases outlined in Table 4.

Table 4 Installation phase outline

Installation Phase	Base case vessels	Example vessels	Notes
Suction anchor installation	1 x CSV	Skandi Acergy (x1)	Install the suction anchors with chain tails. Required deck space and crane capacity.
Mooring pre-lay	1 x AHTS	Skandi Skansen (x1)	Install the mooring line components and wet store. Requires 175mm chain handling capability and substantial locker capacity.
Tow & mooring hook-up	3 x AHTS	Skandi Iceman (x1) Skandi Emerald (x2)	Tow out the FOWT and hook-up the mooring lines. Requires 300 Tonne bollard pull capacity for lead tug.
Cable installation	1 x CLV	Skandi Acergy (x1)	Install the cable system from the reel and carousel spread, including ancillaries. Requires a reel drive spread and VLS (or HLS), with substantial deck space for ancillaries.
Cable pull-in	1 x W2W	Skandi Seven (x1)	Transfer personnel to the FOWT and pull-in the cables to complete the mechanical termination. Requires a capable W2W transfer system.

The cost and schedule requirements for the mooring and cable installation are highly dependent on the vessels selected for the job. Reference is made to the fleet of vessels supported by the EPC contractor that co-authored this report. These are typical of those available in the North Sea fleet and include vessels that had been deployed already on floating offshore wind installation projects.

Vessel day rates have been forecast referencing installation in 2026 and 2027. Vessel day rates make up 85% of the total installation costs and can vary by an order of magnitude depending on capability, and spot market variability, and long-term constraints on vessel supply.

Indicative marine vessels used to perform each of these operations are summarised below.

3.1 Mooring installation vessels

The vessel spread considered for the mooring installation operations is outlined below.

Table 5 Mooring system installation vessel summary

Item	Anchor Handler A	Anchor Handler B	Construction Vessel	Station Keeping Vessels (SKVs)
Case study vessel	Skandi Skansen	Skandi Iceman or Skandi Vega	Skandi Acergy	Vessels similar to the Skandi Emerald
Main Role	Mooring pre-lay	Mooring tow and hook-up	Suction anchor installation	Open water tow and hook-up positioning
Principal dimensions	107m LOA x 24m beam	94m LOA x 24m beam	157m LOA x 27m beam	75m LOA x 17m beam
Bollard Pull	350 Tonnes	320 Tonnes	N/A	200 Tonnes
Chain Locker capacity	2 x 1100 m of 175mm or 6 x 840m of 132 mm	2 x 1100 m of 175mm or 6 x 840m of 132 mm	N/A	N/A
Deck space	1100 m^2	780 m^2	2100 m^2	525 m^2
Relevant Equipment	2 x Work Class ROV 250 Tonne crane 260 Tonne A-Frame	1 x Work Class ROV 260 Tonne A-Frame	ROV survey spread 400 Tonne crane	N/A

An example of a large anchor handler alongside large diameter chain is shown in Figure 10.

Figure 10 – High-capacity AHTS: Skandi Skansen

3.2 Cable installation vessels

The construction vessels in Table 6 below have been selected based on likely availability and versatility towards peak ScotWind construction demand. Dedicated cable lay vessels are likely to be in short supply due to export cable and fixed wind cable installation demand. The vessel types selected for this study are widely available on the market and provide versatility in terms of the required lifting, reel lay, and ROV survey capability.

Table 6 Cable system installation vessel summary

Item	Cable Lay Vessel	Walk to Work Vessel
Case study vessel	Skandi Acergy	Skandi Seven
Main Role	Primary cable lay	Personnel transfer
Principal dimensions	157m LOA x 27m beam	121m LOA x 23m beam [Note 1]
Deck space	2100 m^2	N/A
Carousel	3000 Tonne carousel	N/A
Reel drive spread	4-off reel drive track system for 9.2m diameter 300 Tonne capacity offshore reels	N/A
Relevant Equipment	Vertical Lay System with twin tensioner system 2 x work Class ROV 400 Tonne crane	Walk to work gangway system Cable pull in system (future case only) 1 x work class ROV (future case only)
Note 1: A smaller and lower cost 70m to 90m length SOV vessel could fulfil this role. However, the size of W2W vessel is selected to provide a stable platform for floater-to-floater transfers in greater than 2m Hs conditions		

The 2.5km inter-array cable sections are loaded onto the vessel via a combination of reels and the carousel with a 30km capacity. The longer collector cables are installed exclusively via the carousel.

The Skandi Acergy with a reel drive and Horizontal Lay System (HLS) spread is pictured below; however, a Vertical Lay System (VLS) is used for the base case marine spread. The HLS remains a viable alternative for inter-array cable installation, depending on the vessel and cable system details.

Note that the difference in the Acergy's day rate between the cable and mooring operations is related to the spread and personnel levels required during the relative phases. For example, during the cable operations, the Acergy would have a VLS and cable handling crew onboard.

Figure 11 –Skandi Acergy Subsea construction vessel with HLS and reel drive system. Note the cable can be configured with a VLS system, as used for the base case marine spread setup.

3.3 Vessel mobilisation ports

The mobilisation port for the FOWT marshalling, tow out, and suction anchor loadout is assumed to be Nigg on the Cromarty Firth. Mooring equipment is assumed to be loaded out in Montrose, with cables loaded out at a cable manufacturing facility in Hartlepool. See Figure 12 for the locations of these servicing facilities relative to the case study site.

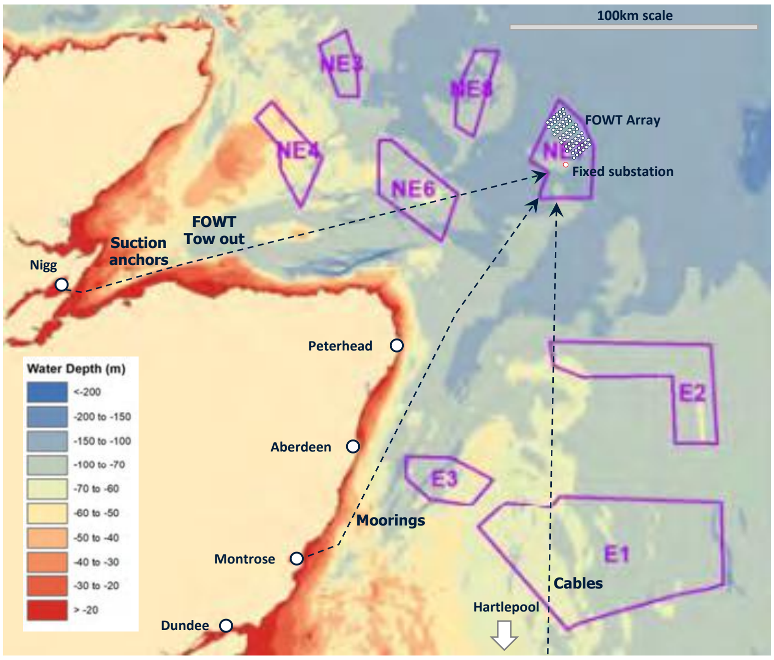

Figure 12 – Locations of servicing ports and harbours

Mobilisation distances and transit times from the applicable ports and harbours are summarised in Table 7 below.

Table 7 Port to FOWT array transit distances and durations

Port	Activity	Distance	Vessel Speed	Transit Duration
Nigg	Suction anchor loadout	220 km / 120 NM	10 knots	12 hours
Montrose	Mooring equipment loadout	185 km / 100 NM	10 knots	10 hours
Nigg	FOWT tow out	220 km / 120 NM	3 knots	40 hours
Nigg	Tow vessel return	220 km / 120 NM	10 knots	12 hours
Hartlepool	Cable system loadout	380 km / 205 NM	12 knots	17 hours

A summary of vessel mobilisation requirements for each activity is provided below.

Table 8 Base case vessel loadout requirements summary

Port	Activity	Typical quantity per loadout	Port return cycle period	Number of loadouts	Quay storage requirements
Nigg	Suction anchor loadout	9 anchors (Note 1)	1 week	11	7000m^2 for 50 anchors, replaced every year
Montrose	Mooring pre-lay loadout	2 mooring lines (Note 2)	2 days	90	4000m^2 for 20 chain lengths, replaced every 2 weeks
Nigg	FOWT tow	1 FOWT per tow	3 to 4 days	60	150m x 150m quay or wet storage area per FOWT
Hartlepool	Cable system loadout	4 cable reels and up to 11 cables on the carousel	2 to 4 weeks	11	Carousel capacity for 80km of collector cables and storage for up to 32 cable reels per year

Note 1: 7 anchors for the larger taut mooring system suction anchors. No anchor mobilisation out of Nigg for the sensitivity case.

Note 2: Constrained by locker capacity for 175mm chain for the base case. Increases to 6 mooring lines of the smaller 132mm chain for the sensitivity case, or 9 mooring lines for the taut mooring future case.

It is assumed that the FOWTs are available for tow over the 2-year installation campaign, with the tow-out and hook-up of 30 FOWTs commencing on the 1st of May and ending on the 14th of September each year. A steady supply of FOWTs ready for tow is assumed in the scheduling i.e., ≈2 turbines per week are marshalled during the tow and hook-up campaign period. In the winter months, it is assumed that no turbines are towed.

Marshalling and assembly of more than one FOWT per week may be unrealistic for many individual marshalling yards. One option is to make use of wet storage sites, where FOWTs are accumulated over the winter period prior to the main summer installation campaign. The availability of wet storage locations and the economics of safely managing dozens of turbines in wet storage is expected to constrain such an approach. Reducing the FOWT throughput to extend the installation campaign to 3 or 4 years is another option. In this scenario, the tow and hook-up vessels may be under-utilised whilst waiting on the next FOWT – hence flexibility to use vessels in multiple roles is useful.

