FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

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FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

FOW COATINGS, CORROSION PROTECTION AND MANAGEMENT

Public Summary Report



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EXECUTIVE SUMMARY

This report has been prepared to strengthen the Floating Offshore Wind (FOW) industry's understanding of corrosion protection and management as relevant to the substructures of Floating Offshore Wind Turbines (FOWTs) within the marine environment of the UK Exclusive Economic Zone (EEZ) via:

- a State-of-the-Art (SoA) review of corrosion protection and management as relevant to the substructures of Floating Offshore Wind Turbines (FOWTs) made of both structural steel and steel reinforced concrete located within the UK Exclusive Economic Zone (EEZ), and
- a Whole-Life-Costing (WLC) exercise for two reference locations within the UK EEZ to compare various Classification Society (CS) code-compliant corrosion protection scenarios for a steel floating semi-sub substructure.

The conclusions of the SoA study are that due to the level of maturity of the industry and commercial sensitivity, direct FOWT-specific field experience is not available, but no reason has been identified why the types of corrosion/durability related deterioration experienced by FOWTs will be materially different to that which has been experienced within the general offshore sector for many years, including floating steel and concrete Oil & Gas (O&G) platforms and fixed bottom offshore wind substructures. This is on the proviso that that the substructures are designed to current CS documentation and constructed to a similar level of workmanship to that which has been historically adopted.

Consequently, the most appropriate corrosion mitigation strategy considering the anticipated service life of a FOWT of 25-30 years is expected to be:

- for steel substructures: Cathodic protection (CP) and organic barrier coating of external and internal surfaces, plus appropriate corrosion allowances at specific sensitive areas, and
- for concrete substructures: Primarily normal construction practices, with measures put in place to ensure construction quality matches the design intent, although with potentially:
    - galvanic CP being applied to the immersed parts if the design of that part is fatigue critical, and
    - the application of a protective coating on the atmospherically exposed site faces, mainly for marine safety (visibility) purposes but with the additional benefit of providing additional resistance to chloride ingress.

No new or innovative measures in development and at a sufficient level of maturity have been identified which have the potential to change the current approaches either generally across the marine sector or specific to FOWT. All the existing approaches have been used generally successfully over many years (and in any event are currently mandated by all CS). Any reduction in corrosion mitigation related costs, is likely to be through the optimisation and tailoring of the current approaches to the specifics of FOWT, rather than adopting a radically different approach.

Based on a review of the environmental conditions in the North and Celtic Seas, whilst there may be modest actual differences in the corrosivity between the two locations, it is beyond the granularity of current knowledge and the guidance given in the appropriate design standards. The only exception to this is in the design of CP systems. Up until recently all commonly used CP design codes adopted an approach which would not have resulted in a material difference across the entire UK EEZ, but

with the introduction of ISO 24656 site specific metocean data is used and so differences in water currents, wave heights and water temperature will all have an effect.

The overall conclusions of the WLC study are that:

- Due to the substantial transportation costs and loss of revenue in taking a substructure back to shore, the lowest WLC approaches are those which do not require any return to port during the service life of the substructure. If a substructure was being returned to land for other reasons, then whilst the transportation costs allocated to these works could be reduced (shared or removed), for reasons of health and safety (H&S) and work planning resulting in the activities being carried out sequentially, the loss of revenue attributable to the time taken to implement the corrosion protection works would likely remain.
- Due to the significant transport costs in reaching the on-station sites, it is also beneficial from a WLC perspective to eliminate as far as is practical the need to visit site. From these perspectives alone:
    - A galvanic anode CP system is technically preferable to an impressed current system due to its inherent high reliability and low maintenance requirement,
    - Subject to the acceptance of the respective CS, the use of permanent monitoring in conjunction with a galvanic anode cathodic protection (GACP) system would be beneficial if it were to allow a reduction in the frequency of undertaking site performance assessment visits. It would also provide secure data on system performance in rough weather and storms, when performing manual performance surveys for CP data are not practical,
    - Splash zone coatings are required to be of the highest achievable durability, both to meet CS requirements and to minimise any possible coating repairs above the calm water level,
    - Above water coatings need to reduce as far as is practical the need to carry out minor onsite coating repairs.

The WLC study also identified that a CP system, of whatever design life, is unlikely to be practically feasible if the submerged part of the substructure is uncoated. With the coatings and coating costs rates assumed in this study, the use of an ISO 24656 Category III coating for the submerged part results in the lowest WLC. If the difference between the cost rates for the different coating types were to be less than assumed, it is possible that a higher specification coating may be preferred or may be needed if the weight and number of anodes associated with a Category III coating is not acceptable from a naval architecture perspective.

A high quality impressed current cathodic protection (ICCP) system is likely to have a higher capital expenditure (CAPEX) than an equivalent GACP system and there will be further costs due to the electricity usage and maintenance. The assessment also suggests that whilst an industry norm ICCP system will likely have a lower CAPEX cost than an equivalent GACP system, much of the benefit is lost in WLC terms when the ICCP's electricity usage is considered, and the ranking reversed once the increased cost of operation and maintenance (O&M) is considered.

The environmental pressures not to use GACP are significant in some regulatory jurisdictions, based on very little evidence considered relevant to the UK EEZ offshore environment. It would seem inevitable that this view will become more widespread, and it is therefore a recommendation that the industry work together to fund the collection and analysis of objective and impartial data on the effects of both types of CP on the marine environment, primarily the release of both zinc and chlorine into the marine environment.

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NOMENCLATURE

ABS	American Bureau of Shipping
ALS	Accidental Limit State
ALWC	Accelerated Low Water Corrosion
AMPP	The Association for Materials Protection and Performance (US based corrosion control society, formed from the amalgamation of NACE and SPSS)
Anchor	Structures on or embedded into the seabed that resists the loads from the floating substructure transferred
Anode/Anodic site	The part of a metal surface (or other electrically conductive material such as graphite) surface in an electrochemical system where there is a predominance of oxidation reaction, such as $Fe \rightarrow Fe^{2+} + 2e^-$. Also, in respect of cathodic protection, the part of the cathodic protection system which is anodic and provides electrons into the metallic circuit (and, by convention, DC current from the anode into the electrolyte to discharge on the cathode of the circuit)
Barge	A major category of floating substructure. It has hull that pierces the waterline and may be ballasted to provide additional stability
BV	Bureau Veritas
CAPEX	Capital Expenditure
Cathode/Cathodic site	The part of a metal surface (or other electrically conductive material such as graphite) surface in an electrochemical system where there is a predominance of reduction reactions, such as $0_2 + 2H_2O + 4e^- \rightarrow 4OH^-$
CBF	Coating Breakdown Factor
CoE	Centre of Excellence
CP	Cathodic Protection
CRA	Corrosion Resistant Alloy (e.g., Stainless steel or Monel)
CS	Classification Society (e.g., DNV, BV, LR, ABS)
DFT	Dry film thickness
DNV	Det Norske Veritas

FA	Fly Ash
FBE	Fusion Bonded Epoxy
FEED	Front End Engineering Design
Floating substructure	A buoyant substructure for turbines, or offshore substations; it includes any transition piece but excludes the turbine and the station-keeping system (incl. mooring lines and anchors)
FLS	Fatigue Limit State
FOW	Floating Offshore Wind
FOWT	Floating Offshore Wind Turbine, comprising both the substructure and turbine
FPSO	Floating production storage and offloading, a floating vessel used by the offshore O&G industry for the production, processing and/or storage of hydrocarbons
GACP	Galvanic Anode Cathodic Protection
GGBS	Ground Granulated Blast Furnace Slag
HAT	Highest Astronomical Tide
High strength steel	For the purposes of this report, steel with a Specified Minimum Yield Strength (SMYS) >550MPa. NB: Offshore standards use a different classification system. For instance, DNV-OS-B101 considers normal strength steel as having a yield strength of 235MPa, high strength steel as that having a yield strength in the range 265-390MPa, and extra high strength being in the 420MPa to 960MPa.
HISC	Hydrogen-induced stress cracking
ICATS	Industrial Coating Applicator Training Scheme
ICCP	Impressed Current Cathodic Protection
ICorr	Institute of Corrosion
LAT	Lowest Astronomical Tide
LCoE	Levelized cost of Energy
LR	Lloyds Register

MDFT	Minimum Dry Film Thickness (of coatings)
MIC	Microbiologically Influenced Corrosion
MMO	Mixed Metal Oxide, a coating of rare earth metals applied to a titanium substrate for use as an ICCP anode
Norsok	A set of standards developed by the Norwegian petroleum industry to reduce costs and improve competitiveness on O&G operations on the Norwegian continental shelf, now managed on their behalf by Standards Norway
OPEX	Operational Expenditure
OREC	Offshore Renewable Energy (ORE) Catapult
OW	Offshore Wind (both floating and fixed bottom)
O&G	Oil and Gas
O&M	Operations and Maintenance
Semi-submersible	A major category of floating substructure. It is relatively large in plan and comprises several buoyant columns or turrets that are connected using pontoons and/or trusses. It is typically ballasted to provide additional stability.
SLS	Serviceability Limit State
SMYS	Specified Minimum Yield Strength
Spar	A major category of floating substructure. It consists of a tall cylinder housing dense ballast in its lower part and has a large draft.
SRB	Sulfate-Reducing Bacteria
Station-keeping system	The part of the FOWT substructure which keep the FOWT in its intended location and stable. This includes the mooring lines, mooring line jewellery (e.g., clump weights, mooring line buoyancy elements) and anchors etc.
TLP	Tension Leg Platform; a major category of floating substructure. It is relatively small compared to other types of floating substructure and its stability is provided by taut vertical tethers.
TSA	Thermally sprayed aluminium

UF	Utilisation Factor (of anodes), the fraction of the galvanic alloy mass in an anode which can be used for cathodic protection current before the galvanic material is no longer supported by the core or the anode can no longer deliver the minimum required current
ULS	Ultimate Limit State
WLC	Whole-life Cost

1 INTRODUCTION

1.1 Background

This report aims to strengthen the Floating Offshore Wind (FOW) industry's understanding of corrosion protection and management as relevant to the substructures of Floating Offshore Wind Turbines (FOWTs) within the marine environment of the UK Exclusive Economic Zone (EEZ).

This report summarises the findings of:

a State-of-the-Art Review (SoA) of:

- Deterioration mechanisms which have the potential to adversely affect the materials used in the construction of the in-scope FOWT substructures through environmental exposure in a marine environment,
- Present means and methods of preventing the identified forms of environmentally induced deterioration, primarily forms of corrosion,
- The environmental conditions (and variation in them) that will be experienced by in-service FOWT substructures across those parts of the UK territorial waters presently being promoted as being suitable for FOW and their effect on the deterioration mechanisms and means of corrosion protection,
- The current rules, standards and procedures etc. required by the primary Classification Societies (CS)/Standards organisations relevant to the prevention/mitigation of deterioration, and
- Environmental issues/restrictions on the use of the current methods of preventing/mitigating deterioration.

a Whole-life Costing (WLC) Assessment comprising:

- WLC assessment of various corrosion protection scenarios for a floating offshore wind farm comprising steel semi-sub substructures at two reference locations within the UK EEZ, and
- a commentary on the reliability issues associated with the different forms of corrosion protection and their impact on the WLC.

1.2 Scope of the Project

Whilst much of the content of this report is generally applicable across all currently known substructure types, the SoA review contained within Section 2 of this report, focuses primarily on the following forms of FOWT substructure:

- Steel semi-submersible
- Concrete semi-submersible
- Steel suspended-weight spar
- Steel tension-leg platform (TLP)
- Concrete barge

The review is limited to the deterioration of the primary construction materials of the substructures and their station-keeping systems (e.g., anchors and mooring lines) because of environmental exposure; the following aspects were not considered:

- Deterioration of the towers, nacelles, or blades
- Deterioration of electrical cables or electrical connectors
- Deterioration of synthetic materials (e.g., fibre-reinforced materials, synthetic ropes etc)
- Structural effects/impacts, including fatigue (although the impacts of corrosion on fatigue life, which may be significant for FOWT substructures, is acknowledged)
- Deterioration of M&E equipment, including pumps, pipework such as those associated with active-ballasting systems.

The combined WLC/Reliability assessment contained within Section 3 of this report evaluates various corrosion protection scenarios applied to a generic steel semi-sub substructure.

2 STATE OF THE ART REVIEW

2.1 Forms of Floating Substructure

2.1.1 General

FOWT floating substructures can generally be categorised into one of the following four types, based on the means of ensuring stability (1):

- Semi-submersible - a substructure which is both buoyancy and ballast stabilised and is intermediate in terms of plan area and draft between the Spar and Barge varieties,
- Spar - long slender high draft substructure which is primarily ballast stabilised,
- Tension-leg platform - a low mass structure stabilised by multiple spatially distributed permanently tensioned mooring lines fixed to anchors in/on the seabed, and
- Barge - relatively large in plan but shallow draft primarily buoyancy stabilised substructure.

Whilst the following sections set out in more detail the primary features of the sub-structure types, it should be noted that most current designs are proprietary in nature and that the level of detail in the public domain is generally very limited. Furthermore, many designs are still being developed and are at varying levels of design maturity; their details will be subject to change as the designs develop and are refined. Consequently, some comments made in this respect are speculative.

2.1.2 Steel Semi-Submersible Substructures

With a steel semi-submersible floating substructure, floatation is provided by multiple, typically three or four, connected steel hollow shells/cells, known as floaters, turrets or columns, which are part air filled providing buoyancy and part ballasted providing stability. The floaters are connected using hollow steel members (known as pontoons or truss elements) to form the overall structure. Some designs also incorporate steel heave plates integral with and at the bottom of the floaters and/or connecting members.

The elements providing the structural connections to the columns can be either permanently underwater, permanently above (excluding wave action) or be part of above and part below, both spatially and temporally.

Some designs contain passive ballasting, using partially or fully water filled elements, but some reportedly include active ballasting with water levels within the floaters being varied by pumping in response to operational need and sea state; those requiring active ballasting are likely to be those where the turbine and mast are not centrally located in plan.

The steel semi-submersible form of substructure currently contains the greatest number of designs of all the categories of FOWT. Examples include Stiesdal's Tetra-Sub (2) and Principle Power's Windfloat (3) designs.