4 BASE CASE INSTALLATION

A summary of the installation durations for each offshore installation step is provided below. Note that whilst contingency time is not explicitly included in the schedule timings, the estimated hours per operation step are based on real-world offshore experience from floating wind and O&G floating platform installation, including Hywind Tampen.

4.1 Suction anchor installation

The mooring system will be pre-laid before the FOWTs are towed out and connected to the laid down moorings. The first stage of this procedure is the installation of the suction anchors. The table below provides a summary of the installation durations for the installation of one anchor. The indicated offshore installation durations do not include transit and loadout times.

Table 9 Suction anchor operation durations (per anchor)

Step Description	Hours
Perform seabed survey (12 hours per batch of 9 anchors)	1.3
Suction anchor over-boarded and landed on seabed	2.5
Suction anchor penetration	6.5
Verification of penetration, survey, and reallocation	3.0
Total	**13**

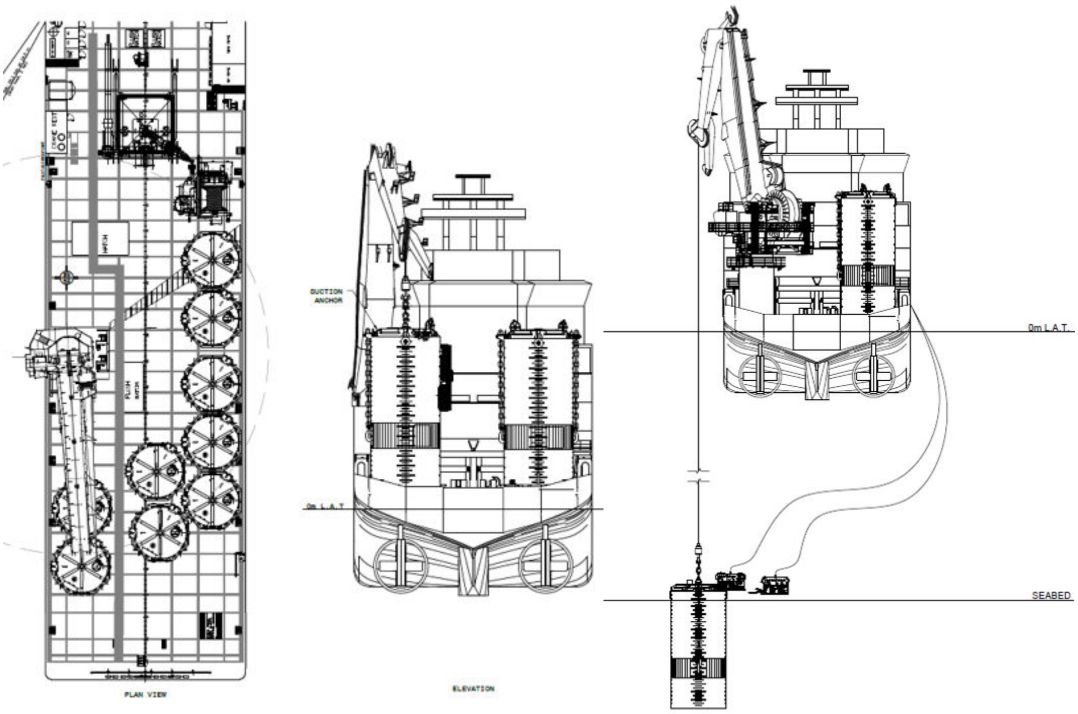

Figure 13 - Suction anchor installation storyboard extracts

4.2 Mooring system pre-lay

Once the first three suction anchors have been installed, the main anchor handling vessel (Skandi Skansen) can pre-lay the catenary mooring system in parallel. A summary of the installation durations for the pre-lay and wet store of one mooring line is provided in the table below.

Table 10 Pre-lay and wet store operation durations (per mooring line)

Step Description	Hours
Survey and connect bottom chain to anchor	6.0
Lay away the ground chain	4.0
Connect and deploy nylon rope	2.0
Connect top chain and recovery rigging	1.0
Lay down and abandon mooring line and perform survey	3.0
Total	**16.0**

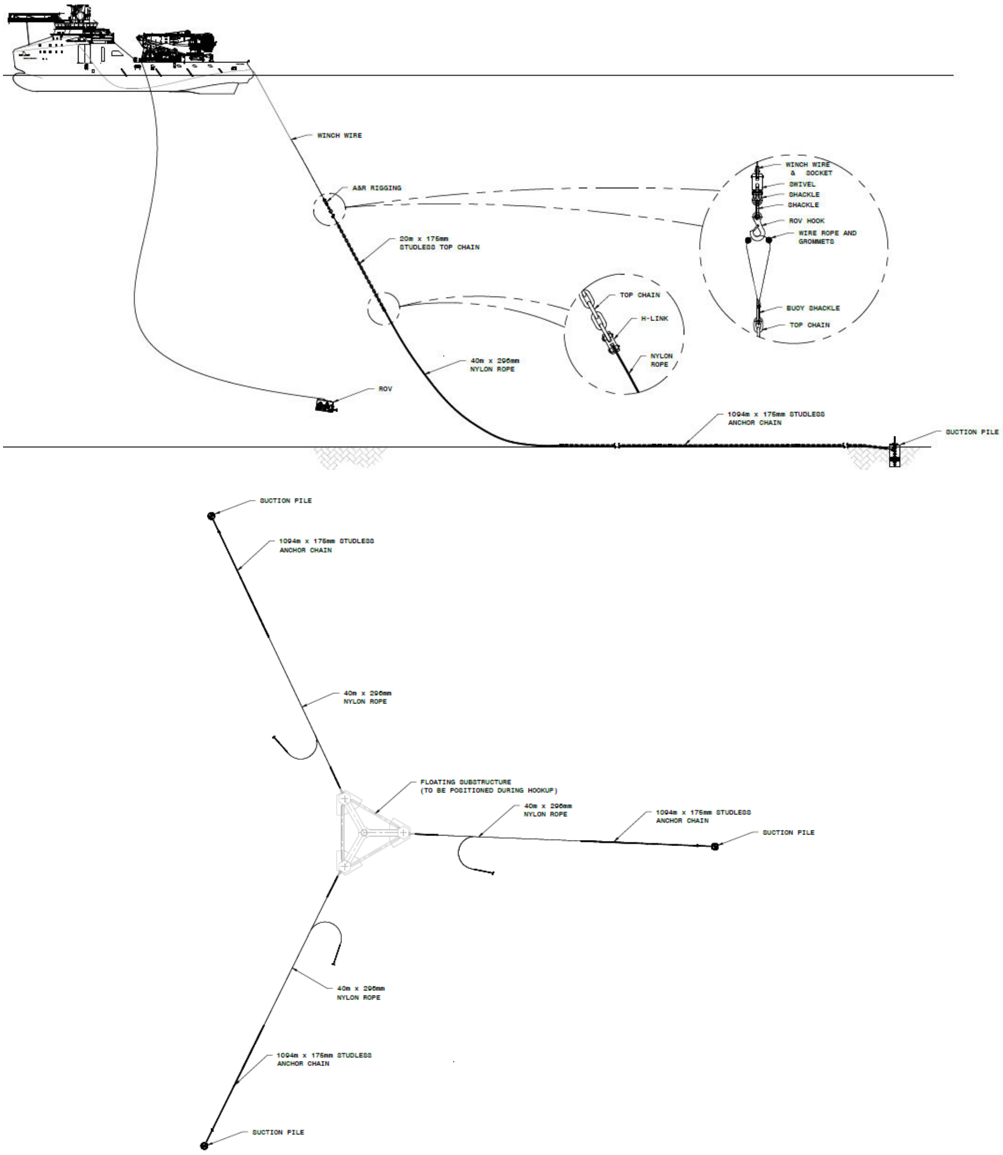

Figure 14 – Mooring pre-lay storyboard extracts

4.3 Marshalling and tow out

For marshalling and tow out of the FOWTs from a fabrication facility, harbour tugs in the vicinity of the port switch to larger vessels for the tow out to the field. The tow to field is performed by a large capacity anchor handler acting as lead tug, with a smaller capacity anchor handler acting as trailing tug. The final smaller capacity vessel meets the tow in the field for hook-up.

The tow speed of 3 knots is expected to require a minimum lead tug bollard pull capacity of 300 Tonnes.