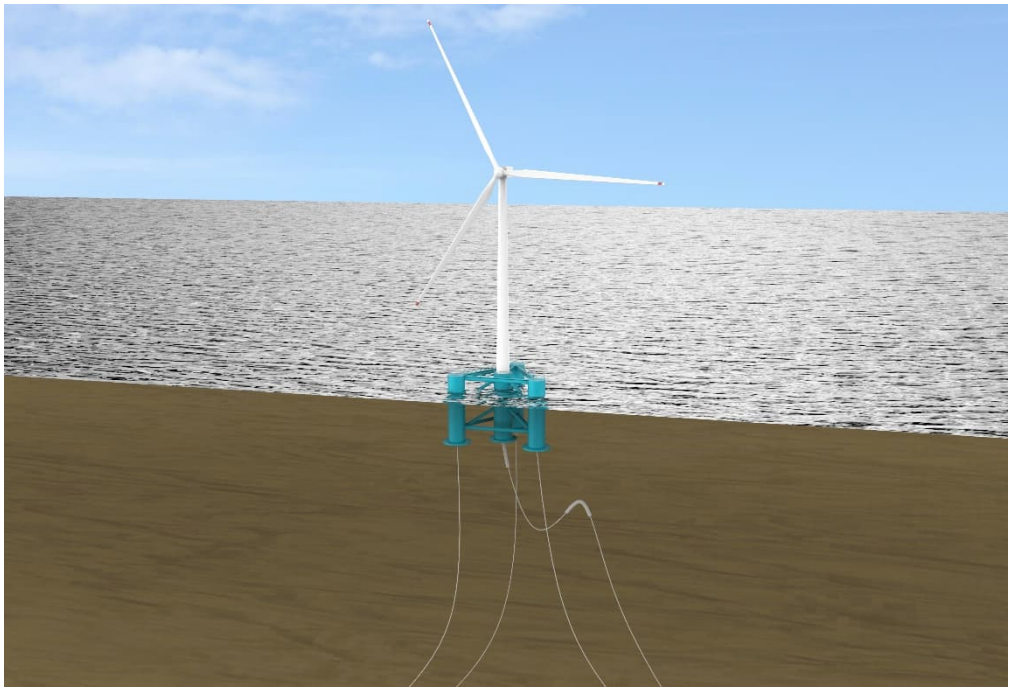


Figure 1 – Life 50+ steel semi-sub render (© ORE Catapult)



Figure 2 - Windfloat steel semi-sub (© Principle Power)

The major components are expected to be fabricated from weldable low carbon manganese steel with a Specified Minimum Yield Strength (SMYS) <550MPa. The individual steel elements are most commonly welded together to form the overall sub-structure, but in one example, Stiesdal's Tetra-Sub, they appear to be connected using large diameter steel pins.

Station-keeping systems are most likely to be of the catenary variety, but there are some examples where semi-taut systems have been adopted/proposed; from a corrosion perspective there is little difference, other than where synthetic mooring lines are used. Based on the current level of publicly available information, the mooring lines appear connected to the floaters rather than the

interconnecting elements. Some designs have the connections at a low level, permanently below the waterline, and some designs have chosen to situate them above the waterline taking them through the splash zone and into the atmospheric zone.

Anchoring systems used will vary depending on seabed ground conditions.

2.1.3 Concrete Semi-Submersible Substructures

As with a steel semi-submersible substructure, floatation is provided by multiple floaters which are in part air filled and part ballasted providing stability, but they are made from steel reinforced concrete (including prestressing). The floaters are interlinked using either solid or hollow (but ballasted) low level connecting concrete members, termed pontoons by some designers. Some designs also incorporate concrete heave plates integral with and at the bottom of the floaters and/or connecting members.

The floaters are semi-immersed in water. The primary elements providing the structural connections to the floaters are generally permanently underwater (NB: connecting members above water may be provided to facilitate access for maintenance and inspection, and these are thought more likely to be made from steel).

All concrete elements will contain standard steel reinforcement, but many (if not all) are also understood to incorporate high strength steel prestressing tendons in ducts. It is not apparent from the publicly available information whether the tendons in current designs are of the bonded variety (encapsulated within their ducts using a cement-based grout) or unbonded (encapsulated within their ducts using a wax or grease).

Some designs contain passive ballasting, using partially or fully water filled elements, but some are understood to include active ballasting.

Examples of concrete semi-submersible substructures are the University of Maine's VolturnUS (4) and the Olav Olsen's OO-Star (5) designs.

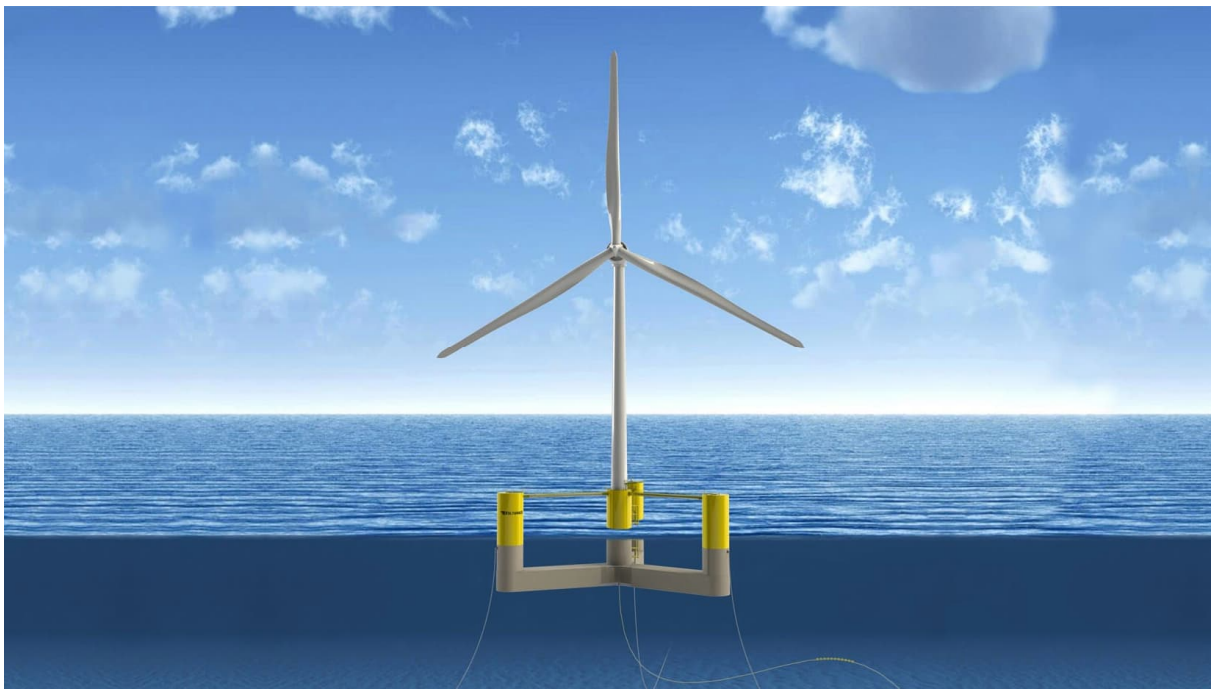


Figure 3 – VolturnUS concrete semi-sub render (© University of Maine)

Station-keeping systems are likely to be mainly of the catenary variety but can be semi-taut. Based on the designs identified and reviewed under this commission, the mooring lines are generally connected to the sub-structure below the waterline.

Anchoring systems used vary depending on seabed ground conditions.

2.1.4 Suspended Weight Spar Substructures

A traditional spar type floating substructure is, in essence, an overall buoyant vertical tube incorporating an integral counterweight placed at the lowest possible point providing stability. As turbines become larger, it requires very long cylinders to provide the required stability, which makes this solution difficult to manufacture, transport, install and decommission.

The suspended weight spar floating substructure, which is the subject of this section, obviates the above issues, by separating the two parts and suspending the counterweight part below the buoyant remainder of the substructure/tower assembly. Although not able to be confirmed it is suspected that the counterweight is suspended below on steel ropes, most likely of the same type as used for mooring.

An example of this form of floating structure is the Stiesdal's Tetra-Spar (2) (6).

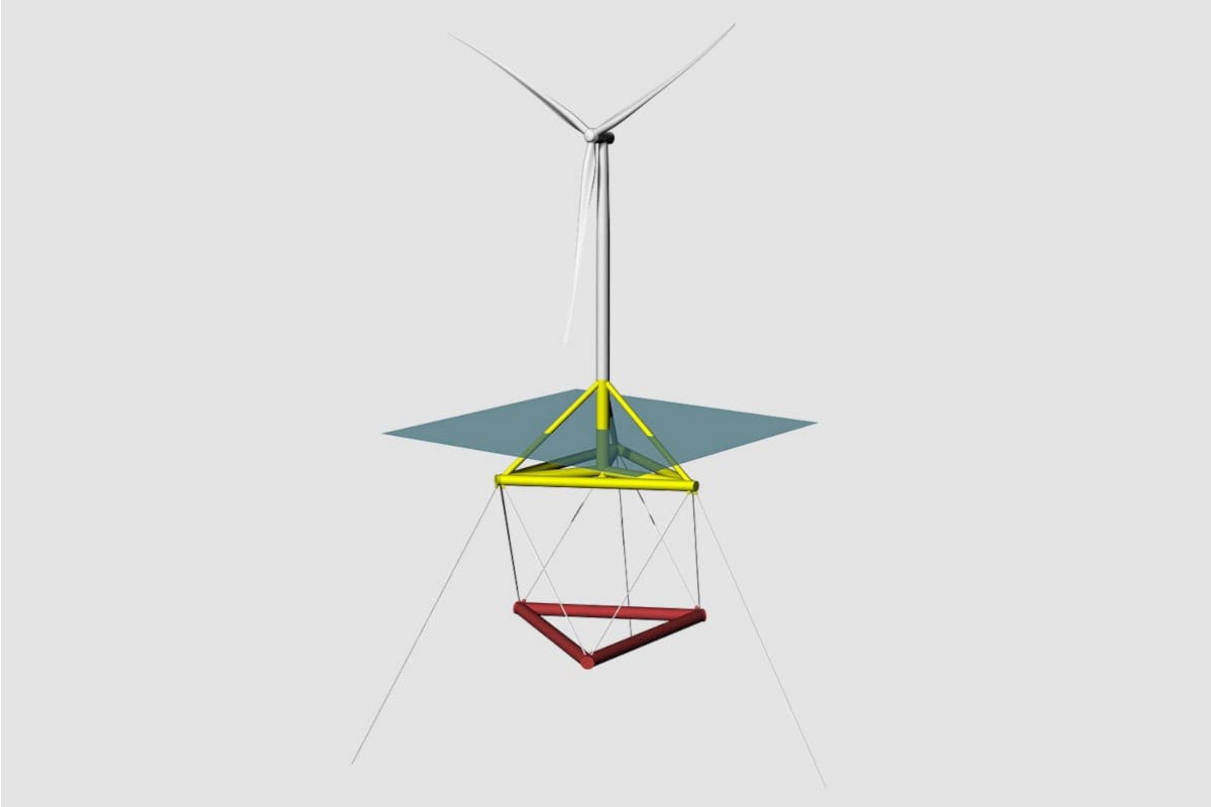


Figure 4 - Tetra-Spar steel suspended spar render (© Stiesdal Offshore)

As with the other forms of steel floating substructure, the major components are likely to be fabricated from weldable low carbon manganese steels with a SMYS <550MPa. In the case of Stiesdal's Tetra-Spar, the various components appear to be connected using large diameter steel pins, but more generally they are likely to be welded together.

Station-keeping systems are likely generally of the catenary variety but can be semi-taut. Based on the designs identified and reviewed under this commission, the mooring lines are connected to the sub-structure at a point, once in service, which is permanently below the waterline.

Anchoring systems will vary depending on the seabed ground conditions.

2.1.5 Steel Tension Leg Platform (TLP) Substructures

A TLP is like a semi-submersible in form, but with smaller, lighter, structural components. TLPs achieve stability through the mooring system. They typically use mooring lines that connect vertically to seabed anchors with a high tensile capacity. The upwards buoyancy force acting on the substructure is sufficient so that the tendons are continuously under tension under all operating loads.

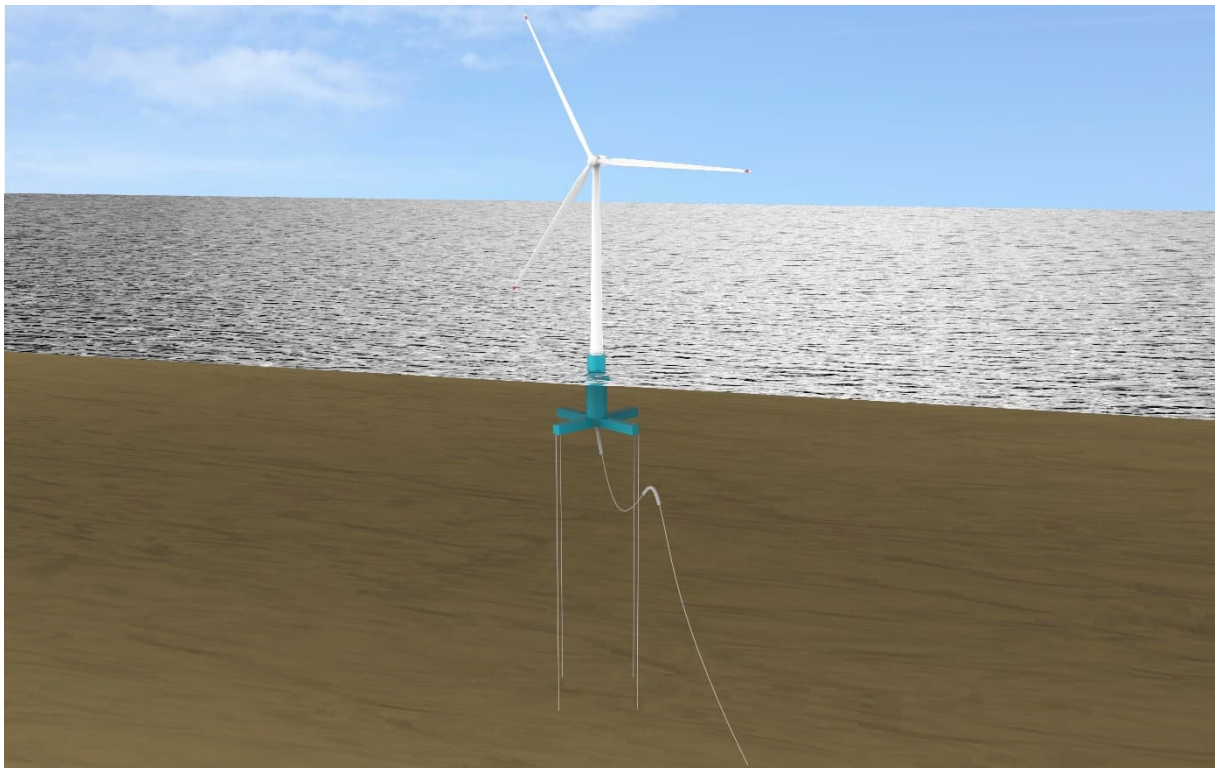


Figure 5 - Life 50+ Steel TLP Render (© ORE Catapult)

Examples of these types of floating substructure include the MPS Pelaflex (7) and Stiesdal's Tetra-TLP (2).

As with the other forms of steel floating substructure, the major components are likely to be fabricated from weldable low carbon manganese steels. The individual steel elements are mostly welded together to form the overall sub-structure, but for Stiesdal's Tetra-TLP, they appear to be connected using large diameter steel pins.

Large TLP floating substructures have been used in the offshore oil and gas sectors, and in these instances, they are typically tethered to the seabed using steel tubular sections anchored to the structure at a point permanently under water. It may be that in the case of FOW, high strength steel-cables or specialised synthetic ropes such as UHMWPE or Aramid (8) (9) may be used instead.

2.1.6 Concrete Barge Substructures

This substructure format is akin to that of a ship, with the length and width significantly larger than the height (of the barge, not the turbine). The floating platform has a large surface area in contact with the water, which is what gives it stability.

Examples of concrete barge substructures are the BW Ideol Floatgen (10) and Saitec Sait (11) designs.



Figure 6 - Floatgen concrete barge (© BW Ideol)

The primary elements are formed from multi-cell concrete elements containing both steel reinforcement and, most likely, prestressing in ducts, for watertightness/crack control as well as for structural reasons.

Station-keeping systems are likely to be of the catenary variety. Of the current known examples, the mooring lines are connected to the sub-structure above the waterline.

Anchoring systems will vary depending on the seabed ground conditions.