Table 11 Marshalling and tow-out durations (per FOWT)

Step Description	Hours
Inshore tow, crew transfer and ballasting operations	14.5
Tow to field (120 nautical miles at 3 knots)	40.0
Return transit to mobilization port (after hook-up)	12
Total	**66.5**

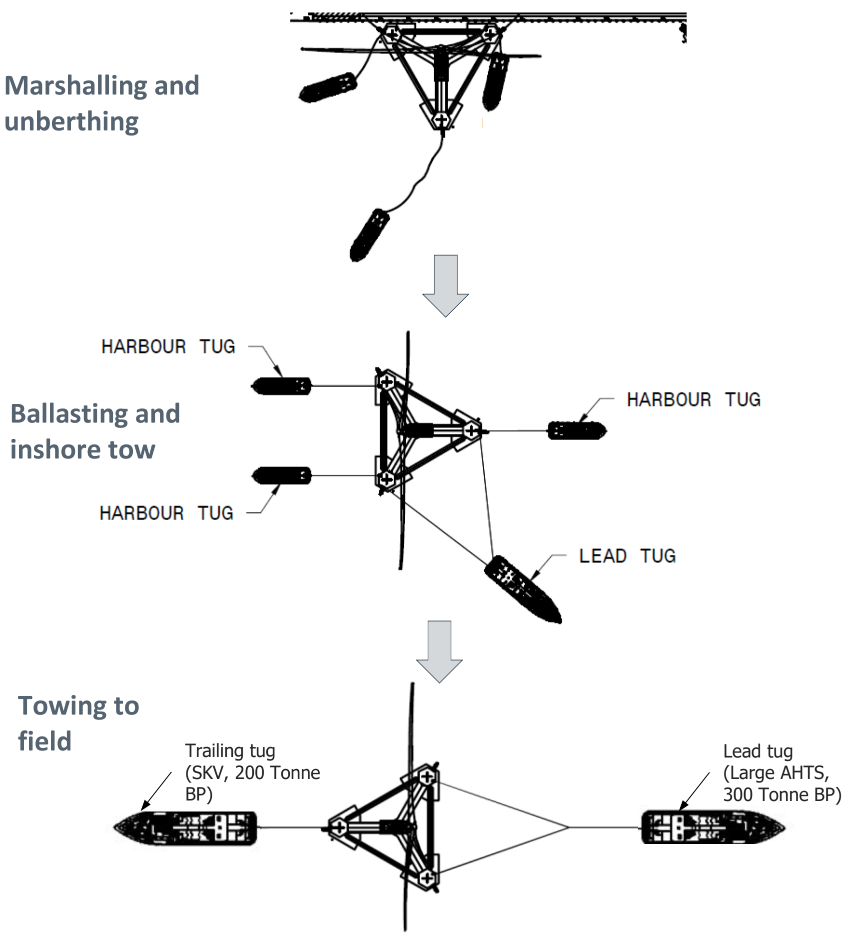

Figure 15 – Marshalling and tow storyboard extracts

4.4 Mooring line hook-up

During hook-up of each of the three mooring lines, the in-field anchor handler (Skandi Iceman) performs the hook-up operation, whilst the smaller Station Keeping Vessels ("SKVs") maintain the FOWT position and heading at the target location.

A summary of the durations for the final mooring hook-up phase for one FOWT is provided in the table below.

Table 12 Hook-up durations (per FOWT)

Step Description	Hours
As-found survey and station keeping tests	4.5
Recovery of first mooring line	1
Pull-in of the first mooring to the FOWT	4
Tow vessel repositioning	2
Recovery of second mooring line	1
Pull-in of the second mooring to the FOWT	4
Tow vessel repositioning	2
Recovery of third mooring line	1
Pull-in of the third mooring to the FOWT	4
Tensioning all 3 mooring lines	6
Tow vessel disconnection and as-left survey	5
Total	**34.5**

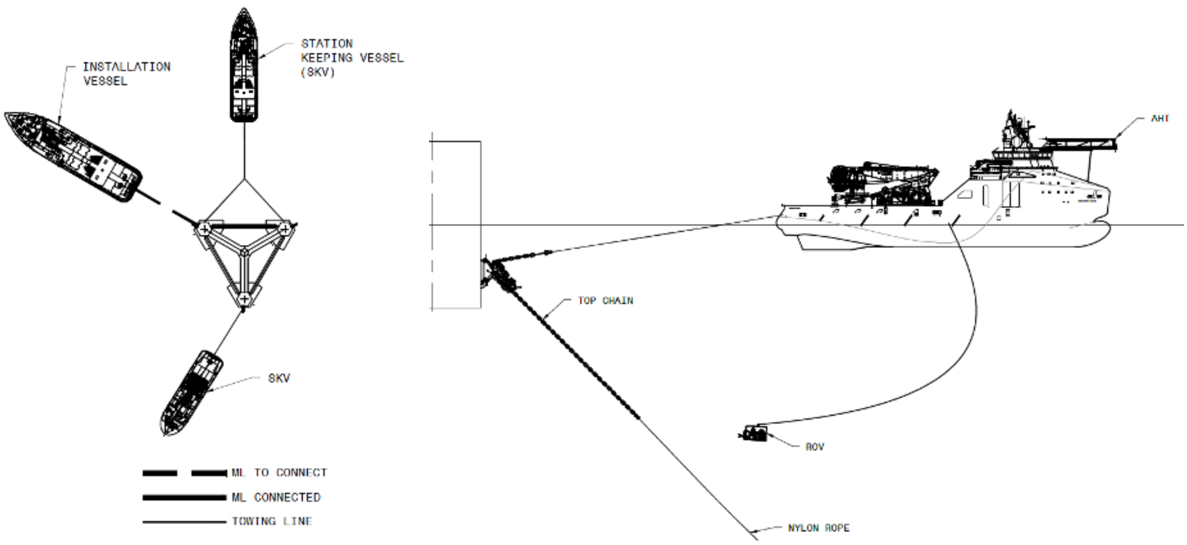

Figure 16 – Mooring hook-up and tensioning storyboard extracts

4.5 Cable first end pull-in

The W2W vessel transfers personnel to the first FOWT to prepare for cable pull-in. A winch, diverter, sheave block and hang-off clamp are rigged for the mechanical pull-in. For the W2W vessel, the required active vessel time per transfer is only 2 hours, or 8 to 10 hours for a complete cable string installation between two turbines, including tower team shift changes. This compares to 49-hours for the inter-array cable connection by the main cable lay vessel. Whilst the tower team are working continuously on the FOWT, the W2W vessel itself is free to support other activities. Approximately 70-80% of the W2W vessel's time would therefore be available to support other survey, transfer, and commissioning operations within the array.

The cable lay vessel will start the cable pull-in operation in parallel with the W2W vessel preparations. The durations the 21-hour first end inter-array cable connection operation are outlined below. Personnel need to remain on the FOWT during pull-in for a duration exceeding 12 hours, which requires a crew change midway through the operation. The CLV must position itself to provide safe access to the W2W vessel for the transfer, which makes this operation complex for planning and logistics, and sensitive to cumulative delays.

Table 13 First end cable lay duration breakdown for the main cable lay vessel

Step Description	Hours
Conduct as-found survey and install 2 hold-down anchors	4.0
Prepare cable ends and secure on tensioner	2.0
Retrieve FOWT-A messenger wire by ROV	2.5
Handover messenger wire to cable lay vessel	1.0
Payout cable and assemble buoyancy and tether clamp	5.5
Pull-in cable to below sheave block	1.5
Fit hang-off clamp and overpull cable end	4.0
Total	**21**

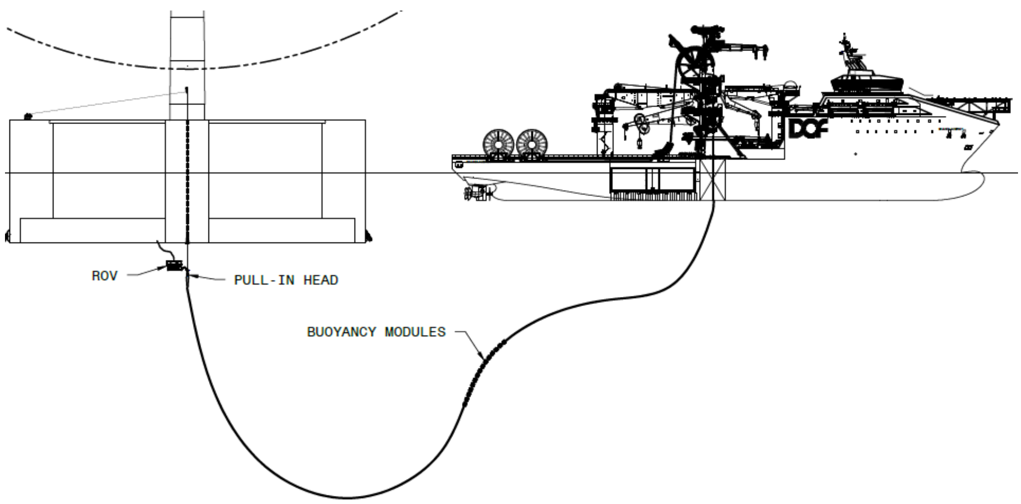

Figure 17 – Cable first end pull-in storyboard extracts

4.6 Cable lay and second end pull-In

Once the cable has been secured with the required overpull length on the first FOWT, the vessel can start to pay out the cable and lay towards the second FOWT. In parallel with the cable lay, the W2W vessel will retrieve the tower team from the first FOWT and transfer to the second FOWT for preparing the cable pull-in system. The installation durations for the 28-hour second end inter-array cable connection operation are outlined below.