2.2 Station-Keeping Systems

2.2.1 General

The station-keeping system keeps the FOWT in its intended location and, in some instances, provides stability. It consists of both the mooring system and the seabed anchor. Except for TLP substructures and those incorporating a turret mooring mechanism (see below), the system adopted appears to be independent of the sub-structure type and is based on a site-specific assessment.

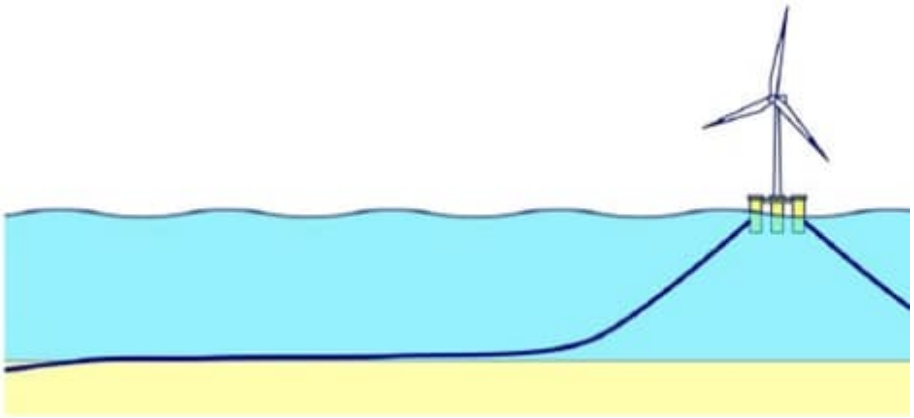
2.2.2 Mooring System

Mooring systems can be categorised into the following forms:

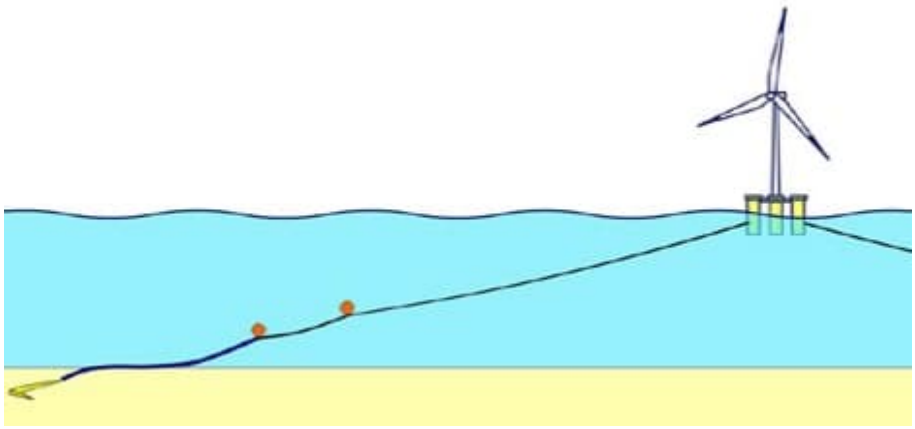
- Catenary
- Semi-taut
- Taut

Mooring lines in catenary and semi-taut systems typically comprise some combination of the following elements, sometime used in conjunction with synthetic ropes. For taut systems, steel cables or synthetic ropes may be the preferred approach.

Catenary



Semi-taut



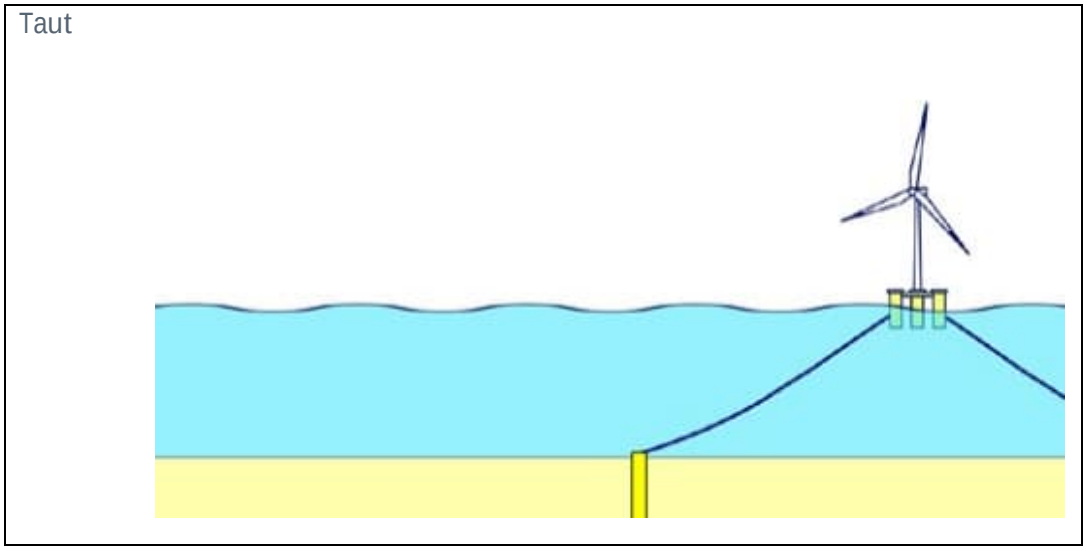


Figure 7 – Primary types of mooring (© First Marine Solutions and Morek Engineering)

2.2.2.1 Steel Chain

Mooring Chains and accessories are typically made from rolled, forged or cast steel of varying SMYS dependent on selected grade, but which can include both low and high strength materials (SMYS >550MPa) (12; 13). Steel Chains are typically uncoated relying solely on a sacrificial corrosion allowance for corrosion mitigation. In some applications effective cathodic protection has been provided from the anchored entity and it is possible, but not widely implemented, to introduce galvanic anodes cast onto specialist links within the chain.



Figure 8 - Steel Chain (© Offspring International Limited)

2.2.2.2 Steel Wire Rope

Steel wire ropes are made from very high strength steel wires and come in two main types, stranded or spiral. Wire for steel rope is specified in terms of its ultimate tensile strength and there is no requirement to specify or measure its yield strength, but the SMYS will be >550MPa in all instances (14).

For long-term mooring applications, it would be normal to use the spiral variety rather than stranded as, amongst other benefits, they are thought to provide better corrosion protection. However, they are less flexible and so their use is limited where winching damage, bending at fairleads is anticipated

or where they pass through the splash zone or touchdown on the seabed, hence why they tend to be combined with steel chains at top and bottom which are not similarly affected.



Figure 9 – Example of spiral strand steel wire construction (© Teufelberger Redaelli)

The ropes are provided with socket terminations at either end, made from cast or forged steel with the rope being fixed in place using either molten metal or resin. The selection of encapsulation material appears to be dependent on the requirements of the relevant CS rules; with a polyester-based resin seemingly preferred.

2.2.2.3 Clump Weights

Clump weights can be attached to mooring lines to improve mooring performance. They are mostly attached to the ground chains on a catenary mooring system near to the touch-down point on the seabed, although other locations on the upper part of a mooring line are sometimes used. Clump weights can be made from cast steel, cast iron or concrete, or a combination.



Figure 10 - Clump Weights being deployed (© FMGC)

2.2.2.4 Mooring Line Buoyancy Elements

Some mooring line configurations incorporate Mooring Line Buoyancy Elements – MLBE (also known as Spring Buoys), to improve the configuration of the mooring line. These are typically made from synthetic material surrounding a steel structure or hollow welded steel elements.



Figure 11 - Example Mooring Line Buoyancy Elements (© Balmoral)

2.2.2.5 Turret Mooring Mechanisms

Some FOWT concepts incorporate a turret mooring system which allows the structure to rotate (weathervane) around it (11). These can be incorporated in the sub-structure itself or be within a remote buoy, sometime situated underwater, to which the substructure is traditionally moored.

Whilst details of the types being proposed in current designs are not known, based on the O&G sector, they are likely to comprise a steel support structure with the movement being accommodated by bearings, the most common being:

- Roller bearings in sealed greased filled units
- Roller systems utilising steel “bogie” wheels on rails
- Sliding bearings utilising self-lubricating low-friction pads on spring supports sliding against a machined stainless-steel surface

Due to their criticality, ready access for both inspection and maintenance would seem essential.

2.2.3 Anchors

Anchors are typically selected and designed based on the seabed conditions as well as the magnitude and direction of loads imposed through the mooring lines, and they can be any of the following types (15):

- Steel drag embedment (fluke) anchor
- Gravity anchor
- Driven steel piles
- Suction steel piles
- Steel drop anchor

- Drag-in plate anchors

They are entirely or primarily fabricated using forged, cast and/or rolled steel elements, potentially in the case of gravity anchors, supplemented using cast-iron or concrete ballast blocks. Steel elements are likely to have a SMYS <550MPa.



Figure 12 - Example Drag-in Plate anchor (© First Energy Development)

2.3 Steelwork Components

2.3.1 Deterioration Susceptibility and Mechanisms

The main components of all steel floating substructure types are constructed from a series of welded steel compartments, usually, but not always, tubular in form.

In the offshore wind sector, for external exposure, there are established definitions of exposure zones (these differ somewhat from those used historically in the O&G sector). These are, based on DNV-RP-0416 (16):

- Atmospheric Zone - The zone above the Splash Zone that will be exposed to sea spray and airborne moisture rich in chlorides. It will be more corrosive than most onshore atmospheric zones,
- Splash Zone - The part of the structure exposed to intermittent immersion due to both tides and waves. It will extend higher than HAT and below LAT. Historically in O&G this was known as the tidal zone, and
- Submerged Zone - The part of the structure that is permanently immersed, i.e., below the lower limit of the splash zone. The zone also includes the buried area.

Internally, the elements could be:

- Originally air-filled but permanently sealed resulting in oxygen depletion after a period,
- Air-filled with some exchange of air from the external environment (say through hatches),

- Partially air and partially seawater filled with some exchange of air and/or seawater with the external environment,
- Partially air and partially seawater filled without exchange of air and/or water with the external environment,
- Fully filled with seawater with some exchange of seawater with the external environment, or
- Fully filled with seawater with no exchange of seawater with the external environment.

It is likely that any air within these elements or compartments will have a high relative humidity and any water a high chloride content; except where permanently sealed these are unlikely to be benign conditions in respect of corrosion. Even above the water level in such compartments there may be significant chloride deposition on the surfaces. If the water level varies internally, the 'tidal zone' may be a high corrosion rate location and may require particular attention.

Due to the lack of publicly available information on the ballasting and access provisions on all the current designs, the corrosion related conditions within the interior of all the floating steel substructures are particularly unclear.

The metallic parts of mooring lines are generally of steel construction, with some parts possibly being galvanized as well. Metallic mooring lines/tendons are mainly permanently submerged in fresh seawater over most of their length; this also includes the part of catenary or semi-taut systems resting on the seabed. The only real exception from a durability perspective is where the tethering point on the sub-structure is not permanently below water, in which case the line passes through the splash zone and, potentially above into the atmospherically exposed zone.

Anchors are typically all, or majority, made of steel. By definition, they are part buried in the seabed (either superficial deposits or to depth) and part submerged in seawater. Generally, those parts not buried can be considered to be permanently exposed to fresh seawater, although silt deposits may increase the risk of MIC. In the case of suction piles and buckets there may be compartments which are filled with seawater but with no exchange with the external environment. Tension piles, driven into the seabed, will be exposed to a gradation of decreasing corrosion risk with depth.

The major components of steel sub-structures are thought likely to be fabricated from weldable low carbon manganese steels with SMYS of less than 550MPa.

Based on a review of relevant standards, it is considered that the following metals are also likely to be used, although this and extent of use will depend to a large degree on the design of the station-keeping system:

- Cast iron,
- High strength steels (SMYS > 550MPa), or
- Corrosion resistant alloys (CRA), primarily stainless steels.

The likelihood of any particularly specialist CRAs (i.e., excluding stainless steels) being used in the FOWT is considered small and if present should only have been selected following a thorough evaluation by competent specialists.

Based on the above the following deterioration mechanisms are considered worthy of comment.

2.3.1.1 Uniform Corrosion

True uniform corrosion is considered to be relatively unusual in a marine environment. However, if it does occur, there will be a general wastage of the metal and reduction in thickness over the entire exposed surface area. Even with uniform corrosion the reduction in section thickness will not be constant across the affected surface although variations will not be as severe as in pitting corrosion.

The more specialist CRAs used in a marine environment, such as the higher grades of stainless steel, titanium, Monel etc are generally resistant to this form of corrosion, but low-carbon manganese steel, which is the most used material in steel FOW sub-structures, is not.

2.3.1.2 Microbiologically Influenced Corrosion

Microbially influenced corrosion (MIC), which can result in very high rates of corrosion, is possible but thought unlikely on the floating external elements of FOWT installations. However, it can occur:

- under biofilms,
- in seabed silts,
- in deposits or stagnant water in ballast tanks, or
- in water contaminated fuel oil tanks (where present).

2.3.1.3 Galvanic Corrosion

Galvanic corrosion occurs between two dissimilar metals in seawater containing dissolved oxygen when connected electrically (e.g., when physically contacting). The metal with the more negative potential (termed the anode) corrodes more rapidly than it otherwise would and the one with the less negative potential (termed the cathode) is effectively protected from corrosion.

Whilst the potential difference between the two materials gives an indication of the risk of galvanic corrosion, it provides no information of the severity; that being governed by the availability of dissolved oxygen, solution conductivity, fluid flow, surface characteristics of the two materials and their relative surface areas. The latter is particularly important; a small anodic area connected to a large cathodic component can suffer particularly intense corrosion and conversely there may be little impact if a large anode is connected to a small cathode.

2.3.1.4 Crevice Corrosion

Crevice corrosion occurs in narrow, flooded, crevices present at a metal surface or between metal surfaces exposed to an aerated aqueous corrosive environment. As time progresses, oxygen levels in the flooded crevice become depleted compared to the outside which drives a corrosion cell with the metal inside the crevice corroding preferentially. It takes time to initiate but is both rapid and difficult to stop once it has.

Crevice corrosion does occur with low carbon manganese structural and also with lower grades of stainless steels in marine environments. It may occur at:

- bolted flanges that are permanently or intermittently immersed, both at the flange faces, within the flange bolt holes,
- potentially within static pinned joints as is used on some forms of steel floating sub-structure.

- in crevices formed between two similar or dissimilar metals, or a metal and a non-metal, or under deposits on a passive metal surface.

2.3.1.5 Pitting Corrosion

Pitting corrosion is expected to be the primary form of corrosion for low carbon manganese structural steels in a marine environment in the absence of effective corrosion control methods. Given the expected extensive use of these types of steel in steel floating substructure construction, this deterioration mechanism is of primary importance.

Pitting corrosion has a significant negative impact on fatigue life; corrosion fatigue may reduce the service life of fatigue sensitive elements and, for example, DNV-RP-C203 requires different design S-N curves to be employed for 'free corrosion' exposure and exposures in seawater (with effective CP) and (benign) atmospheric exposure.

Pitting corrosion also occurs on lower durability grades of stainless steel in seawater. Local failure of the passive film results in restricted areas of intensely localised corrosion often surrounded by un-attacked metal.

2.3.1.6 Electrical Interaction or Stray Current Corrosion

Interaction (stray current) corrosion can occur where impressed current cathodic protection or large current galvanic anode arrays are used and where adjacent infrastructure, or parts of infrastructure, are not electrically connected to the protected structure.

If operating faults in any on-board electrical systems result in DC current flow from the surface into the seawater, then any exposed carbon steel will suffer additional corrosion proportional to the current flowing. Stainless steel will suffer from severe pitting attack if the current flow shifts the surface potential by more than ca. +0.2V, and more general corrosion will occur at potential shifts above ca. +0.5V. AC current can produce a similar, but much lesser, effect by both induction and conduction.