Table 14 Second end cable lay duration breakdown for the main cable lay vessel

Step Description	Hours
Connect FOWT-A tether to hold-down anchor	2.0
Lay the cable to FOWT-B	6.0
Pay out cable and assemble buoyancy and tether clamp	5.5
Handover messenger wire to cable lay vessel	1.5
Handover pull-in head to FOWT winch wire	1.5
Pull-in cable to below sheave block	1.5
Fit hang-off clamp and overpull cable end	4.0
Connect FOWT-B tether to hold-down anchor	2.0
Perform route survey	4.0
Total	**28**

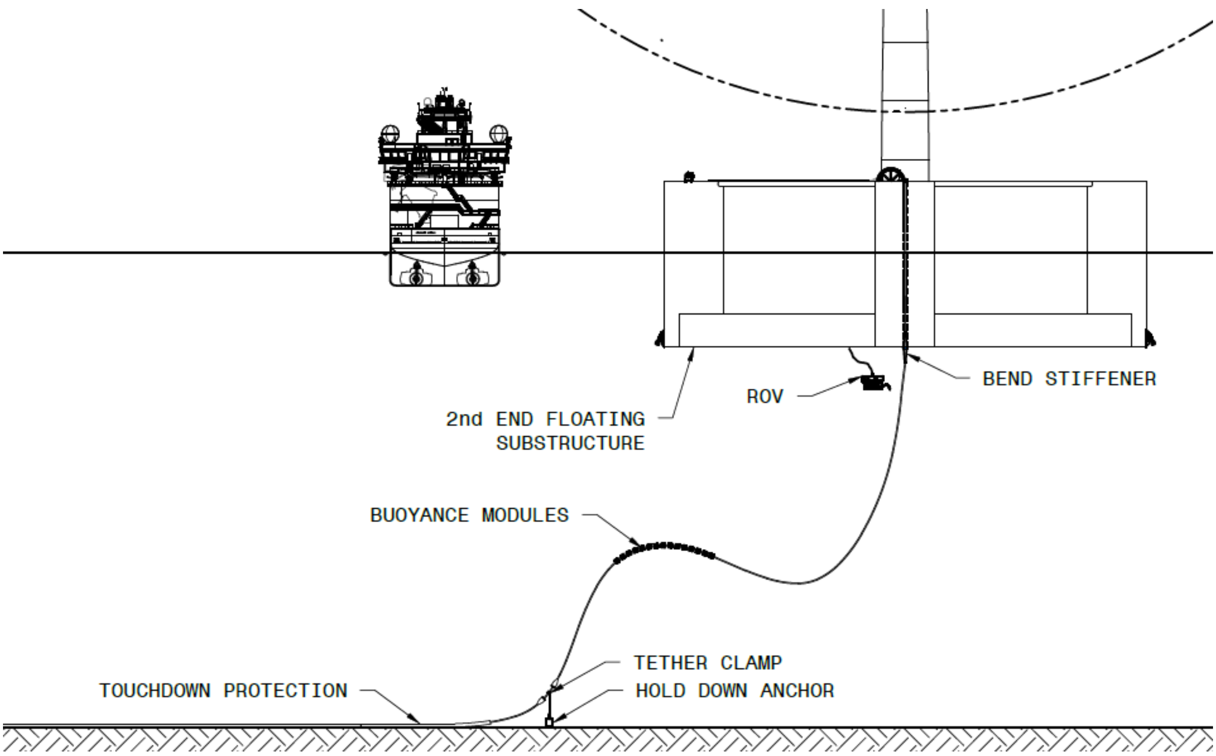

Figure 18 – Cable lay away and second end pull-in storyboard extracts

5 BASE CASE INSTALLATION FINDINGS

The base case installation durations and costs are summarised in Table 15. This is translated to the installation schedule in Figure 19. Temporary installation equipment and fuel make up 16% of the total installation cost. Weather downtime is not included in the cost or schedules.

Table 15 Base case installation duration summary

Activity Description	Vessels Required	Vessel Example	Duration per offshore operation	Vessel Hire Duration (Note 1)	Vessel Hire Cost (% of total hire cost)
Suction anchor installation	1 x CSV	1 x Skandi Acergy	13 hours per anchor	3.5 months	9%
Mooring pre-lay	1 x AHTS	1 x Skandi Skansen	16 hours per line	9.1 months	18%
Tow out and return	3 x AHTS	1 x Skandi Iceman 2 x Skandi Emerald	67 hours per FOWT	6.2 months	22%
Mooring hook-up	3 x AHTS	1 x Skandi Iceman 2 x Skandi Emerald	35 hours per FOWT	2.9 months	11%
Cable installation	1 x CLV	1 x Skandi Acergy	49 hours per cable section (2 ends)	8.1 months	23%
Cable pull-in	1 x W2W	1 x Skandi Seven	49 hours per cable section (2 ends)	7.3 months	17%
Note 1: On-hire time for the lead vessel over the two installation years. Includes vessel mobilisation, demobilisation, time in port, crew change allowance, and transit time.					

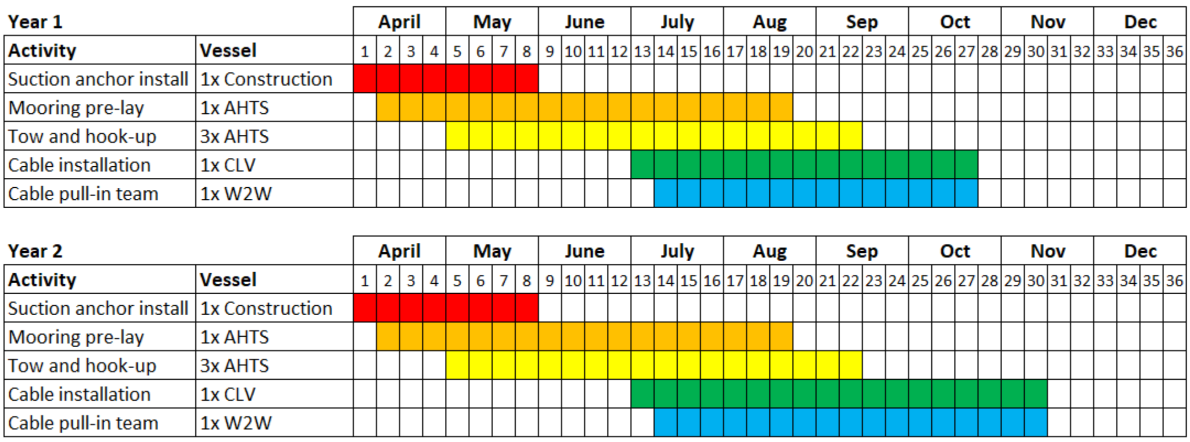

Figure 19 – Base case schedule overview

It is apparent that two complete seasons are required to install a Gigawatt scale wind farm. The work begins in April and completes at the end of October each year.

The weather limit for the cable installation operation is driven by the nominal 2m Hs W2W connection limit. The cable installation is likely to be severely impacted by weather downtime for the more exposed ScotWind sites in the September and October, with an increasing chance of cascading delays as the schedule is pushed into winter. A rough approximation of seasonal weather downtime and cumulative delays is shown in Figure 20.

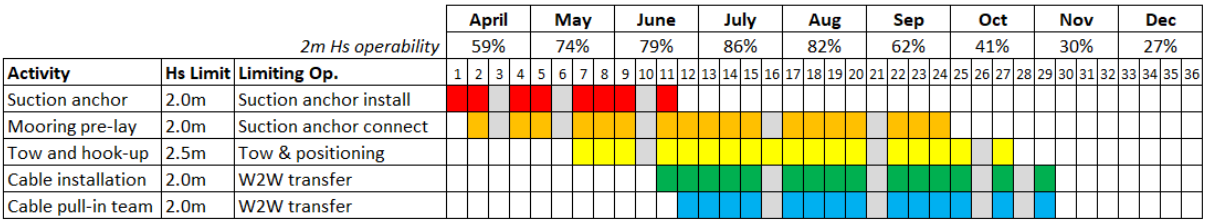

Figure 20 – Base case schedule with a feasible proportion of non-operable weather (grey cells)

The above figure demonstrates how weather delays can push the cable pull-in operation deeper into the winter months, which incurs further weather downtime as the weather worsens. This figure should be used for qualitative illustration only; a separate detailed uptime analysis would be required to translate operability into accurate weather downtime durations, and should include a combination of weather windows, alpha factors, weather spells analysis, and contingency plans.

The reported schedules and costs end at the mechanical cable hang off at the FOWTs. Hence, they do not address inter-array cable, export cable, turbine, and substation electrical termination, testing and commissioning.

6 SENSITIVITY TO MOORING DESIGN VARIATION

Three mooring designs have been assessed in the study – defined as the 'base case', 'sensitivity case' and 'future case'. A comparison of the three mooring design concepts is shown in Figure 21 and detailed in Table 16.

Table 16 Base, sensitivity, and future mooring system design definition

Mooring base case	
Mooring design	3 line catenary moorings composed of a 1100m length 175mm ground chain, a 40m Nylon stretcher, and a 50m section of 175mm top chain
Anchoring design	Suction anchors, shared within array units of 2 rows of 6 turbines
Mooring pre-tensioning setup	Anchor handler tensioning of moorings via a platform mounted system
Mooring sensitivity case	
Mooring design	6 line catenary moorings composed of a 850m length of 132mm ground chain, a 40m Nylon stretcher, and a 50m section of 132mm top chain
Anchoring design	Non-shared drag embedment anchors
Mooring pre-tensioning setup	Line tensioning as above, but with an additional anchor proof loading step
Mooring future case	
Mooring design	3 line taut nylon moorings composed of a 50m length of 175mm ground chain and a 250m Nylon section connecting directly to the FOWT via a quick-connect.
Anchoring design	Non-shared suction anchors
Mooring pre-tensioning setup	Anchor handler tensioning of moorings via a suction anchor mounted system