Some OWF developments are intending to utilise High Voltage Direct Current (HVDC) export systems. It is theoretically possible that these may introduce increased corrosion rates due to DC stray current during normal operation and any continued operation permitted by the design under a partial fault condition.

2.3.1.7 Dealloying

Although other metals can be susceptible, in the context of FOW sub-structures, the only identified risk of dealloying occurring is with cast-iron elements used as clump weights and in gravity anchors etc.

Cast-iron is an iron-carbon alloy. Under corrosive conditions, the carbon can form a galvanic cell with the iron resulting in corrosion of the iron leaving the cast-iron with a porous structure of rust, voids, and graphite. This results in loss of strength and its metallic properties in the affected area but with no obvious visible signs.

Graphitisation (or graphitic corrosion as it is also known) only affects Grey cast-iron, with Ductile, Malleable or White cast-iron being unaffected either due to their micro-structure or low levels of carbon.

2.3.1.8 Intergranular Corrosion

Intergranular corrosion is a localised form of corrosion which affects the boundaries of the different grains within an alloy or the area immediately adjacent to the boundaries, leaving the bulk of the material unaffected. In extreme cases, entire grains of material within an alloy can become separated from the remainder of the materials.

It can affect austenitic stainless steels (such as Grade 316) and Grade 304 stainless steel if heated for a significant period, such as a result of multi-pass welding. Austenitic grades of stainless steel can also be affected following welding resulting in a specific type of corrosion known as "knife-line" attack of the part of the element immediately adjacent to the weld material.

2.3.1.9 Corrosion-enhanced Fatigue

All structural elements subjected to cyclic loading are at risk of cracking and eventually failure at a stress lower than the static ultimate limit state (ULS)/ accidental limit state (ALS) structural design requirements would predict because of fatigue (fatigue limit state, FLS), but the ability to endure the cyclic loading is further reduced in the presence of corrosion pits or other similar features.

Many metallic materials used within the marine sector are susceptible to corrosion-enhanced fatigue, including low carbon manganese steel and stainless steel.

2.3.1.10 Hydrogen-induced Stress Cracking

None of the main grades of low carbon manganese steel likely to be used in FOW sub-structure construction are vulnerable to hydrogen-induced stress cracking (HISC) or reduced fatigue life due to hydrogen generated by cathodic protection (CP), if the welding processes and inspection are appropriate.

However, some frequently used alloys such as high strength steels, duplex or martensitic stainless steels, and Monel and high-strength copper-nickels can be susceptible if their metallurgical structure is insufficiently well controlled.

Experience also shows that embrittlement can be significant by the application of conventional CP with the wrong choice of materials. However, HISC will not occur under properly operated CP, if correct material selection and metallurgy is ensured and high stresses are avoided.

2.3.2 Corrosion Protection Technologies/Methodologies

The following sections set out the corrosion protection technologies and methodologies likely to be used on steel FOW substructures. Due to the lack of detailed information on present and planned FOW developments, it is based on current practice on fixed bottom OW installations, and both fixed and floating O&G assets, applied to what is presently known of FOW designs.

2.3.2.1 Corrosion Allowance

It is a common requirement/recommendation of most CS requirements governing the design of FOW structures to make some allowance for corrosion during the service life of an asset.

Corrosion allowances are defined in the various certification / classification standards and design guidance documents, but these are generally based on "uniform", albeit most likely rather conservatively assessed, corrosion rates.

CS standards generally stipulate a uniform corrosion rate allowance (in mm/year) to be used per face for a particular set of conditions, although under some circumstances a simple corrosion allowance (in mm) is adopted, irrespective of design life.

For hollow elements, the external and internal conditions will invariably differ and therefore so will the corrosion rate allowance on either side of the plate.

However, irrespective of the above, it is anticipated that many components of floating substructures will be fatigue sensitive, and buoyancy can be impaired by localised perforation however small the hole. In such cases any general corrosion allowances can be irrelevant.

2.3.2.2 Barrier Coatings

Barrier coatings are widely used, and mandated in many instances under CS rules, on FOW and similarly exposed and constructed steel structures. The general types of barrier coatings, and a basis for their specification, can be found in both NORSOK M-501 (17) and ISO 12944-9 (18).

The requirements for coatings are quite different in the different exposure zones. In the atmospheric and upper splash zone, the priorities are for integrity of the barrier coating to reduce as far as is possible, the need for coating repairs, or more extensive re-coating campaigns either offshore or in dry dock. It is likely that UV tolerant topcoat will be required.

In the permanently immersed zone, the need for a coating is more related to the need to reduce the size of the CP system. The CP design and performance are intimately linked with the coating performance.

It is likely that all internal plates and stiffeners plus the internal surfaces of external plates will require coating. This is mandated in some circumstance by some of the CS's.

It is not normal to coat all the steel buried to depth (i.e., excluding Steel drag embedment or Drag-in plate anchors). The limited corrosion data available indicates that corrosion rates are low, except in the presence of active MIC, which is generally accepted to be limited to the top 1-2m layer of seabed silts. Other reasons for steel piles being uncoated, at least over most of their depth, are, in addition to their low corrosion rates, their low CP current density requirements compared with steel in seawater and the expectation of significant coating damage during piling.

In all environmental exposure categories, it must be emphasised that, in addition to the appropriate selection of coating type, specification and source, it is the quality of all stages of the surface preparation, coating application and the detailing of the structure being coated which will determine the performance of the coating system. It is a commonly held view that significant improvement in performance compared with some past offshore wind experience is likely to be by improvements in quality of application.

The coating and corrosion protection of carbon steel bolt heads and nuts/washers has proven problematic and requires specialist attention.

Very high build glass flake epoxy and polyester coatings may offer very good and long-term performance in all exposure zones. However, areas of structural complexity, most likely associated with those areas above water and internally may render glass flake high build coatings impractical due to difficulties in application into complex areas.

Those FOWT owners also with offshore oil/gas experience will already be aware of the huge costs of offshore coating repair and recoating campaigns. The nature of FOW devices, with multiple, relatively small devices, is likely to increase the mobilisation and access costs compared with large,

fixed O&G jacket structures. Coating repair underwater is considered impractical and generally ineffective; it is far more effective to overcome unexpected coating damage or failures with CP.

2.3.2.3 Cathodic Protection

CP is routinely used on steel structures immersed in a marine environment to protect against metallic corrosion and it use is mandatory under all applicable CS rules. If designed and operated correctly, it obviates all the forms of corrosion related deterioration except for some forms of crevice corrosion and HISC; in the case of crevice corrosion of some grades of stainless steels CP may prevent its initiation, but it is unlikely to stop it once it has initiated. Arguably its greatest benefit, though, is in terms of the structural design of fatigue sensitive marine structures. Its incorporation improves corrosion fatigue performance and permits the use of more favourable fatigue damage curves for the design of immersed elements/components.

CP can be delivered by one of two alternative processes:

- Galvanic anode CP (GACP)
- Impressed current CP (ICCP)

With GACP, the galvanic anodes used in seawater applications are almost exclusively made from an alloy of aluminium which are electrically connected to the structure, usually by direct welded connections, the aluminium alloy corroding preferentially to the steel. The most obvious benefit is that they are effectively self-controlling and if properly designed and installed, they are extremely reliable and require minimal maintenance, beyond intermittent performance assessment.

With ICCP, the anode is most commonly a relatively inert material connected electrically to the structure via a permanent external DC power supply to deliver the CP current. Impressed current systems are not naturally controlling and unless performance monitoring sensors and feedback circuits are included as part of the system, they require periodic adjustment to optimise system life and corrosion protection. The DC power supplies need to provide current constantly (excluding occasional periods of CP system shutdown for maintenance), so need to be provided with power even if the turbine is not actively generating. Due to their intrinsic complexity compared with galvanic anode systems, impressed current systems demand significantly more inspection, maintenance and often repair work than the more reliable GACP systems.

CP of internal flooded chambers presents design and operational challenges, both in terms of anode distribution and dissipation of the gases generated at anodes and steel cathodes. All CP systems normally generate low volumes of hydrogen gas. Impressed current systems will generate, in addition, chlorine gas, with the potential to create significantly more of both gases if not properly operated. When applied externally, these gases vent to the atmosphere, but internally the hydrogen presents a threat of explosion and the chloride gas a significant corrosion threat both to structural steel above the water level and to secondary steel, including ventilation systems, including those of stainless steel.

2.3.2.3.1 Design

DNV-RP-B401 has traditionally been widely used for the design of CP systems of offshore wind substructures, despite it being originally produced for use in the O&G sector. Due to recognised deficiencies DNV produced DNV-RP-0416 specifically for the corrosion protection of offshore wind renewables.

Historically, the use of the default (NB: not mandatory) values from the DNV documents have resulted in some failures of CP systems to adequately protect offshore renewables infrastructure and this provided the impetus for the development of a new standard, ISO 24656.

ISO 24656 was drafted to be compatible with the full intent of DNV requirements, but with the more OW focussed design parameters.

2.3.2.3.2 System Reliability

Impressed current systems have their operational advantages, particularly in low salinity environments (not applicable to the UK EEZ). In addition, where the design life required of the system is long or the structure being protected is largely uncoated there may be considerable weight reduction with impressed current.

However, the history with O&G offshore structures clearly shows that GACP systems are much more reliable than ICCP systems (19). Experience has demonstrated that ICCP systems need to be very well, and robustly, designed for reliable operation as well as being well operated and maintained, in which case they can cost more than GACP systems. The ICCP systems on many ships do not function, even though they have 'resident 24/7' engineering staff to maintain them. FOW structures will not be permanently manned, and access will likely be constrained by service vessel and maintenance personnel availability plus also suitable weather windows.

Practically all CS and other industry guidance makes clear the advantages of GACP and requires a much more rigorous assessment and design process, with full disclosure to the owner of the possible disadvantages of ICCP in terms of operational expenditure (OPEX).

More detailed information is provided in Section 3.

2.3.2.3.3 Applicability to Station-keeping Systems and Export Cables

A critical part of the CP design for any FOWT installation will be the appropriate provisions for:

- Moorings and their terminations, and
- Connectors for export cables.

Both may be in moonpools which can present confined spaces for the electrolyte, which may impact on the choice of galvanic anode materials and may also cause CP current and potential attenuation resulting in localised under-protection.

Both may utilise high yield steels or CRAs which could be susceptible to HISC and may require reconsideration. CRAs may cause localised galvanic couples, increasing the corrosion rate or CP current density demands.

Whilst there is comprehensive advice from the CS bodies in respect of corrosion allowances to be used for chains, for permanently moored FOW devices the intended extensive design life may dictate consideration of cathodic protection being applied to the mooring components to extend their service life. The electrical continuity between chains and metallic ropes and the floating devices will ensure some degree of CP is delivered to the moorings from the CP system for the device. If protection is required for the full length of chains, it is likely that specific CP design implementations will be necessary. This was proven in 1960's as viable and involved anodes being cast over chain links and, in some cases, additional electrical continuity being provided with steel wire ropes.

Undamaged wire rope moorings should neither require CP, nor be adversely affected by it, subject to the integrity of the extruded polyethylene sheath or jacket. Anchors will require specific assessment in respect of their corrosion protection durability and their possible vulnerability to HISC.

2.3.2.3.4 Environmental Considerations

Some authorities and organisations have reached a view that ICCP should be used in preference over GACP for environmental reasons. In essence this is to prevent any release of metals, and in particular zinc, into the marine environment, although:

- with apparently little, if any, hard data to demonstrate that in open water the quantities of metals released through CP are damaging,
- with little consideration of the impact on the cost of renewable energy generation, and
- without ensuring all available measures to reduce the releases to as low as is possible have been investigated (such as using low zinc aluminium galvanic anode alloys and increasing the extent and quality of barrier coatings).

Within Europe, including the UK, the legislative background to limiting the release of zinc into the marine environment appears to stem from the EU Directive on the Environmental Quality Standards (EQS) for water, which identified zinc as a specific pollutant. Noting that the threshold levels are subject to periodic review, the UK currently limits the long-term zinc concentration in the seawater (i.e., mean value) because of any activity to 6.8µg/l over and above the background level. It should also be noted that the same list of pollutants also includes iron and chlorine; iron would be released through corrosion of steel in the absence of any corrosion protection and chlorine is evolved at the surface of an impressed current anode for which the limit is a maximum short-term (95 percentile) dissolved limit of 10µg/l. This should also be considered in the context that GACP systems are self-regulating so only that needed is utilised (the rest remaining in solid form on the anode so not causing pollution), whilst ICCP systems are not self-regulating and will likely create more chlorine than is needed to provide protection.

This is clearly an area of particular importance, and it would seem likely that surveys of water quality could and should be undertaken at current and future sites incorporating either GACP and ICCP to provide objective and impartial data on the effects of both types of CP on the marine environment.

2.3.2.4 Wraps

Anti-corrosion petrolatum-based wraps, tapes and heat shrink sleeves are sometimes used on marine structures to provide corrosion protection, usually to tubular elements such as jetty piling. However, they tend to be used as a remedial measure, such as if there are issues with the originally specified organic coating which are not discovered until after pile driving, and it is preferable/not practical for the end client to insist on replacement, or once the coating has reached the end of its functional life and recoating is not feasible in the environment.

The authors do not consider them to be an equivalent to a high-quality paint system in terms of corrosion protection. There is likely also a limitation on the diameter of the component to which they can be practically applied, and there will be difficulties/compromises when applied at junctions between elements or non-tubular elements.

2.3.2.5 Corrosion Resistant Alloys (CRAs)

Most of any steel FOWT substructure will be constructed from weldable low alloy carbon manganese steels, with CRAs being reserved generally for specific high importance uses. Due to their relatively high cost per volume, availability and in some instances issues in fabrication, it is not feasible for them to be used more widely in FOWT substructure construction.

2.3.2.6 Corrosion Inhibitors/Oxygen Scavengers/Oxygen Depletion

For internal areas only, it is possible, at least in theory, to change the corrosivity in interior voids (either air or seawater-filled parts) using:

- Vapour phase corrosion inhibitors for the air-filled parts,
- Liquid phase corrosion inhibitors for seawater filled parts,
- Liquid phase oxygen scavengers for seawater filled parts,
- Liquid phase antibacterial treatment for seawater filled parts for prevention of MIC, and
- Natural oxygen depletion for both air and seawater filled spaces because of corrosion or microbiological processes.

However, each one has their own issues from both a technical and environmental perspective, so need detailed consideration prior to use.

2.3.2.7 Thermally Sprayed Aluminium (TSA) Coatings

TSA coatings, and aluminium-zinc alloy coatings have been proposed and championed by a number of bodies, for both atmospherically exposed and immersed applications.

There has been considerable success in some instances, for example with the Conoco Hutton TLP in the North Sea for which the tubular tension leg members received TSA with a penetrating sealant.

It has been published that TSA was used on the foundations of the Arkona fixed bottom offshore wind development in the Baltic, but no performance data have been released. It is understood that there are provisions for possible retrofit of galvanic anodes to these foundations should the performance of the TSA not reach expectations, and that there were some concerns regarding performance in the tidal/splash zone.

The use of TSA overcoated with organic coatings has also been promoted as a durable ‘duplex coating’ system. Some reports indicate considerable success for atmospheric exposure, but others indicate otherwise (20). Poor performance was reported in 2004 by Statoil, now Equinor (21).