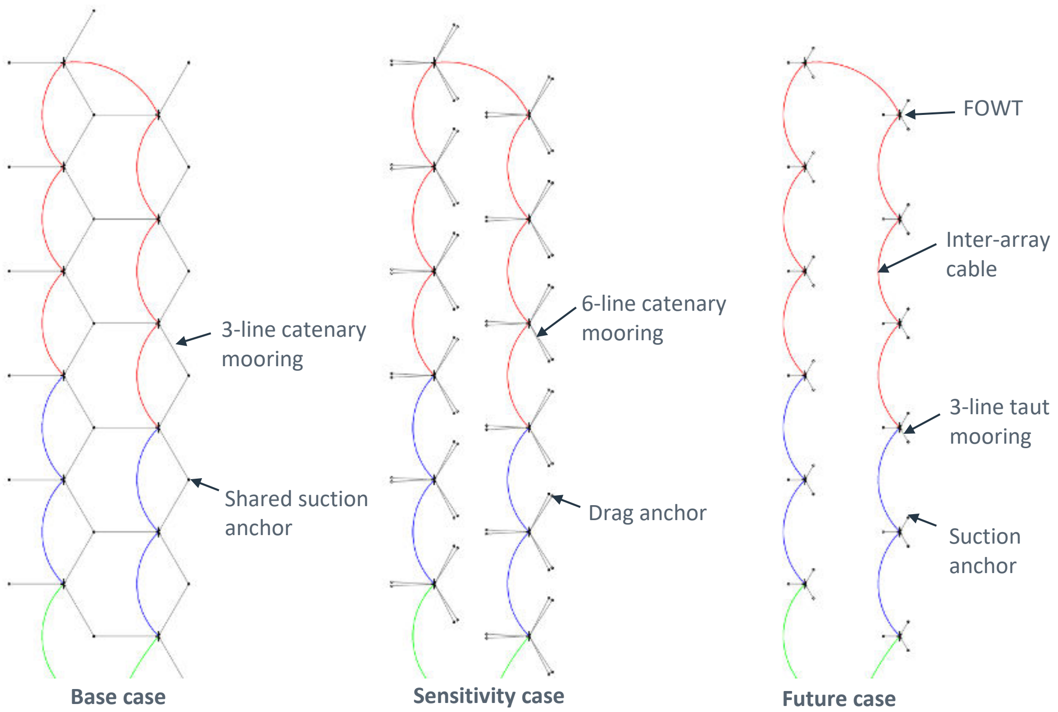

Figure 21 – Comparison of 12-FOWT cluster layout for base case, sensitivity case, and future case mooring systems

6.1 Six line mooring system overview – 'sensitivity case'

The nominal mooring chain diameter for the base case is 175mm bar diameter. This chain size severely restricts the selection of anchor handling vessels. An alternative mooring arrangement, with six lines per FOWT and drag embedment anchors, has been studied as a sensitivity case. For the six line sensitivity case, the chain is a more manageable 132mm bar diameter, which may resolve procurement and vessel capability associated with very large diameter chain. Using more mooring lines offers the opportunity to provide some additional protection to the power cable and maintain power production in the case of single line failure.

Drag embedment anchors are considered to be a viable alternative to suction anchors in suitable soil conditions and have been used on demonstration projects such as Kincardine and WindFloat Atlantic. Using non-shared drag anchors enables the use of 200m to 400m shorter mooring lines but the six-line design increases the number of anchor points from 100 to 360.

Using drag embedment anchors introduces the requirement for anchor test tensioning. The maximum intact anchor tension from the mooring analysis has been used to define an anchor installation test tension requirement of 500 Tonnes. The drag anchor tandem test loading is shown below, taking 14 hours from anchor lowering to the end of the proof loading step. The minimum required nameplate bollard pull capacity for each vessel in this configuration is 320 Tonnes.

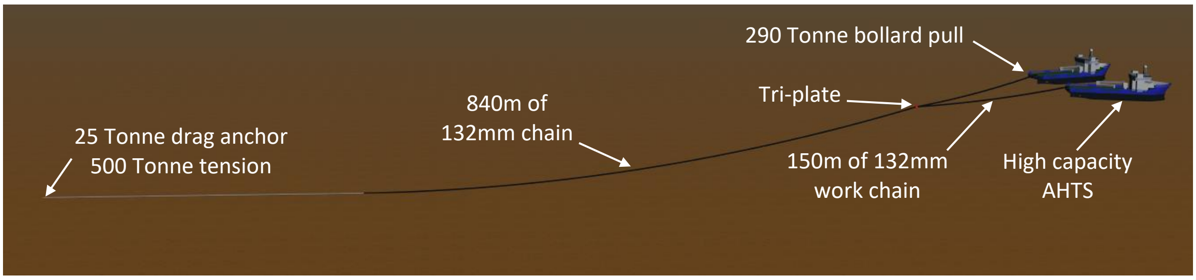

Figure 22 – Drag anchor test tensioning load path

Six of the smaller and shorter mooring lines can be installed on each vessel loadout, which is four more than the base case. The drag anchors are installed as part of the mooring pre-lay process; therefore a separate construction vessel is not required. However, due to the onerous anchor tensioning requirements described above, two AHTS vessels are required to perform the pre-lay operation. A third high-capacity AHTS is required to perform the tow and hook-up, as the other AHTS vessels are likely to be fully occupied on pre-lay.

6.2 Taut mooring system overview – 'future case'

The base case mooring is a catenary system, with long lengths of expensive and difficult to handle large diameter chain. A taut nylon mooring has been selected as a promising technology to replace the large diameter chain with short lengths of lightweight synthetic rope. A 'future case' taut mooring design uses a 250m length of nylon rope, which offers the elasticity required to keep peak mooring tensions within manageable levels in harsh environments. The taut system is coupled with an anchor-mounted tensioning system to reduce wear, corrosion, and fatigue issues associated with top chain connections.

The taut system offers opportunities to improve mooring performance, ease procurement bottlenecks, and accelerate the mooring pre-lay process. The taut mooring design uses shorter lengths of more transportable synthetic rope – ten lines can be loaded out at a time, which greatly reduces the mooring pre-lay transit and loadout times.

Due to the short taut lines, the suction anchors cannot be shared. This increases the number of anchor points from 100 to 180. An anchor-mounted mooring tensioning device is used to avoid the need for a section of chain at the FOWT connection. This design avoids fatigue and wear issues associated with top chains, and reduces the vessel handling load requirements during pull-in.

6.3 Mooring design variation results

The year 1 mooring installation schedules and costs for the three mooring designs are shown below.

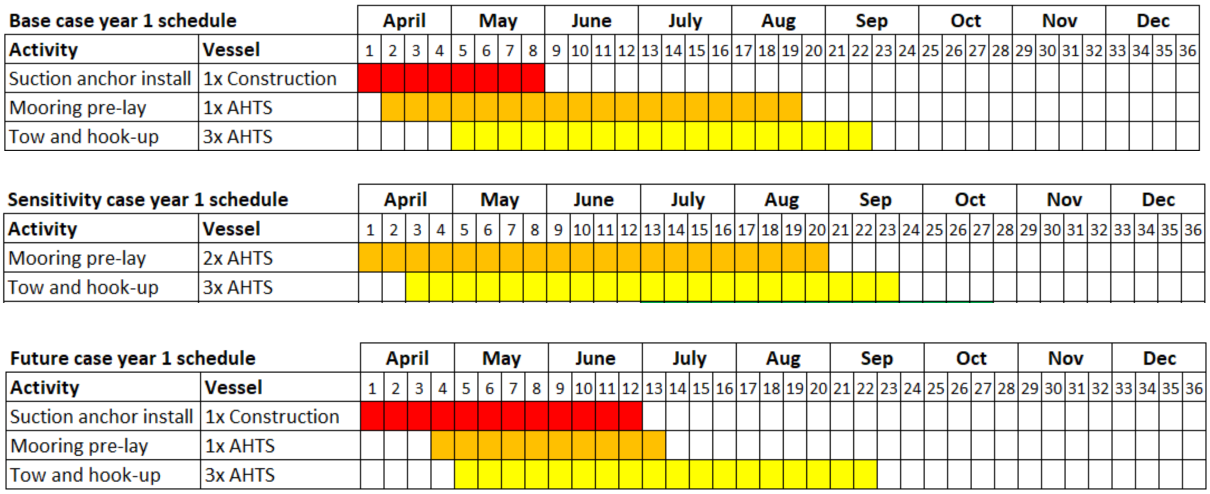

Figure 23 – Mooring schedule comparison

Table 17 Overall mooring installation cost comparison

Installation Cost Element	Base Case		Sensitivity Case		Future Case	
	Hire Duration (months)	Cost (% of base case total)	Hire Duration (months)	Cost (% of base case total)	Hire Duration (months)	Cost (% of base case total)
Suction anchor install	3.5	13%	-	-	5.9	21%
Mooring pre-lay	9.1	25%	10.3	53%	5.3	14%
Tow & hook-up	9.1	44%	10.5	51%	8.8	43%
Fuel and equipment	-	19%	-	19%	-	17%
Total	-	**100%**	-	**122%**	-	**96%**

The six line drag anchor system accounts for a 27% uplift on the mooring vessel costs. The cost difference is strongly influenced by the increased number of vessel days associated with laying and test tensioning drag anchors, as well as the greater number of lines to be connected. Any anchor installation delays would further push the mooring and cable hook-up operations into the undesirable winter weather. Such delays are foreseeable from experience of O&G unit anchor tensioning in variable soil conditions and the high anchor installation loads. There could be cost savings and vessel availability gains through a smarter risk-based approach to anchor tensioning.

The taut mooring design, which uses shorter lengths of more transportable synthetic rope, reduces the need for frequent mooring chain loadouts, and therefore accelerates pre-lay. The taut mooring pre-lay can be completed six weeks earlier than the base case each year. This reduces the dependency of tow and hook-up on the mooring pre-lay operation i.e. there is a lower risk of cumulative delays. There is also a reduced risk of weather delays by avoiding pre-lay in September. This time saving is partially offset by a four week longer suction anchor installation campaign.

7 AHTS VESSEL REQUIREMENTS

The assessment of vessel requirements for the floating wind array would indicate that the following AHTS are required as a minimum:

- 1 x 300 Tonne bollard pull vessel for mooring pre-lay (up to two full seasons)
- 1 x 300 Tonne bollard pull vessel for mooring hook-up (two full seasons)
- 2 x 200 Tonne bollard pull vessels for positioning (two full seasons)

This is for a single 900MW floating wind array. A conservative estimate is for 10GW of floating wind to be constructed in the UK between 2030 and 2040 [15 & 16]. At least two Gigawatts (60 FOWT of 15MW size) will be constructed concurrently each year, with three or four Gigawatts expected to be deployed in some years [19]. This means that four to eight high capacity 300 Tonne bollard pull AHTS, and another four to eight 200 Tonne bollard pull AHTS could be required to be dedicated to the service floating wind construction throughout this decade.

Once the first large arrays of low serial number FOWTs have been installed, a large number of major component exchanges are expected to be required – in the order of 10% per FOWT per year [17]. By 2035, this could mean that 30 FOWTs could require tow to port every year. The tow and hook-up operation must be completed twice for each FOWT (30 disconnect and tow operations plus 30 tow and hook-up operations), meaning tow to port could require the dedicated use of four 300 Tonne bollard pull AHTS each year. Servicing and decommissioning the fleet of North Sea O&G drilling and production vessels will further constrain the availability of AHTS vessels.

The available fleet of 200 Tonne bollard pull AHTS is not currently highly constrained, with 39 vessels operating in the North Sea [10]. However, the available fleet of North Sea of AHTS above 300 Tonne bollard pull is 9 vessels [10], with only 6 vessels worldwide identified as capable of handling 175mm chain. This compares unfavourably with the eight to twelve vessels required to service floating wind installation and tow to port demand in the 2030s. Unless the global fleet of highly capable AHTS vessels grows substantially in the next decade, it may prove impossible to source vessels to handle the required construction and tow to port demand at acceptable cost.

Accounting for year-on-year variability in vessel demand, day rate squeezes due to constrained capacity can lead to increases in vessel hire costs of up to a factor of four, as was seen in the summer of 2022 [18]. The UK is expected to make up only a third of global floating wind construction in this period, therefore there may be a demand on the North Sea AHTS fleet to operate globally. It is recommended that further supply chain support activities are considered in this area to bridge the gap between expected demand and vessel supply.

A method of reducing the dependence on hiring vessels at peak day rates is to install components off the critical path, and wet store in the field for later connection. Provided that mooring components are available to load out, a more flexible mooring line pre-lay strategy could be adopted to allow two or even three mooring pre-lay AHTS vessels to be hired in periods of favourable weather and day rates. A mooring pre-lay and FOWT hook-up campaign over three years will also ease the pressure on AHTS vessel demand.

Given the scale of the installation challenges and portfolios of some floating wind developers, long term charter or ownership could also be considered to smooth out day rate spikes and de-risk the installation costs.

8 CABLE INSTALLATION METHOD VARIATION

Variations in cable system installation method have been studied in detail. The base case and future case cable systems studied are compared in Table 18.

Table 18 Base and future case cable system summary

Cable base case: continuous end-to-end installation	
Cable installation sequence	Cable installed after hook-up of foundations is complete (without wet storage)
Cable pull-in system	Cable pull-in via dedicated winches mounted on each floating wind turbine
Cable terminations	Cables stripped back and terminated on the wind turbine via manually spliced connections, as is the current industry practice for fixed offshore wind turbines
Cable future case: pre-lay and wet store with optimised pull-in	
Cable installation sequence	Cable wet stored prior to FOWT arrival
Cable pull-in system	Cable pull-in via a winch mounted on the installation vessel
Cable terminations	Cables terminated on the wind turbine via pre-fitted dry mate electrical connections, as is the practice for some oil and gas umbilicals

The future case cable system is designed to be pre-laid and wet stored, ready to be pulled-in via a separate lower cost W2W vessel upon FOWT arrival.

The base case cables are unterminated (except for endcaps) on the cable reels and carousels during loadout. After pull in to the FOWT, the cables are stripped back and terminated on the FOWT deck, via manually spliced connections. The base case is understood to be current industry practice for fixed offshore wind turbines. The future cable scenario adopts cables that are pre-terminated with dry mate electrical connections at both ends, fitted in the factory. It is believed only one recent floating wind demonstration project has used pre-terminated cables [8]. Once pre-laid, the cables are wet stored on the seabed prior to arrival of the FOWTs, as shown in Figure 25.

The future case cables are pulled in via a winch and suitable sheave on the W2W vessel, as compared to having a dedicated winch and sheave system mounted on each floating wind turbine for the base case. A sketch of the comparative pull-in and termination setup is shown in Figure 26.