The conclusions drawn from the mixed track record are that TSA may be a valuable option for parts of FOW foundations, but it is very sensitive to quality during application, more so than conventional high performance barrier coatings, and that the use when overcoated with barrier coatings may be very poor. It is suggested that further research and extensive field testing should be employed before extensive applications in FOW.

2.4 Concrete Components

2.4.1 Deterioration Susceptibility and Mechanisms

Steel reinforced concrete elements in a marine environment are subject to both deterioration of the concrete and the embedded steel reinforcement (including any prestressing tendons present). Also, unlike steel substructures, where there is no interaction between the internal and external faces of an element from a corrosion perspective, concrete is a porous and ionically conductive material, so the environmental conditions on one side of the element can have an impact on the condition of the other.

The following deterioration mechanisms are considered worthy of comment.

2.4.1.1 Alkali-aggregate Reaction (AAR)

AAR is a general term used to describe one of three deleterious chemical reactions which occurs when the alkali inherently present in concrete reacts with certain minerals in the aggregate in the presence of water causing expansion, and over time causing cracking.

In addition to the obvious effects on the structural properties of the concrete, AAR also increases the stresses on the embedded reinforcement and will jeopardise the watertightness of the element. The cracks will provide a rapid route for chlorides to access the interior of the concrete and initiate reinforcement corrosion.

There is no curative measure for AAR that would be effective in a marine environment. It may be possible to keep an affected FOW structure in service for a period, but eventually the affected turbine would need to be taken out of service. Due to the unrestricted presence of seawater, it is best avoided by limiting the quantity of reactive mineral in the aggregate.

2.4.1.2 Delayed Ettringite Formation (DEF)

DEF occurs when concrete reaches too high a temperature during the initial setting and curing phases of its life, either a result of intentional heating to speed strength gain, or because of the heat naturally evolved by the chemical reactions which occur when concrete hardens.

This exposure to heat changes some of the minerals formed during the hydration process, which over a period of years and in the presence of water, revert to what they would have been if they had not been heated; this latter process is expansive.

The effects are like AAR and if it were to occur, there is no curative measure that would be effective in a marine environment. Eventually the affected turbine substructure would need to be taken out of service. It is best avoided by limiting the core temperature of every concrete pour, which given the likely thin sections required to ensure buoyancy in most FOW concrete elements, should not be onerous to achieve.

2.4.1.3 Frost Damage

Concrete is porous and the pores contain a certain amount of water depending on the external environment. At low temperatures, the water freezes, expands and causes cracking. Unless the temperature conditions are extreme and in place for a long period of time, these cracks tend to be surface cracks only. Whilst they may cause surface scaling/erosion, on their own they are unlikely to cause any significant structural distress. However, repeated erosion of the surface will reduce the cover to the reinforcement and hence may accelerate the onset of any reinforcement corrosion.

Due to the buffering effect of the sea on air temperature, it is not anticipated that any FOW installation in the UK EEZ will be exposed to very low temperatures for any significant period, but some minor damage to horizontal saturated surfaces may occur. It can be avoided by using a high strength of concrete or adding an air-entraining admixture as well as using frost resistant aggregates.

2.4.1.4 Seawater Attack

Upon exposure to seawater, the hydrated cement can soften and disintegrate. However, any deterioration affects the first few millimetres of the surface only, so is not significant unless also combined with abrasive/erosive conditions that cause the softened material to be continually removed. The general durability of concrete is demonstrated by the extensive use of concrete within the maritime environment.

2.4.1.5 Pitting Corrosion of Embedded Reinforcement

When originally constructed steel reinforcement embedded in sound, well compacted, defect free concrete is protected from corrosion by the high internal pH levels (pH 13-14). However, when exposed to a marine environment, over time chloride ions from the seawater migrate/diffuse into the concrete and once they reach the reinforcement in sufficient levels it can result in pitting corrosion.

All elements in the upper tidal, splash and atmospheric zones are at risk if not adequately designed and constructed due to the unrestricted availability of both chlorides and oxygen. Here the corrosion products are expansive, and cracking of the concrete will generally become readily apparent before structural integrity is compromised.

Steel reinforced concrete members that are seawater immersed on both faces for a significant proportion of the time will be subjected to very low, or negligible, corrosion rates. Whilst the level of chloride contamination in the concrete can be high, due to water saturation of the pores in the concrete there is insufficient oxygen to support the corrosion reaction.

For concrete that is seawater immersed on only one side, the other being exposed to oxygen as could be the case above the internal seawater ballast level of a concrete FOWT floater, the reinforcement may be vulnerable to non-expansive corrosion of the steel reinforcement on the outer seawater exposed face. Theoretical considerations have indicated there is a risk, there has still not been any categoric evidence of it being seen on marine structures in reality, at least not that have been made publicly available, although there have been several reported incidences in tunnels.

A further possible at-risk location identified in the literature is where seawater exposed cracks intersect reinforcement, and the reinforcement is electrically connected to other steel with sufficient oxygen at the steel surface to support the corrosion (cathodic) electrochemical reactions. It has been concluded that the cathodic sites could be immersed metalwork, such as pipework and the like, or potentially reinforcement on the ‘dry’ side of a hollow element. This has been seen, on a very limited scale, in the walls of a service gallery underslung and located in the tidal zone beneath a marine jetty.

2.4.1.5.1 Pitting Corrosion of Ducted Prestressing Tendons

Prestressing tendons are also susceptible to corrosion if exposed to both chlorides and dissolved oxygen. The tendons are mostly likely to be situated within non-metallic or galvanised steel ducts cast into the concrete members which are then, after stressing, are filled either with a corrosion-inhibiting grease/wax, or, more commonly, a cement-based grout so chlorides and oxygen can only reach the surface of the tendons through the end anchorages, vent tubes (if present) and joints in the ducts if they coincide with a defective construction joint/crack in the concrete element etc.

However, if saline water enters the ducts, it can affect the tendons remote from the point of entry as the water can travel through interstices, such as the space between the individual wires which make up multiwire tendons and any voids in the encapsulation.

As corrosion develops at a location, the cross-sectional area of individual wires of each tendon reduces and at some point, will fracture, and the stresses be transferred to any remaining wires within the tendon increasing the risk of further fractures.

Where the ducts are adequately filled with cement-based grout any fractured ends will re-anchor a short distance either side resulting in the loss of prestress over only a relatively small distance. If ducts are filled with wax/grease they would de-stress over their entire length with far more serious structural consequences.

2.4.1.5.2 Corrosion-enhanced Fatigue of Reinforcement and Prestressing Tendons

As with structural steelwork, both the reinforcement and prestressing tendons are at risk of fatigue under cyclic loading at stresses lower than static ULS/ALS structural design requirements would otherwise predict, although it is generally considered less of an issue than with steel structures. However, when the reinforcement or prestressing is corroding, it becomes more of an issue due to the presence of corrosion pits.

2.4.1.5.3 Hydrogen Embrittlement of Reinforcement and Prestressing Tendons

Steel reinforcement used in the UK and Europe has a SMYS of 500MPa so the risk of HISC because of overprotection from cathodic protection (if provided) is not a concern, provided it has not been inappropriately welded. Elsewhere in the world higher grades are available and may be more susceptible.

Prestressing tendons, on the other hand, are made from high strength steel with a SMYS well above 550MPa (typically > 1500MPa) so can be susceptible, especially if already corroded. With post-tensioned construction using plastic or galvanised steel ducts the stressed part of the tendons is shielded from the applied current generating the hydrogen by the ducts, so any theoretical residual risk is further mitigated provided they are not perforated.

2.4.2 Deterioration Mitigation Technologies/Methodologies

Concrete structures can be and are designed to provide the required level of durability in a marine environment for more than the anticipated 25-to-35-year operational life of FOWT, by using standard construction materials and practice without any additional protection or mitigation. There are several concrete O&G installations that have been operating in the North Sea since the 1970s and 1980s. Whilst they are not “defect free” when it comes to durability, they have performed adequately, and since the time they were built there has been an improvement in the level of knowledge regarding both the causes and prevention of deterioration.

Durability is normally achieved through the selection of an appropriate combination of long-term low porosity concrete, with low levels of cast-in chloride, an adequate ‘cover’ thickness, and critically, the avoidance of deleterious cracks and construction defects.

Over and above the well-known issues with concrete construction, the main issues that are worthy of note are given below.

2.4.2.1 Cement Type

The cement (or binder) type used in the concrete plays a major role in the durability of concrete, with blended cements (containing materials such as Fly ash (FA), Ground Granulated Blast Furnace slag (GGBS) in addition to Portland Cement), performing better than traditional Portland Cement alone in a marine environment.

Due to the de-carbonisation of both the energy generation and iron and steel industries, the availability of these materials in the UK is becoming an issue, with FA not being available and most GGBS needing to be imported. To allow the cement industry also to de-carbonise there is also a move to use types of 'low(er)-carbon' cements, but their durability performance is not yet established. Until the durability performance of these new binders has been established, the use in a marine environment would appear a high-risk strategy.

2.4.2.2 Chloride Content

All CS and UK standards seek to limit the cast-in chloride in the concrete prior to exposure to the sea to protect against the premature onset of reinforcement corrosion. The maximum chloride level in the concrete at the time of production in all CS documents is 0.1% by mass of cement. Since the CS guidelines were first developed, environmental pressures have resulted in cement plants using alternative sources of fuel which has resulted in an increase in the chloride content of the raw cement and using unwashed sea-dredged aggregates in concrete production is standard practice in many parts of the UK.

Currently, 0.2% Cl by mass of cement is normally achievable in the UK with land-won aggregates and 0.3% for sea-dredged, but for simplicity UK standards specify 0.3% for all reinforced concrete construction.

2.4.2.3 Detailing

Although not widely referenced in standard design guides, experience has shown that certain construction details are more susceptible to reinforcement corrosion than others. Generally flat surfaces perform better than a beam and slab type construction, with the edges and corners being the vulnerable locations.

Most of the large O&G platforms constructed for use in the North Sea utilised well rounded geometry, such as large circular caissons, and many were slip formed, reducing construction joints. This is thought, at least in part, to have contributed to their longevity.

2.4.2.4 Construction Supply Chain

One of the stated benefits of using concrete over steel in substructures production is that it allows greater use of the local (to the site of operation) supply chain and resources. This can be beneficial in many respects, but it does increase the risk of inadequately trained and supervised workmanship being provided and potentially loss of the benefit of lessons-learnt from previous projects. Personnel involved may also not be aware of the issues with and requirements for ensuring durable concrete construction when operating in an aggressive marine environment and the contractual arrangements may not promote the necessary standards of workmanship.

The widespread use of sub-contracting within the UK construction industry, and movement of personnel from site to site, can also be detrimental to quality.

2.4.2.5 Concrete Production

For reliable supply and quality of the concrete a well-run modern dedicated site-specific batching plant is preferable. There will still be some variability due to changes in the properties of the raw materials and batching tolerances etc., but generally:

- a dedicated on-site plant, not providing concrete to other site/contracts, will be producing a lower number of concrete mixes, using the same materials reducing cross-contamination and gross errors (i.e., accidentally dispatching the wrong mix to the wrong site),
- a site batch plant provides more oversight of the raw materials, calibration of weighting/dispensing equipment, mixing plant set up and maintenance.

2.4.2.6 Inadequate Grouting and Sealing of Post-tensioning Ducts

Ensuring that the post-tensioning system is appropriately protected against corrosion requires competent detailing of the design, detailing, materials, and workmanship.

Anchorages are usually located in recesses that are filled after stressing. This can result in a line of weakness most likely because of shrinkage of the infilling material, allowing penetration of chlorides, corrosion of the anchor plates and general degradation of the fill material. It has been reported that during the construction of the North Sea O&G platforms, the most successful approach was to prime the anchorage recess with an epoxy bonding compound, fill the recess with either a small aggregate concrete (latex modified) using a letter-box system and then overcoating the final surface with an epoxy coating (22). If this practice were followed, but a CP retrofit was necessary to prevent corrosion, such use of epoxy could prevent CP current flow in the concrete.

For durability, post-tensioning using solid bars or groups of individual wires is preferrable compared to stranded tendons. With the latter any seawater able to enter the ducts, especially at anchorages, can travel unimpeded in the gaps between the individual wires once grouted. However, for very valid practical reasons stranded tendons may be preferred and may be the only viable option in some instances. Where ducts undulate then there is the potential for the tendon to contact the side of the duct upon stressing, so the grout is unlikely to fully encapsulate any tendon at any point of contact, leaving them vulnerable to early corrosion if chloride migrates to these locations. There is a similar effect with the interstices in stranded wire.

Post-tensioned segmental construction has been identified as a particular concern and to be avoided. The construction of new post-tensioned segmental bridges has been essentially prohibited in the UK since 1992 (23).

Vents, located periodically and at high spots in the line of any post-tensioning ducts, can play an important role in ensuring the durability by allowing any air voids/bleed water to be removed. However, after grouting they can provide a route for chloride ingress if not effectively sealed. It was once a requirement for vents to be no further than 15m apart, but this was not always adhered to and no longer appears to be a specific requirement. Present guidelines in DNV-ST-C503 are more performance-based.

The condition of the grout used to encapsulate the tendons will play an important role in limiting any corrosion that does occur if seawater or migrating chlorides are able to get into the ducts. Research carried out in the 1980s and 1990's following bridge collapses has resulted in the development of proprietary pre-bagged cement-based grouts with less bleed, no shrinkage, longer set times and higher flowability compared with the site-batched materials used previously (24).

2.4.2.7 Additional Protective Construction Measures

Whilst normal concrete construction practices can provide the required level of durability for a concrete FOWT substructure for the anticipated operational life of 25-35 years on their own, there are several additional protective measures that can be incorporated. These are primarily for use with longer service life structures (e.g., 50 years+) in aggressive environments within the wider concrete construction industry, where it is not feasible to provide an appropriate combination of low porosity concrete and concrete cover, but there are issues with them all. Options include:

- Alternative types of reinforcement – not fully proven and can be issues with fabrication,
- Controlled permeability formwork – benefit varies and not readily quantifiable,
- Corrosion inhibiting admixtures - benefit varies and not readily quantifiable,
- Surface coatings/sealants - benefit varies and not readily quantifiable, and
- Cathodic Protection – effective, but above water expensive to install and is a significant maintenance liability to maintain.

2.5 Effect of Differing Environmental Exposure conditions

2.5.1 General

The following sections set out the effect of the primary environmental parameters that affect the various forms of deterioration and the effectiveness of the identified preventative measures.

However, as will become apparent, many of the parameters are inter-related or leading to complex relationship which result in different outcomes to might be expected. Also, there are no models that can reliably relate a particular set of environmental parameters, which in any event at any specific location may vary from day to day and season to season, to a particular rate of deterioration with any proven accuracy.

To determine site specific deterioration data, particularly for steel substructures, onsite exposure monitoring would appear the logical way forward, although this is not without its challenges and limitations, not least the available timeframe to collect the data and the physically challenging environment. During the development of offshore fixed and floating bottom wind farms there will likely be masts or buoys deployed for several years prior to construction commencing to collect meteorological and metocean data and the like, but there is no evidence of the same infrastructure being used to collect site-specific corrosion data which could be used to verify/refine the default values given in CS guidance which tend to be used by default in the absence of any more site-specific data.

Information is also provided on how the major CSs relate their design requirements/input parameters to different environmental exposures/geographical locations.

2.5.2 Atmospheric Exposure

2.5.2.1 Air Temperature

Increases in temperature will increase corrosion rates of both unprotected metalwork and also steel embedded in concrete only once the environment surrounding the embedded steel is corrosive. Higher temperatures will also tend to concentrate chlorides on exposed metallic surfaces which can

have either a deleterious or beneficial effect but will shorten the period of surface wetness which is generally beneficial.

In the case of concrete structures, the rate at which the chlorides migrate through the concrete increases with temperature reducing the time to the onset of corrosion.

2.5.2.2 Time of Wetness

The proportion of the time water is present on the surface of a metallic surface will affect the rate of corrosion; the longer the time there is a layer of moisture on the surface of a steel area, the greater the corrosion. Except during periods of actual precipitation and because of seawater spray, the time of wetness is affected by the humidity of the surrounding air, plus also the temperature of the surface. The time of wetness is also affected by any hygroscopic surface contaminants, such as salt, present on the surface in question.

As concrete is a porous material, a proportion of any moisture that forms on its surface will be absorbed into the body of the concrete increasing the rate of ingress. The increased presence of water will also increase the speed of any AAR or DEF that may occur.

2.5.2.3 Contaminants

In a marine environment, all surfaces are subjected to the deposition of solid and liquid contaminants; primarily salt particles/droplets. Both wind (direction and velocity) and rain play a major role in the rate of deposition and removal.

Any steelwork not protected by a surface coating will be negatively affected by the presence of contaminants and in the case of concrete construction, the increase in surface concentration increases the rate at which the chlorides diffuse into the concrete and hence reduces the time to the onset of reinforcement corrosion.

For North Sea concrete O&G structures, it has been seen that the chloride concentration on surfaces facing southwest were approximately twice that of surfaces facing other directions (25).

2.5.2.4 Rainfall

On metallic surfaces rainfall will generally wash chlorides off the surfaces, thereby reducing corrosion rates generally, but it may result in them being concentrated in horizontal surfaces below and in crevices, worsening the corrosion at these locations.

For concrete surfaces, regular rainfall will tend to reduce the surface chloride concentration, therefore slowing down its diffusion in the concrete and delaying the onset of corrosion, but will accelerate any AAR/DEF.

2.5.2.5 UV Radiation

UV radiation increases the temperature of both metallic and concrete surfaces over and above that of the ambient air temperature. This increase can result in increased corrosion rates and concentrate chlorides on exposed metallic surfaces but can also shorten the period of surface wetness.

UV radiation can also cause the deterioration of organic barrier coatings. Epoxy resins are not UV resistant in themselves, although formulations will likely contain a UV resistant additive. This additive provides a degree of protection, but a better outcome is usually provided by applying a UV resilient polyurethane topcoat which are inherently UV resistant.

2.5.3 Immersed Exposure

2.5.3.1 Water Salinity

Corrosion rates in seawater and brackish waters vary only marginally within the range of salinity found in practice. The corrosion rates vary within the full range of salinity by < 30%, but they peak near the salinity of typical ocean seawater. Typical ocean seawater is ca. 3.5% NaCl; the Northern Baltic is ca. 0.7% NaCl. Salinity does not vary significantly with depth.

2.5.3.2 Water Temperature

Overall increases in temperature will decrease the corrosion rates of unprotected metalwork underwater as it reduces the amount of dissolved oxygen in the water. Increasing temperature also improves the quality and ease of formation of protective calcareous deposits (see below), such as when a CP system is operational.

Water temperature changes with depth and whilst the substructure itself will be exposed to surface temperatures, the station-keeping system will experience the full range in temperature, from that at the surface through to that on the seafloor, which is generally colder.

2.5.3.3 Scale-forming Minerals

Seawater contains both dissolved calcium, magnesium, and bicarbonate ions, which can form in-situ protective scales on both steel and concrete surfaces, generically termed calcareous deposits. In the case of steel surfaces, it is a result of the alkalinity produced through cathodic protection and in the case of concrete due to their reaction with the internal alkalinity in the concrete which is leached out.

2.5.3.4 Dissolved Oxygen

The dissolved oxygen content in seawater varies with temperature, salinity and water depth; low levels of dissolved oxygen result in lower corrosion rates and also decreases the current densities required for CP protection. However, a certain level of dissolved oxygen is needed to ensure the corrosion resistance of certain CRMs, such as stainless steel, is maintained, although low oxygen levels will reduce the rate of any resulting corrosion.

The above relationships are applicable to open seawater. In fully, or partially enclosed, compartments, corrosion rates of carbon steel may reduce with time as oxygen is depleted.

2.5.3.5 Velocity

In low flow rate (velocity) conditions in seawater, uncoated carbon steel corrodes an average rate of approximately 0.13mm/year, with localised pitting at about twice the average rate. However, under the high flow conditions, which increase oxygenation at the metal surface, higher rates of corrosion will occur. Corrosion rates of >0.8mm/year have been reported at 5.5m/s flow rate in seawater (26).

2.5.3.6 Suspended Matter

If there is a combination of suspended solids, such as fine sands, and high velocity, the corrosion rate will increase as the abrasion of the surface disrupts otherwise semi protective corrosion products. If cathodic protection is being applied, the protective calcareous deposits may also be disrupted thus increasing CP current demand. It may also, in extreme cases, damage barrier coatings on metalwork and the surface of concrete.

2.5.3.7 Marine Growth

Immersed steel corrosion rates are affected by marine growth. Corrosion under marine growth, without CP, can be both increased (by marine growth that damages protective coating, and by aggressive secretions from, particularly, hard marine growths) or alternatively can be reduced by reduction of the water flow rates proximate to the steel surfaces. Partial coverage of surfaces may increase localised corrosion rates under the fouled surfaces due to oxygen concentration cells.

2.5.4 Treatment of Differing Environmental Conditions on Corrosion Protection/Durability Measures in CS documentation

2.5.4.1 Metallic Elements

2.5.4.1.1 Corrosion Allowance

The various CS requirements do require different corrosion allowances to be used based on the exposure category for the part of the substructure being considered (e.g., Atmospheric, Splash, Submerged zones etc).

Over and above this, and although adopting slightly different systems/descriptions, the corrosion allowances set out in all the major CS documentation, where given, at best only differentiate between broad climatic zones, such as temperate, sub-tropical, tropical etc. Under all the various categorisations the UK EEZ is always classified within the temperate climatic zone and consequently the same corrosion allowances would apply for both the Celtic and North Seas.

2.5.4.1.2 Coatings

The specifications for coatings provided in the rules of all the major CSs reviewed do not amend their guidance or requirements based on geographic location, with requirements only differing depending on the exposure category for the part of the substructure being considered (e.g., Atmospheric, Splash, Submerged zones etc).

2.5.4.1.3 Cathodic Protection

DNV-RP-B401 historically is arguably the most widely used marine CP design code and considers the effect of different environmental conditions (temperature, dissolved oxygen and calcareous scale forming ability) by providing recommended design current densities for steel structures as a function of depth and climatic region based on an, assumedly mean, surface water temperature. It also requires seawater resistivity, if not directly measured, to be based on water temperature and salinity. Under these groupings, substructures in both the North and Celtic Seas would utilise the same design current densities, and the only variable would be small changes is water resistivity as a result primarily of small differences in mean water temperature.

BV-NI-423 differentiates between design current densities in terms of geographic region, and from the perspective of the UK EEZ it differentiates between those areas above 62°N (above a line approximately level with the Faroe Isles), between 62°N and 55°N (above a line level with Newcastle), and below 55°N It is believed that there are no plans to use areas north of 62°N for FOWT, but any site in the North Sea above Newcastle would have different requirements from those below and also in the Celtic Sea.

The recently published ISO 24656 provides CP current density data divided into the same climatic regions as those found in DNV, but thereafter places far more focus on metocean data and, in

particular water velocity. Design differences will be apparent between sites even in the same nominal area.

2.5.4.2 Steel Reinforced Concrete Elements

None of the design documents relate durability/corrosion of embedded steel to the environmental conditions and make any allowance for differing environmental effects (other than the differentiation between submerged, splash, spray, and atmospheric exposure). Hence the CS requirements for corrosion mitigation and durability do not differ between the North and Celtic Seas.

2.5.5 Comparison of Environmental Conditions in North and Celtic Seas

The data indicate that there are only minor differences between the conditions in the Celtic and North Seas, probably the difference in tidal velocities being the most significant. However, the differences are such that it is not believed that it would result in an entirely different approach to corrosion mitigation being required or being stipulated under CS requirements.

There will likely be some difference in aggressivity between the two sites and it is expected that for steel substructures, corrosion may be marginally greater in the Celtic Sea than in the North Sea primarily due to the increased tidal flows. However, and as stated previously, the impact of many of the parameters on deterioration are complex and inter-related, with there being no models that can reliably relate a particular set of environmental parameters into deterioration rates. The level of granularity set out in the various primary CS design requirements also would not currently require different design values to be adopted. To quantify any difference with any certainty it would need to be assessed via on-site testing, at the same time as metocean and metrological design data is collected.

The one exception to the above though is in the detailed design of CP systems to ISO 24656. Whilst other commonly used standards only base the design input parameters based on broad geographical location, ISO 24656 considers metocean data in detail, so it is likely that higher capacity CP systems will be required in the Celtic Sea than those required for the North Sea.

3 WHOLE LIFE COSTING

3.1 Introduction

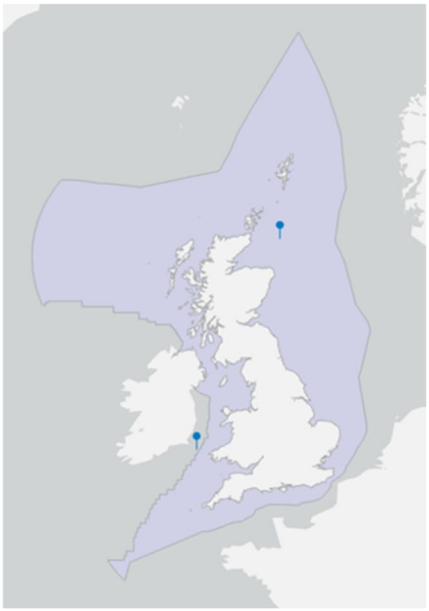
This section comprises the findings of a WLC exercise to compare various approaches to CS code-compliant corrosion protection scenarios for a generic steel semi-submersible floating substructure. Also provided is a commentary on the reliability issues associated with the different forms of corrosion protection and their impact on the WLC.

3.2 Scenarios

The assessments were based on a theoretical ~1GW floating wind farm comprising 67no. 15MW generic four column central tower floating steel semi-sub substructures with an operational design life of 30years. Two reference locations, as shown in Table 1, were considered.

Table 1: Reference Site locations

Parameter	Northern North Sea	Celtic Sea
Water Depth Average (m)	109	96
Distance to O&M Port (km)	85-105	50-70
Distance to Construction Port (km)	175-195	50-70



The evaluation considered the exterior part of the substructure only; consequently, the following components were not included within the assessment:

- the turbine or its tower,
- internal compartments of the substructure,
- the station-keeping system (anchoring device and mooring lines),
- the inter-array power cable(s).

The analysis considered the ‘above’ and ‘below’ the still waterline parts of the substructure separately to recognise the characteristics and challenges of maintaining corrosion protection of the two different environmental exposure regimes. Whilst coatings extend both above and below the still water line, and CP will provide some partial protection above, for the purposes of this assessment and allocation of costs, the dividing line between the two was taken to be at the still water level.

For above the still waterline, three different generic coating systems suitable for use in the atmospheric and splash zone were considered.

For below the water line, a variety of combinations of cathodic protection and coatings were considered.

3.3 Sources of Data

All input data used in the analysis was obtained from one of the following:

- public sources,
- delivery team knowledge
- discussion with industry contacts, and, in extremis,
- "order of magnitude" engineering judgement.

NB: Given the state of maturity of the floating offshore renewable energy industry and commercially sensitivity around cost data, there is uncertainty around the accuracy of some of the input data used in the analysis. Whilst it is believed that the findings are sufficient to identify at a high level the likely lowest WLC option, they cannot be relied upon, and organisations should carry out their own specific assessment of costs and performance / reliability prior to making any commercial decisions.

3.4 Methodology and Assumptions

The assessment adopted a probabilistic approach to whole life costing using a Monte-Carlo simulation to make an allowance for uncertainty in both current and future costs and intervention periods and extents.

All costs were current day values and costs incurred in the future were discounted at a standard rate of 3.5% per annum. NB: Future costs were not increased to allow for cost inflation.

The assessment considered initial Capital expenditure (CAPEX) and both reactive and planned OPEX costs, including transportation of the structure back to an appropriate port where required in the scenario under consideration and the associated loss of energy generating revenue for the time the sub-structure is off station. The following definitions/categories were adopted.

It was considered likely that in the case of planned works, and non-urgent reactive works, the works would be programmed/grouped such that multiple activities would be undertaken at the same time allowing transportation costs to be "shared" across the different activities (i.e., turbine/mast maintenance or mooring line maintenance). As it cannot be predicted how an individual organisation will programme their work activities, the full transportation costs were included in the assessment but itemised separately so that they could be reduced by others if considered appropriate.

Table 2: Definition of cost categories and types

Cost category	Cost type	Definition
CAPEX	Work	All costs associated with initial provision/installation of coatings and CP
Programmed OPEX	Work	Programmed works such as minor onsite repainting works and CP performance monitoring
Programmed OPEX	Transport	Transportation costs associated with undertaking programmed works (i.e., accessing the FOWTs)
Programmed OPEX	Lost Revenue	Loss of revenue due to electricity supply requirements of operational ICCP system
Reactive OPEX	Work	Reactive works, such as rectifying ICCP component failures and major repainting off station
Reactive OPEX	Transport	Transportation costs associated with undertaking reactive works
Reactive OPEX	Lost Revenue	Loss of revenue when FOWT is disconnected from the substation undertaking reactive works requiring a return to shore*
Notes: * assumes the turbines which remain on station are still connected and are generating electricity		

3.4.1 Above Water

In all scenarios it was assumed that the area from still water to the top of the splash zone was coated with a current Norsok M501 7A/ISO 24656 Type V coating (2 x 500µm dft. glass flake epoxy/polyester). Above this line, the following coatings were assumed:

- High durability – ISO 12944 CX /Norsok M501 1A coating (2 x 150µm dft. epoxy), or
- Very High durability - ISO 12944 CX /Norsok M501(2012) 7A coating (2 x 300µm dtf. epoxy) and
- Very High durability - ISO 12944 CX Norsok M501(2022) 7A coating (2 x 500µm dtf. Glass flake epoxy/polyester)

Five yearly programmes of onsite maintenance coating were included, but with repairs only to the areas above the top of the splash zone. The duration of work on each sub-structure was longer for the ‘High’ durability coating than for the ‘Very High’ durability coating. It has been assumed that minor maintenance coating repairs would be undertaken on station.

It was assumed that major maintenance repainting above the water line (for the ‘High’ durability coating only) would be undertaken off-station with the FOWT being removed to a major maintenance port. Whilst transportation costs and loss of electricity generating revenue were considered, no allowance was made for costs incurred from the use of a major maintenance facility, if not already owned by the FOW farm operator. The proportion of the above still water area to be recoated during major maintenance was assumed to be >10% of the relevant surface area.

3.4.2 Below Water

For all 'below the still water level' scenarios the corrosion protection strategy comprised CP protection with, for most scenarios, the use of coatings.