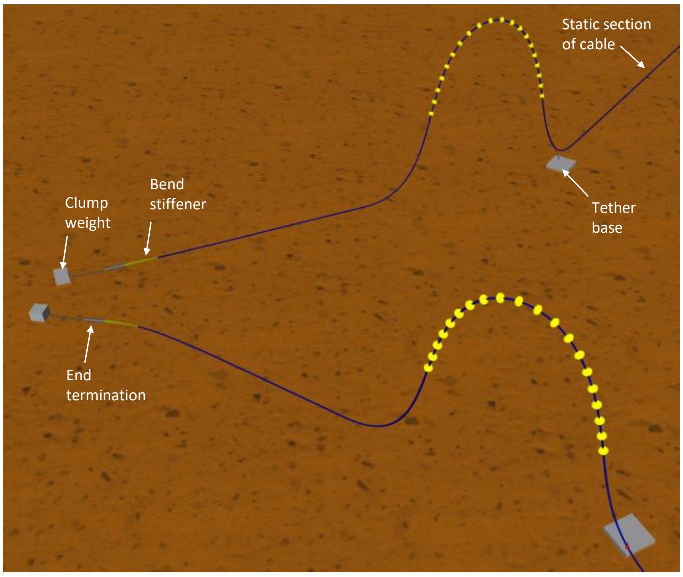

Figure 24 Cable wet store configuration

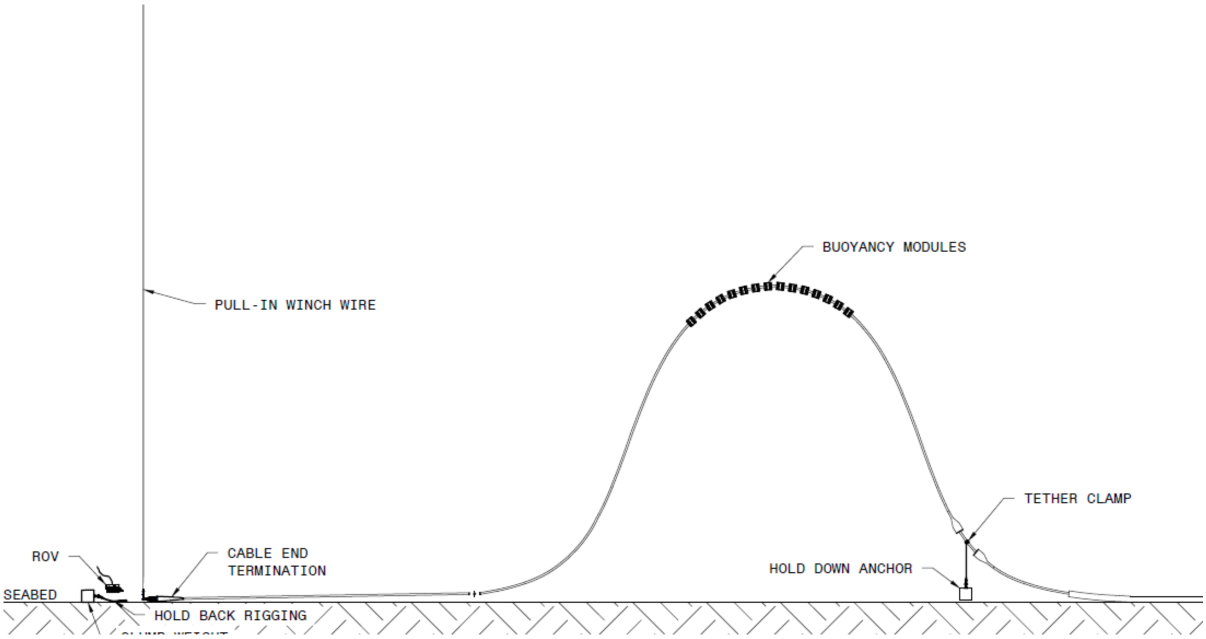

Figure 25 – Pull-in of one wet stored cable end

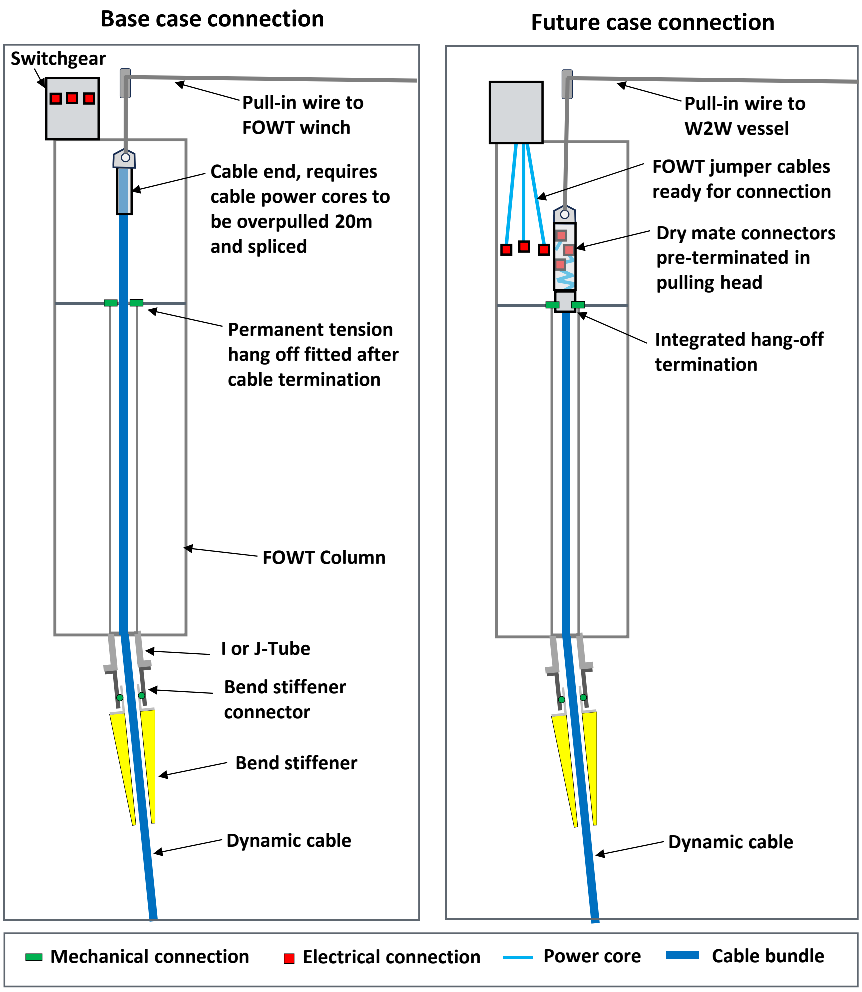

Figure 26 – Comparison of floating substructure base case and future case pull-in setup

8.1 Cable installation method findings

The schedule in Figure 27 shows the year 1 future case schedule for both the taut mooring and cable system. A rough approximation of seasonal weather downtime and cumulative delays is presented in Figure 28 for the first year of the overall future case installation schedule.

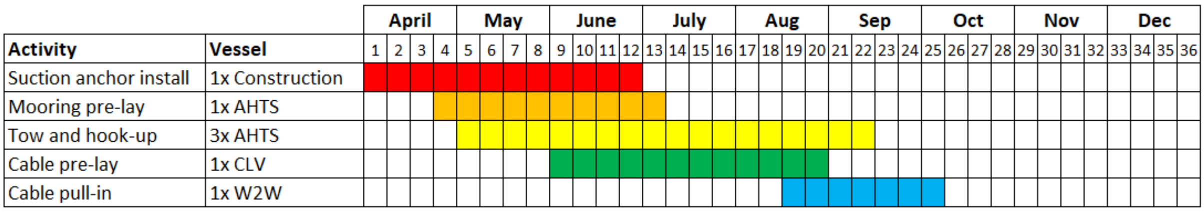

Figure 27 – Future case schedule with operations split over 2 years

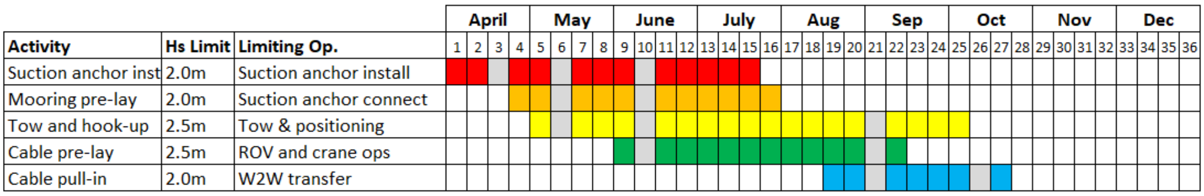

Figure 28 – Future case schedule overview with feasible weather delays

Pre-terminating, pre-laying, and wet storing cables speeds up and de-couples the cable pull-in process from the project critical path. The more efficient cable pull-in process allows the cable pull-in time to be halved, with installation completed earlier in the year. Cable pre-lay, which does not require W2W and the associated weather limits, can be performed with fewer weather interruptions. An important change is that the maximum weather window for the cable pull-in operation has reduced by 75% from 49 hrs to 12 hours. This is expected to significantly reduce the weather downtime associated with the final cable connections taking place later in the installation year.

A summary of comparative installation times and costs are presented below. The results demonstrate substantial savings for the future case cable system.

Table 19 Overall cable installation cost comparison

Installation Cost Element	Vessels Required	Base Case		Future Case	
		Hire Duration (months)	Cost (% of total base case)	Hire Duration (months)	Cost (% of total base case)
Cable installation	1 x CLV	8.1	51%	5.7	35%
Cable pull-in	1 x W2W	7.3 (Note 1)	36%	3.2	16%
Fuel and equipment	-	-	13%	-	5%
Total	-	-	**100%**	-	**57%**
Note 1: W2W vessel is available to support other transfer operations. This is not considered in the study.					

Use of more novel future systems – such as taut nylon and wet stored cables – comes with installation risks as well as opportunities.

9 EMERGING CABLE INSTALLATION TECHNOLOGIES

High potential technology that is in an earlier stage of development has also been studied in this report, for example the use of subsea hubs and platform quick-connect solutions.

9.1 Cable technology overview

9.1.1 Reel lay optimisation

The base case cable lay is performed by a representative construction vessel, the Skandi Acergy. Whilst four cable reels are deployed on the vessel, most of the cables are installed via the carousel. The strengths of reel-based cable installation for the inter-array cables could be maximised by deploying a custom reel lay setup. Figure 29 shows where vessel deck layout has been maximised to accommodate cable reels. Eight lengths of pre-terminated 2.5km inter-array cables can be accommodated on the reels, whilst the carousel is used for longer collector cables only. This is intended to reduce carousel transpooling times and cable handling complexity. The cost saving would need to be traded off with increase reel drive spread hire costs, and available deck capacity for cable reels and ancillaries.

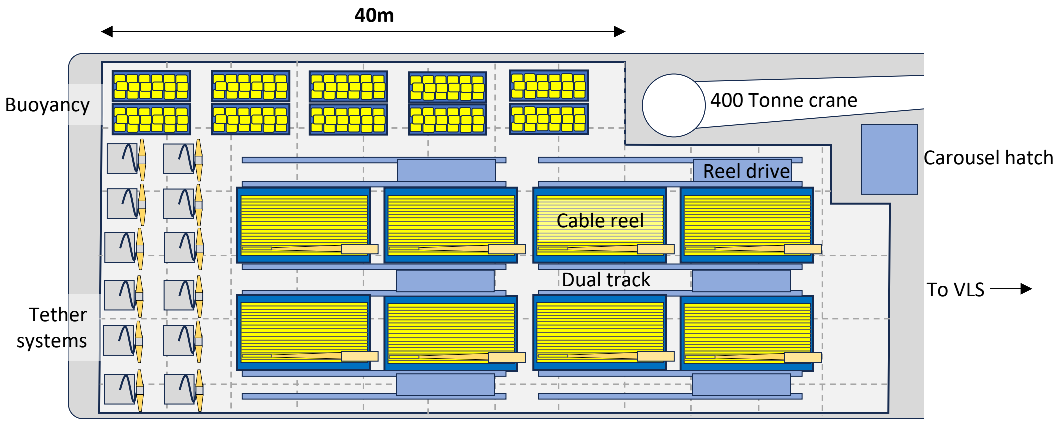

Figure 29 – Reel lay optimised spread

9.1.2 Wet and dry mate subsea hubs

The conventional daisy-chained cable array could be replaced with a star array configuration pictured below. The technology that enables this configuration is a subsea hub (made up of wet mate connectors and a 6-way electrical hub), which is designed to connect multiple cables on the seabed via wet-mate subsea connections.

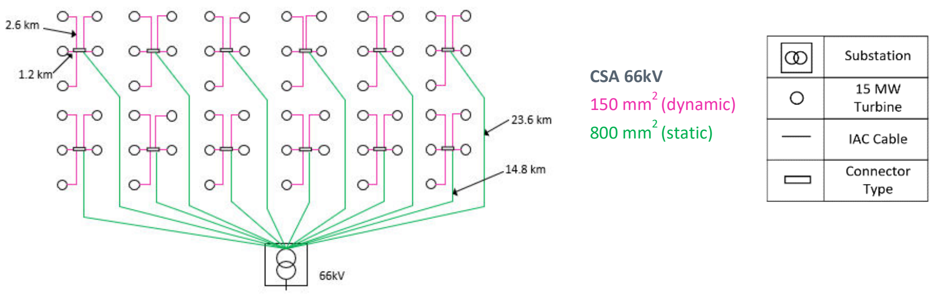

Figure 30 – 66kV star cable configuration

An alternative to the wet mate subsea hub system is to use dry mate connections, which are more widely used and qualified at higher voltages of 132kV. However, installing such an array is particularly challenging due to the need to deploy the subsea hub with multiple pigtail connections.

9.1.3 Cable quick connect system

Cable quick-connection systems target improved efficiency of connection and disconnection operations, especially to facilitate quick installation and tow to port operations with a limited vessel spread. The figure below shows the evolution in the pull-in process efficiency from the base case to the future case, and finally to a quick-connection solution. The trade-off with a quick connection solution is more expensive and less proven connection technology, and a more complex pre-lay phase.

A conceptual scenario building on the efficiencies of the previous subsea hub section has been developed, where a FOWT quick-connect device is integrated within a subsea hub array topology, as shown in the figure below.