It was assumed in all scenarios that the area from still water down to the bottom of the splash zone was coated with a current Norsok 7A/ISO 24656 Type V coating (2 x 500µm dft. glass flake epoxy/polyester) and below that either:

- No coating,
- An ISO 24656 Type III coating (2 x 175 µm dft. epoxy),
- An ISO 24656 Type IV coating (2 x 300 µm dft. epoxy), and
- in some scenarios only, an ISO 24656 Type V coating (2 x 500 µm dft. glass flake epoxy).

The scenarios assumed cathodic protection was provided by either aluminium alloy GACP, or ICCP using Mixed Metal Oxide (MMO) coated titanium anodes.

The costs for the cathodic protection were based on Front End Engineering Design (FEED) level designs specific to each of the two reference locations. All designs were in accordance with ISO 24656 for both galvanic and impressed current systems and for the system design lives (15year and 30year).

It was assumed that any required renewals/upgrades of those CP systems with a system design life of 50% of the substructure design life would be undertaken off-station with the FOWT being removed to a major maintenance port. It was assumed that it would be necessary to dry dock the substructure so that any necessary welding can be undertaken in the dry. Transportation costs and loss of revenue were included in the cost estimate, and an order of magnitude estimated cost was made for drydocking the substructure. However, no costs associated with the use of the major maintenance facility has been allowed for if not already owned by the farm operator and therefore is payable.

Under all scenarios it was assumed that no recoating of the underwater section part of the floating substructure would be undertaken, even if taken off station and out of the water for major maintenance.

In the case of the ICCP systems the FEED designs were intentionally high specification to try and minimise as far as is practicable the ongoing maintenance requirements. This had an inevitable impact on the CAPEX cost and if compared to impressed current systems which may be present on existing facilities, may be expensive in comparison. For limited scenarios the likely WLC of a 'higher end' industry-norm ICCP system was estimated to allow the impact of increased maintenance works to be evaluated and for comparison against the equivalent GACP system. It would be expected that any experience with 'lower end' industry-norm ICCP systems will have resulted in lower CAPEX and higher OPEX than the estimates used here. Very little information is available in the public domain on ICCP systems used in the offshore renewable sector.

3.5 WLC Findings

The average whole life cost is given in the following sections in discounted terms along with any necessary commentary on the practical feasibility of the scenario.

3.5.1 Above the Waterline

The scenarios evaluated and their WLCs are as listed in Table 3 and shown graphically in Figure 13.

Table 3: Above water WLC scenarios

Scenario Ref	Location	Coating above upper limit of splash zone	Mean Discounted WLC
A1	Northern North Sea	High durability (Norsok 1A)	£82.4M
A2		Very High durability (Norsok 7A 2012)	£49.8M
A3		Very High durability (Norsok 7A 2022)	£71.0M
A4	Celtic Sea	High durability (Norsok 1A)	£77.9M
A5		Very High durability (Norsok 7A 2012)	£49.6M
A6		Very High durability (Norsok 7A 2022)	£71.1M

The results indicate that for both the Celtic and Northern North Sea reference locations, the lowest whole life cost option (highlighted in bold) is the one which minimises on-site maintenance and removes the need to return the sub-structures to shore for major maintenance repainting.

It is understood that there is some debate within the industry whether a Norsok M501 7A:2022 system will actually provide improved performance above the waterline over the previous (2012) requirements, but assuming a worst case scenario that there is no actual improvement (and therefore no reduction in the need to carry out on-station minor maintenance), it is still less expensive than having to disconnect each turbine in turn, tow it to a suitable port and undertake major coating repairs as anticipated with a 'High' durability system.

If the onshore works associated with using a 'High' durability coating were combined with other activities then it can be argued that the allocated transportation costs can be reduced, but it is still anticipated that for H&S and planning reasons most activities will have to be carried out sequentially and therefore the cost associated with loss of generation revenue for the repainting works would not be reduced.

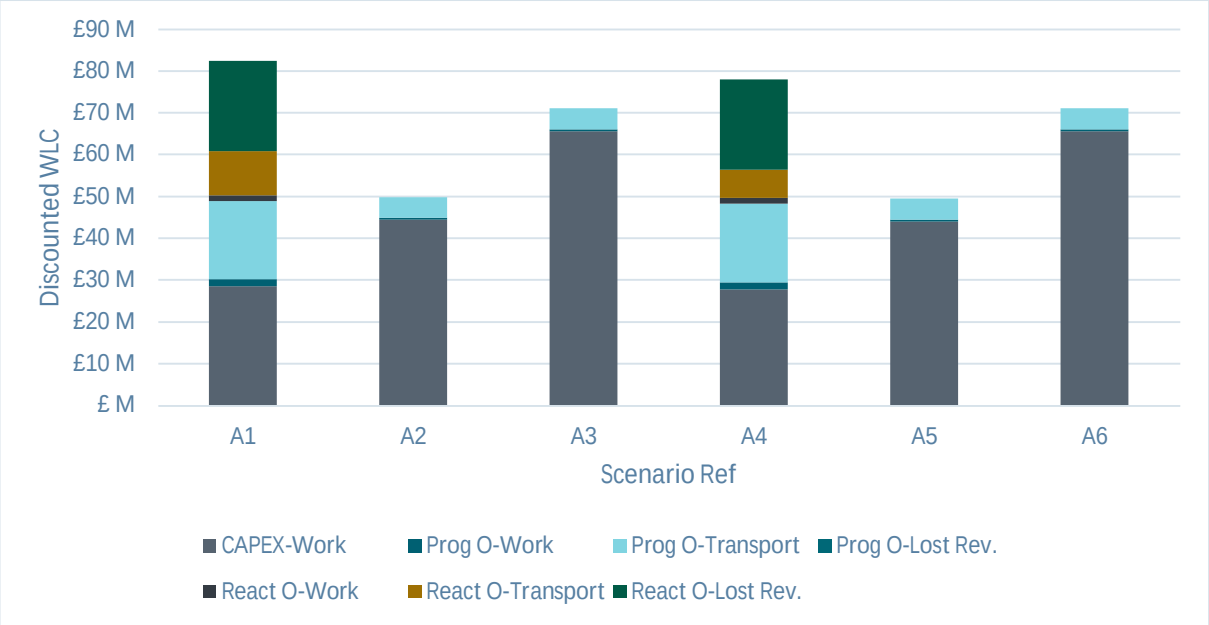


Figure 13: Mean discounted WLC for above water scenarios

3.5.2 Below the Waterline

The results of the WLC assessment for the 'below the still water line' scenarios are presented in Table 4 with the lowest cost scenarios highlighted in bold. The costs for those scenarios considered both feasible and logical are also presented graphically in Figure 14, with the costs broken down into the different cost categories.

Table 4: WLC of below water scenarios

Scenario Ref	CP type	CP Design Life	Location	Coating below lower limit of splash zone	Mean Discounted WLC	Comments
B1	Galvanic CP	15	Northern North Sea	None	£71.1M	Number of anodes not practically feasible¥/Not logical*
B2				Category III	£101M	Not logical *
B3				Category IV	£111M	Not logical*
B4			Celtic Sea	None	£84.3M	Number of anodes not practically feasible¥/Not logical*
B5				Category III	£109M	Not logical*
B6				Category IV	£113M	Not logical*
B7		30	Northern North Sea	None	£71.1M	Number of anodes not practically feasible¥
B8				Category III	£72.6M	
B9				Category IV	£88.2M	
B10				Category V	£123M	
B11			Celtic Sea	None	£84.3M	Number of anodes not practically feasible¥
B12				Category III	£79.9M	
B13				Category IV	£92.2M	
B14				Category V	£125M	
B15	Impressed Current	15	Northern North Sea	None	£180M	Number of anodes and PSUs not practically feasible¥/Not logical*
B16				Category III	£209M	Not logical*
B17				Category IV	£181M	Not logical*
B18			Celtic Sea	None	£191M	Number of anodes and PSUs not practically feasible¥/Not logical*
B19				Category III	£211M	Not logical*
B20				Category IV	£214M	Not logical*
B21		30	Northern North Sea	None	£180M	Number of anodes and PSUs not practically feasible¥
B22				Category III	£174M	
B23				Category IV	£187M	
B24				Category V	£222M	
B25			Celtic Sea	None	£191M	Number of anodes and PSUs not practically feasible¥
B26				Category III	£183M	
B27				Category IV	£191M	
B28				Category V	£224M	

¥ Note that the difference is anode quantity and costs between the North Sea site and the Celtic Sea site are due to metocean data, higher water velocities and higher CP current densities.
* The 'not logical' comment is based on the assessment that the very significant costs of dry docking/breaching vs. the minimal theoretical cost saving in the size of WLC of the installed CP system, see main text for more explanation

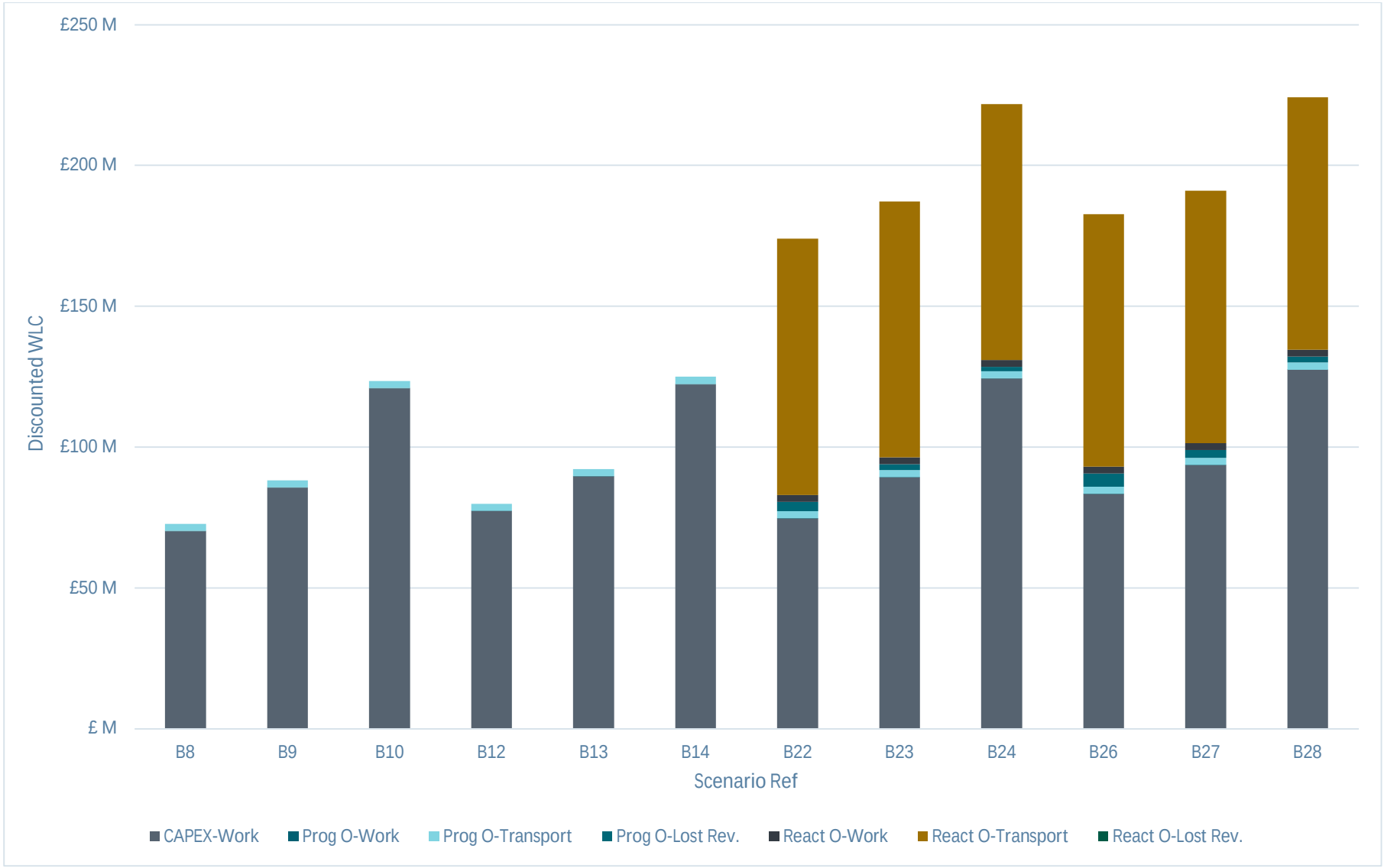


Figure 14: Mean discounted WLC for below water scenarios

Whilst WLCs have been calculated and are reported for all the scenarios considered, a number are considered not to be practically feasible. These are all scenarios where the area below the splash zone is uncoated. In these incidences, the number and mass of galvanic anodes or number of impressed current anodes and PSUs is large and the effect on the sub-structure is considered unacceptable[1].

For all scenarios where the design life of the CP system (as opposed to that of the structure) is 15 years, returning the sub-structure to land and upgrading the CP system does not appear logical. In all these incidences, the size of the CP system (both galvanic or impressed current) is dependent on the 'final' current demand, and such is heavily dependent on the coating breakdown factor at the end of the CP system design life. This results in the design at the end of the second 15year period being practically the same as the end of the comparable 30year design life scenario. As such the only benefit of this two-stage approach is to delay a part (<50%) of the initial CAPEX expenditure and take the benefit of the 3.5% discount rate on that amount. However, on the opposing side the cost of bringing each turbine back to shore, dry docking and then installing the additional works is far more significant. Furthermore, and from a more practical perspective, retrofitting additional current capacity so that uniform protection is achieved both in phase 1 (the first 15-year period) and phase 2 (the second 15-year period) is unlikely to be straightforward. In developing the WLC for these cases, the Phase 2 system cost has been assumed to be the difference between the cost of the 15year design life and the 30year equivalent, but it is likely to be greater due to loss of economies of scale and the likely need to amend the first phase installation[2].

Of the remaining scenarios considered to be both logical and feasible, then the lowest WLC cost is for a galvanic anode system, designed for the full 30year substructure design life where the permanently submerged parts are coated with an ISO 24656 Category III coating. It is noted that for fixed bottom offshore wind monopile (MP) structures, experience may be different in that CP current and voltage attenuation from anodes to remote steel, which is important in reducing the number of anode cages on MPs, may lead to Category IV or V coatings being necessary for lowest WLC. This does not apply to FOW.

The reduction in anode quantity and costs between Category III, IV and V coatings are due to their increasing durability (higher electrical resistance, for longer periods) and the reduction in CP current densities due to this.

Whilst the increased performance of the coating reduces the size/capacity of the CP system, the validity of this assessment is highly dependent on the relative costs rates for the application of the various coating types. A sensitivity analysis indicates that the difference between the rate for the Category III and a Category IV coating would need to reduce from the currently assumed £35 per sq. m down to £18 per sq. m. for a Category IV coating to become the lowest cost option. For a Category V coating to result in a lower WLC than a Category IV, the difference in rates would need to reduce from the assumed £56 per sq. m to £8 per sq. m.

As stated previously the FEED ICCP designs prepared for this study are intentionally high-specification with the aim of reducing the OPEX maintenance liability, but as a result they are anticipated to be substantially more expensive than what would likely be the industry-norm, when the system is

[1] The assessment regarding feasibility has been made on a qualitative basis by the report authors based on perceived practicality. It is possible that a more stringent requirement may be necessary based on the Naval Architecture requirements and this may override the current assessment.

[2] The costs presented for the CP 15year design life options include both the phase 1 and phase 2 works, i.e., for the full 30year design life of the substructure.

procured based on lowest CAPEX cost. In order to investigate this, the WLC of an assumed 'higher end' industry-norm 30year ICCP system for the Celtic Sea location has been calculated (Scenario Ref B26a), assuming the CAPEX cost being 50% of the FEED design but with a higher component failure rate, based on author expectations. The outcome of this assessment is that due to the cost of access, a higher CAPEX cost but with greater reliability ICCP system has a lower WLC (Mean discounted WLC of £183M vs £197M), but this is still higher than an equivalent GACP system (Mean discounted WLC of £79.9M), see Figure 15.

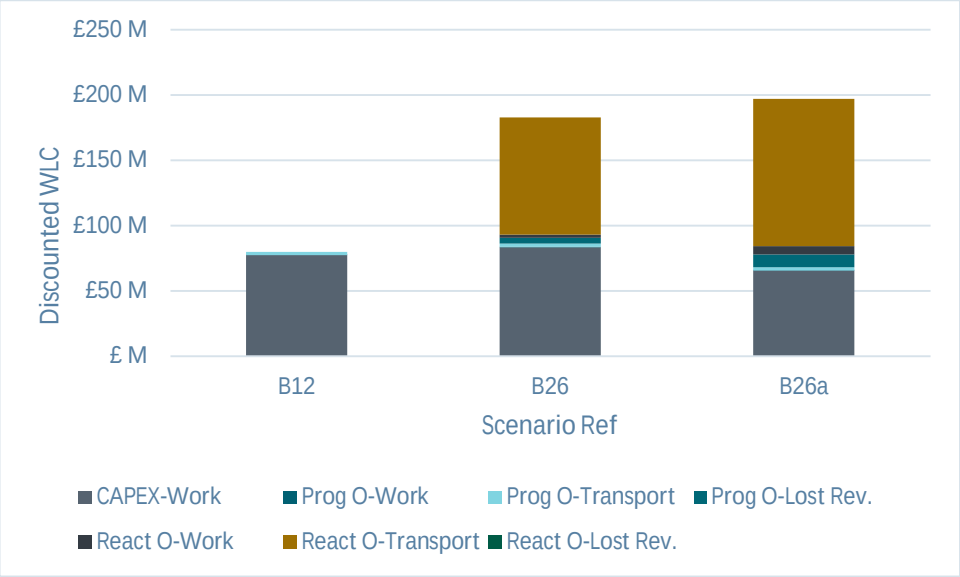


Figure 15: Mean WLC comparison of Celtic Sea, Cat III coating 30yearDL GACP and "ISO compliant" and "high end industry norm" ICCP systems

The 'ISO 24656 compliant' ICCP system was designed for high reliability and resilience in performance, by way of modular multiple power supplies (proven for reliability over >25 years in other CP applications) and proven ship hull mounted anodes. These utilise through-hull entries with ship proven cofferdams and all cables are managed inside the main tubulars.

Reference electrodes, necessary to control the CP system current output are similarly mounted with internal cables. Unlike existing commercial systems, but in accordance with ISO 24656, they are proposed both close to and remote from anodes to detect and avoid both under and over protection. All these differences from existing and ISO compliant CP systems add significant cost but are considered essential to provide reliability.

The 'industry norm' ICCP system is based on one proposed by a relatively new entry into the market with limited track record. However, it was judged that their system would likely be more reliable than may have been installed on fixed bottom turbine structures (where at least in one farm it was reported that around 20% of all systems need maintenance during each year, with each visit taking some 6months to arrange). The system considered has more anodes (for some degree of redundancy) and more reference electrodes (some remote from the anodes, to detect and prevent under-protection) than this company would normally offer, but this was considered necessary by the authors to deliver competent (if not fully reliable) ICCP.

Based on the assumptions made, whilst the CAPEX cost of an "industry-norm" ICCP is less than the equivalent GACP system (for the ICCP alone, £18M over the entire farm vs £29.9M) much of the benefit is lost once the cost of the electricity needed to power it is considered (which is approx. x2 greater than the 'ISO compliant' equivalent due to the smaller size of the anodes and hence higher

required DC operating voltage). The analysis suggests that once the electricity usage has been factored in, the industry norm ICCP option is within 10% of the equivalent GACP WLC (£27.6M vs £29.9M for CP alone; £77.2M vs £75M for CP and below water coatings), leaving little to offset the cost of maintenance that will inevitably be required of the ICCP system, see Figure 16.

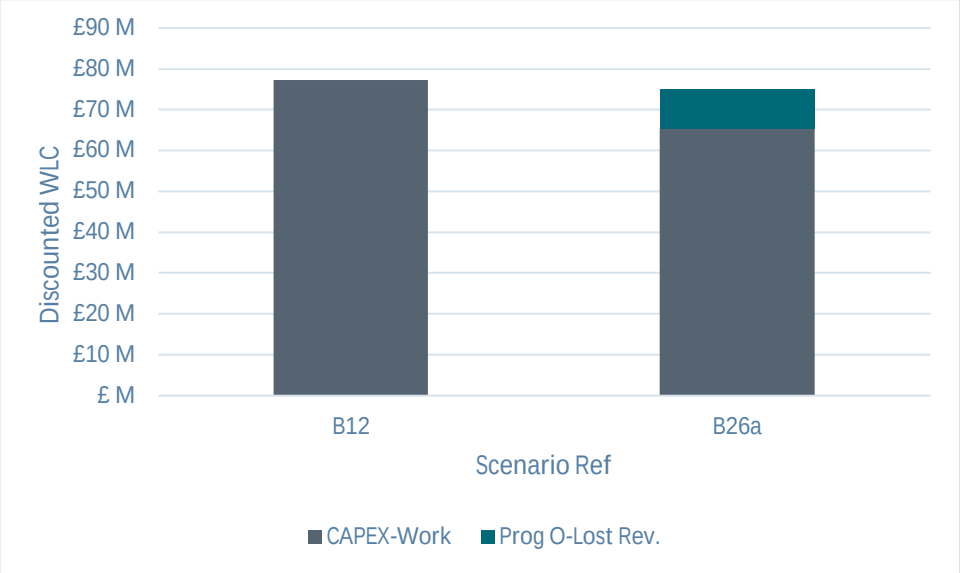


Figure 16: Sample CAPEX and Electricity consumption only WLC cost comparison between GACP and 'industry norm' ICCP

3.6 Commentary on Durability and Reliability

OPEX costs are highly dependent on the durability/reliability of the installed works. Assumptions as to durability and reliability of the various corrosion protection measures are included within the WLC assessment, but a wider commentary is provided below.

3.6.1 Barrier Coatings

Due to commercial sensitivity, there is very limited information in the public domain regarding the performance on barrier coatings in practice on offshore wind farms.

Anecdotally, however, there are indications that properly applied marine coating systems currently in use are generally adequate, at least thus far, with most reported damage being as result of impact, such as from service vessels mooring against the structures rather than deficiencies in the coatings themselves.

Where problems are expected to manifest themselves in time are, not surprisingly, likely to be in the splash zone. It would seem likely in the case of FOWT, points where mooring lines come aboard and terminate will also likely be high risk locations when they are above the water line. Both locations will be hard to protect using coatings alone.

3.6.2 Cathodic Protection

3.6.2.1 Galvanic Anode Cathodic Protection

In the early days of offshore oil and gas development there were failures of galvanic anode design and manufacture. These issues were largely resolved by the 1980s.

Due to their simplicity, if properly designed and installed, they are now extremely reliable and require no maintenance, requiring only periodic performance assessment. In the event one or two

anodes were to be lost in service, say, because of impact with a service vessel the effect on the level of protection will be minor as the remaining anodes, which in a good design would be distributed over the surface of the structure, will automatically output more current to compensate, with just a small reduction in overall service life.

Some failures/issues have occurred in MP fixed foundation offshore wind developments in more recent times, which were design related, but the issues are well understood and have been addressed in ISO 24656.

3.6.2.2 Impressed Current Cathodic Protection

Many historic ICCP failures have been structural failures of anodes or cable management systems. Others have been failures of power supplies, control systems, reference electrodes and anodes.

Table 5 provides a summary of the consequence of failure of the component and the remedial measures likely to be required.

Table 5: Consequence of ICCP component failure

Failure of	Consequence	Likely Remedial measures
AC LV power supply, incl local circuit breaker trips or fuse failure	No corrosion protection to entire sub-structure until rectified	Electrician to attend site to fault-find and replace failed component or reset devices as appropriate
DC power supply	No corrosion protection of that part of the structure protected by the failed unit (some residual protection may be provided by adjacent anodes supplied by other power supply units)	Electrician to attend site to fault-find and replace failed component. Repeat visits may be required to detect, source and fit failed component. Electrician may require specific CP PSU training
Anode	Loss of protection to the part of the structure being protected by that anode (some residual protection may be provided by adjacent anodes supplied by the same and other power supply units)	CP technician to attend site with diving team to fault-find and replace failed component, potentially also replacing the cabling length back to a suitable “dry” connection point.
Reference electrode	Unable to establish whether corrosion protection at a location is optimal	CP technician with diving team to fault-find and replace failed component, potentially also replacing the cabling length back to a suitable “dry” connection point.
SCADA system	Unable to establish whether corrosion protection at a location is optimal	Electrician/SCADA technician to attend site to fault-find and replace failed component. CP technician to attend site periodically until SCADA system is rectified to manually adjust CP system

The most common anode material for marine applications, at present, is titanium coated with mixed oxides of ruthenium, iridium, and titanium (MMO), known as MMO/Ti. Different compositions of MMO are consumed at different rates and generate different amounts of chlorine gas. Differing

surface treatments of the Ti dictate the adhesion and durability of the coating as does the different deposition practice of how manufacturers deposit MMO. Some manufacturers will not disclose details of these. Some present detailed accelerated life test data from their own testing and there is an industry standard accelerated testing method (27).

The positive (+ve) side of the CP system, the cables from the power supplies to the anodes and the connections to the anode themselves, can suffer from rapid and catastrophic failures if insulation is less than perfect and DC current is discharged from copper conductors or other consumable elements.

Coating damage is likely if steel/seawater potentials are more negative than -1.10V with respect to Ag/AgCl/seawater reference electrode. It is unlikely that over- protection, with potentials more negative than -1.10V will generate any significant hydrogen embrittlement risk in the normal S355 steels, unless welding procedures have been poor and there are high hardness areas associated with welds. However, it is extremely poor practice to permit excessively negative potentials beyond the limit in the standards and there is some evidence that fatigue life can be adversely affected. Coating deterioration with associated deterioration in attenuation of CP current and protection levels remote from anodes will be a likely outcome.

Reference electrodes can be vulnerable to failure; ICCP systems without accurate functioning reference electrodes are 'flying blind' and unable to respond to short or long term metocean changes. Some power supply systems respond to such failures by reverting to maximum current output, with significant risks of over-protection and resultant damage.

Historically, the track record of impressed current systems has not been good with practically all standards warning to various degrees against their use, for instance:

- DNV-RP-0416 states "Even with adequate design, ICCP systems are more vulnerable to environmental damage and third-party damage than GACP systems, in particular cables to anodes and reference electrodes are vulnerable".
- ISO 24656 states that the system "will not function if there is either a loss of electrical power or damage to the connecting cables or reference electrodes, or both" and highlights the risks and costs on unmanned facilities "from a non-functioning CP [system] in cases of power failure, fuse or circuit breaker trip activation, reference electrode failure, electrical or software failure and anode, or cable failure". The point is also made that "there is a risk of system failure as a result of lightning events where the anodes act as part of the earthing system through the power supplies".

The biggest challenge for ICCP systems is that FOW devices will be un-manned, and failures or faults will require costly transfers of specialist staff, possibly firstly to assess and then to return with spare parts or replacements. There is very little documented quantitative data on the actual failure rates of the various components in modern CP systems in a marine environment. Manufacturers of power supplies quote figures like 0.7% failure rate per annum, but some organisations who manage these systems quote 20-25% of the systems at any one time having some component having failed and needing replacement and that such repairs can take 6 months to plan and undertake. Limited reports of recent ICCP systems for offshore wind developments are consistent with this past track record experienced in the O&G sector, which had the advantage that that those platforms were generally permanently manned.

Aside from the obvious maintenance liability the consequences of a non-operational CP system are more likely to influence the fatigue performance of the structure, rather than ULS or ALS

performance. Due to the inherent factors of safety in the structural design process, the likelihood of an actual fatigue failure is low unless the CP system were non-operational for an extended period (probably extending into years), and the issue may be more with the calculated fatigue design life and justifying to the relevant CS that the original calculated fatigue life remains valid.

4 SUMMARY

Due to the level of maturity of the industry and commercial sensitivity, FOWT-specific field experience related to Corrosion Protection and Management is not available, but there is no reason to indicate that the types of corrosion/durability related deterioration experienced by FOWTs will be materially different to that which has been experienced within the general offshore sector for many years, including floating steel and concrete O&G platforms and fixed bottom offshore wind substructures. This is on the proviso that that the substructures are designed to current relevant CS documentation and constructed to a similar level of workmanship to that which has been historically adopted.

With the above in mind, the most appropriate corrosion mitigation strategy considering the anticipated service life of a FOWT of 25-30 years is expected to be:

- For steel substructures: Cathodic protection and organic barrier coating of external and internal surfaces, plus appropriate corrosion allowances at specific sensitive areas,
- For concrete substructures: Primarily normal construction practices, with measures put in place to ensure construction quality matches the design intent, although with potentially:
    - galvanic CP being applied to the immersed parts if the design of that part is fatigue critical, and
    - the application of a protective coating on the atmospherically exposed site faces, mainly for marine safety purposes but also providing additional resistance to chloride ingress.

No new or innovative measures in development have been identified which have the potential to change the current approaches either generally across the marine sector or specific to FOWT. All the existing approaches have been used generally successfully over many years (and in any event are mandated by all CS). Any reduction in corrosion related costs, is likely to be through the optimisation and tailoring of the current approaches to the specifics of FOWT.

Based on a review of the environmental conditions in the North and Celtic Seas, whilst there may be modest actual differences in the corrosivity between the two locations, it is beyond the granularity of current knowledge and the guidance given in the appropriate design standards. The actual differences could only be determined through site-specific long-term (approx. 1 year) pre-construction corrosion surveys (in a similar way to metocean and wind data is currently collected), but that is only likely to provide material benefit if the design of the specific element under consideration is not fatigue-life driven, and any deviation from CS requirements are acceptable. The only exception to the above is in the design of CP systems. Up until recently all commonly used CP design codes adopted an approach which would not have resulted in a material difference across most of the UK EEZ, but with the introduction of ISO 24656 site specific metocean data is used and so differences in water currents, wave heights and water temperature all have an effect. However, this should be to the betterment of the industry by providing a greater certainly that CP systems will provide the required level of protection for the required design life.

A WLC assessment undertaken suggests that GACP on a fully coated structure with the anodes sized for the full design life of the sub-structure, with the coating sufficient to remove the need to carry out major repainting above the water line and minimise minor coating remedials will provide the lowest WLC.

The replacement of GACP with ICCP will likely provide the lowest initial CAPEX if a current industry norm specification system is used, but the increased OPEX costs will likely more than offset any benefit. A high specification ICCP system will likely have a greater CAPEX cost than an equivalent GACP system, and whilst OPEX costs will be lower than an industry norm ICCP system, they will still be higher than with GACP.

The environmental pressures not to use GACP are significant in some regulatory jurisdictions, based on seemingly very little evidence relevant to the UK EEZ offshore environment. It would seem inevitable that this view will become more widespread, and it is therefore a recommendation that the industry work together to fund the collection and analysis of objective and impartial data on the effects of both types of CP on the marine environment, primarily the release of both zinc and chlorine into the marine environment.

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