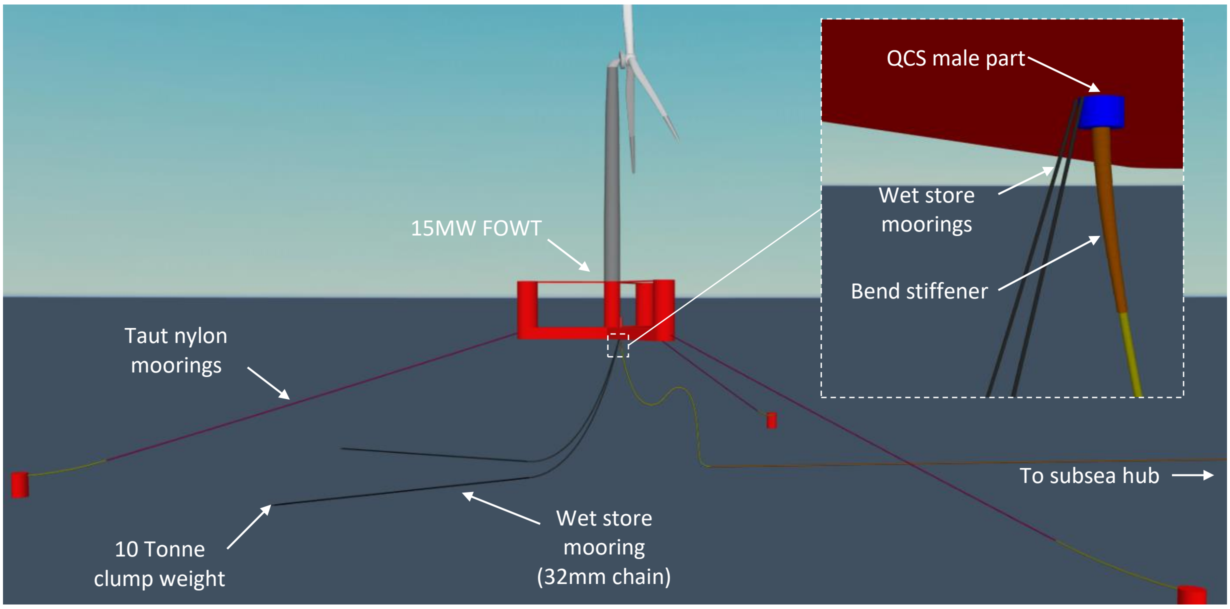

Figure 31 –System footprint after FOWT connection

9.2 Cable technology results

The installation costs for different cable connection scenarios are summarised in the table below.

Table 20 Cable installation cost comparison

Cable installation scenario	Vessel hire cost (% of base case total)		
	Cable system pre-lay	Cable pull-in	Total
Base case (see Section 5)	58%	42%	**100%**
Future case (see Section 8)	41%	19%	**59%**
Reel lay optimisation	36%	19%	**55%**
Wet mate subsea hub	49%	13%	**62%**
Dry mate subsea hub	71%	13%	**84%**
Cable quick connection	69%	2%	**70%**

A reel-focussed lay spread, which could be enabled by hosting up to 8 reels on a construction vessel deck, could save 10% of the future case vessel hire cost.

The total wet mate hub installation costs were estimated to be 5% greater than the future case. The cost savings on pre-lay and hook-up vessel time are balanced against the additional subsea hub installation time. Dry mate subsea hubs are substantially more complex to install and are estimated to cost 41% more than the future case.

Cable quick connection to the FOWT is explored in combination with a subsea hub. Installation costs were expected to be 20% more than the future case. However, cable pull-in costs and duration were only a tenth of the future case, which represents an opportunity to optimise tow to port operations.

10 CONCLUSIONS AND RECOMMENDATIONS

10.1 Installation findings

Achievement of a two-year installation campaign depends on favourable weather and no major unplanned delays to any of the operations. Delays to one installation activity can impact the next, which can bring the mooring and cable connection operations into mid-winter, precipitating spiralling weather downtime. Options to accelerate the schedule are more likely to preserve the schedule against emergent delays and avoid a prolonged winter or third installation season.

10.1.1 Mooring installation findings

To address some of the bottlenecks found in installing the base case mooring system, a detailed study has been performed for two alternative mooring solutions – a six line drag anchor system (sensitivity case), and a taut mooring system (future case).

For mooring pre-lay, tow, and hook-up operations two AHTS capable of capable of handling 175mm chain with at least 300 Tonne bollard are required. The available fleet of such vessels worldwide is highly constrained and is likely to present a major commercial risk to floating wind projects.

The drag anchor sensitivity case is found to be 22% more expensive. The installation cost for the six-line system is driven by the complexity of test tensioning the anchors to high loads using two vessels in tandem.

The taut mooring design, which uses shorter lengths of more transportable synthetic rope, reduces the need for frequent mooring chain loadouts, and therefore accelerates pre-lay. This time saving is partially offset by a four week longer suction anchor installation campaign.

10.1.2 Cable installation findings

The base case cables are installed in a continuous operation between two FOWTs. A ‘future case’ array installation scenario has been studied using wet stored dynamic cables, which are pre-terminated and pre-laid.

The future case cable system enables a more efficient cable connection process. The cable pull-in time is halved, with installation completed earlier in the year. The maximum weather window for the cable pull-in operation has reduced from 49 hours to 12 hours. This is expected to significantly reduce the weather downtime associated with the cable pull-in taking place later in the installation year.

10.1.3 Cable emerging technology findings

A reel focussed lay spread, which could be enabled by hosting up to 8 reels on a construction vessel deck, could save 10% of the future case vessel hire cost.

The total wet mate hub installation costs were estimated to be 5% greater than the future case. Dry mate subsea hubs are substantially more complex to install and are estimated to cost 41% more than the future case.

Cable quick connection to the FOWT is explored in combination with a subsea hub. Installation costs were expected to be 20% more than the future case. However, cable pull-in costs and duration were only a tenth of the future case, which represents an opportunity to optimise tow to port operations.

10.2 Recommendations for further work

10.2.1 FOWT marshalling and assembly

The schedule relies on the delivery of two FOWTs every week ready to tow from the marshalling yard. It is understood that marshalling and assembly of more than one FOWT per week may be unrealistic for many individual marshalling yards. A study into marshalling and assembly yard capacity to deliver such a requirement, and risk profile of delays, is recommended. Operations to improve marshalling capacity could be studied – such as optimised yard throughput, procurement from multiple yards, wet storage buffer, and extended installation campaigns.

10.2.2 Vessel specific operating limits

Indicative operating weather limits for the installation operations have been provided in this report. Actual W2W limiting wave conditions are highly dependent on the vessel size, motion characteristics, installation system capability, wave period and heading relative to the vessel orientation. Detailed installation analysis could be performed for critical weather limited operations such as the W2W transfer and mooring hook-up to better understand sensitivity to weather limits.

10.2.3 Weather downtime

An uptime analysis study is recommended to translate operability into accurate weather downtime durations. Such an analysis should include a combination of site specific metocean data, detailed weather limits described above, weather windows, alpha factors, weather spells analysis, and contingency plans.

10.2.4 Risk-based drag anchor tensioning

Prescriptive requirements for anchor tensioning can make the installation of a drag anchor system cost prohibitive. There is an opportunity to develop a smarter risk-based approach to anchor tensioning requirements, provided that sufficient attention is paid to enhanced exploratory testing, analysis, and survey. The development of such an approach is recommended to be undertaken by a consortium of floating wind developers, classification bodies, and insurance or marine warranty representatives.

10.2.5 Nylon mooring qualification

The nylon rope used by the taut mooring system is intended to be wet stored on the seabed for a period of several months. Suitable qualification and in-field testing of nylon is required to mitigate against long term integrity risks from particle ingress and abrasion during the wet store phase.

Further qualification and risk mitigation against fatigue, external damage and other failure modes may also be required.

More research and knowledge sharing are required on nylon rope permanent creep and pre-stretching requirements in order to better predict and mitigate the risk of pre-tension reduction.

10.2.6 Cable long-term wet store qualification

There is a risk of water ingress, marine growth accumulation, abrasion, and other forms of degradation during wet store on the cable system. Further design and qualification work is required to reduce this risk for commercial 66kV and 132kV inter-array cable and termination designs.

Storing the cable reels over the array life after installation may be challenging. Pooling of spare cable reels and ancillaries between multiple floating wind arrays would help to reduce the requirement for spares. Some level of standardisation of cable design would be required to make this possible.

10.2.7 Installation considerations for tow to port

The applicability of the mooring hook-up and cable pull-in procedures to tow to port connection and disconnection operations should be investigated further. Whilst the mooring and cable disconnection and wet store during tow to port could be a reverse of the installation procedures, there will be key differences, such as the need to maintain electrical continuity following FOWT disconnection. This is addressed in ORE Catapult's PR45 project on tow to port and off station management [17].

10.2.8 AHTS vessel build-out support

The available fleet of North Sea of AHTS above 300 Tonne bollard and capable of handling 175mm chain is highly constrained. Unless the global fleet of highly capable AHTS vessels grows substantially in the next decade, it may prove impossible to source such vessels to handle the required construction and tow to port demand at acceptable cost. It is recommended that further supply chain support activities are considered in this area to bridge the gap between expected demand and vessel supply.

10.2.9 Lifecycle cost comparison

The work presented in this project covers only costs directly associated with installation. A separate study is recommended to consistently quantify through-life CAPEX and OPEX costs for the mooring and cable system elements in these projects.

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