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CORROSION MONITORING
CIG Report

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Abbreviations

AE	Acoustic Emission
CFD	Computational fluid dynamics
CP	Cathodic Protection
CUI	Corrosion Under Insulation
DAQ	Data Acquisition (System)
DO	Dissolved Oxygen
EC	Electrical Conductivity
EIS	Electrochemical Impedance Spectroscopy
ENM	Electrochemical Noise Method
ER	Electrical Resistance (Probes)
ICCP	Impressed Current Cathodic Protection
ISE	Ion Selective Electrode
LPR	Linear Polarisation Resistance
MP	Monopile
ORP	Oxidation-Reduction Potential
OWF	Offshore Wind Farm
RBI	Risk Based Inspection
RFID	Radio-frequency identification
ROV	Remotely Operated Vehicle
RUL	Remaining Useful Life
SACP	Sacrificial Anode Cathodic Protection
SCC	Stress Corrosion Cracking
SHM	Structural Health Monitoring
TSA	Thermally Sprayed Aluminium
UT	Ultrasound

1 Introduction

Structures and devices for offshore energy generation are typically unmanned and located some distance from shore. This presents a challenge when it comes to keep track of the conditions of your assets and their energy generation capacity. Therefore, a lot of remote monitoring tools have been installed in for example offshore wind turbines (i.e. sensors that allow monitoring the structure without the need to send personnel offshore). Until now, monitoring has mainly focused on monitoring of structural aspects and the energy generation capacity. However, tools also exist or are being developed for monitoring of parameters related to corrosion, which also presents a threat to the structural integrity, especially in aggressive offshore conditions.

Corrosion monitoring is currently not yet implemented by default and many questions remain as to the available technology, but also the potential gains of implementing corrosion monitoring. Within the framework of the OPIN project[1], a Collaborative Innovation Group (CIG) on Corrosion Monitoring was established. The CIG consists of a consortium of companies and research institutes that want to bring together the knowledge and experiences available within this consortium on the topic of ***Corrosion Monitoring of steel structures*** for Offshore Renewable Energy generation. The available knowledge and experience will be compared to needs and expectations and potential technology and knowledge gaps identified.

This report does not aim to be a comprehensive, international state-of-the-art review. It is rather a review of the information available within the consortium, extended with the results from a public questionnaire to obtain better insight in the needs and expectations from the sector, and finally identify opportunities for further R&D into this topic.

2 Corrosion Monitoring needs and expectations

Before looking into available technology, it is important to map the expectations of the offshore energy sector with respect to corrosion monitoring. I.e. what do we want to achieve with corrosion monitoring. The information below is based on a number of interviews with companies and organisations from the value chain, as well the ***replies to an online survey performed in Q1 of 2021***. In total 33 responses were received, including:

- 21.2% of responses were received from University/Research institutes
- 18.2% of responses were received from Ocean Energy technology developers (Floating wind, Wave, Tidal)
- 15.2% of responses were received from Offshore operations or support service providers
- 12.1% of responses were received from Engineering design/consulting companies

2.1 Goals and objectives of corrosion monitoring

A number of possible goals and objectives were identified during interviews and are listed below (random order, i.e. not according to level of importance). Generally speaking, many of the items listed below are related to a reduction of uncertainty. This uncertainty can be related to many aspects of

[1] Ocean Power Innovation Network (OPIN), https://www.nweurope.eu/projects/project-search/opin-ocean-power-innovation-network/

the design, operation and financing of offshore energy installations. However, in all cases, uncertainty, and the measures taken to deal with this uncertainty lead to higher costs.

- ***Monitoring of Cathodic Protection systems***
  - Is the potential below -950mV everywhere on the structure? Especially locations behind fouling, below the mudlines, etc. which are difficult or impossible to inspect using ROVs.
  - Is the current consumption as expected, especially when complex interaction occur (potential behind the fouling, the scour protection and in the mud)?
  - Remaining lifetime of sacrificial anodes (can be lower than that of the structure + if no monitoring, requires underwater inspections)
- ***Monitoring corrosion of foundations and structures***
- ***Monitoring corrosion of electronics and mechanical components*** with an impact on device functionality
- ***Checking of Design assumptions***
  - Expected corrosion rate equal to measured corrosion rate (zero)?
  - In case of closed monopile design, are the oxygen levels indeed low enough to prevent corrosion?
  - Is the ICCP or SACP design in accordance with reality?
    - Protection potential as designed? If not, why?
    - Check if pH, etc. remain within design constraints. Do water refreshment holes (to prevent pH increase in case of internal CP protection) work as they should?
  - Use of environmental monitoring to estimate what the risk on pitting corrosion is.
- ***Design optimisation*** of future devices based on actual in-field values
  - What are required corrosion allowances? Can they be reduced in order to make the structure cheaper (i.e. required safety factor, tighter design limits, updated S/N curves).
  - How to handle the time between foundation installation and CP operation, should the foundation be coated? Is TSA instead of CP suitable?
  - Detect and solve the causes of corrosion: Corrosion monitoring allows you to observe changes in corrosion rates (time of occurrence, speed of occurrence, fluctuations, etc.), making it easier to detect the cause of corrosion. Local sensors in combination with computational modelling (digital twin concept), allows to extrapolate monitoring data to the entire structure and identify critical locations for corrosion. This allows to take mitigating actions and/or adapt designs to prevent or reduce the corrosion.
  - Learn where the critical parts of the installation/structure are in terms of corrosion.
  - Collect data from early demonstrators on corrosion protection design (including materials, coatings and CP) and environmental factors (water characteristics, biofouling, mud) to feed into later designs, instead of first focussing only on functionality and only in a last stage start thinking about corrosion protection. By having data and experiences from earlier demo's, the final corrosion protection design will be much easier to realise, providing less uncertainty about the lifetime,

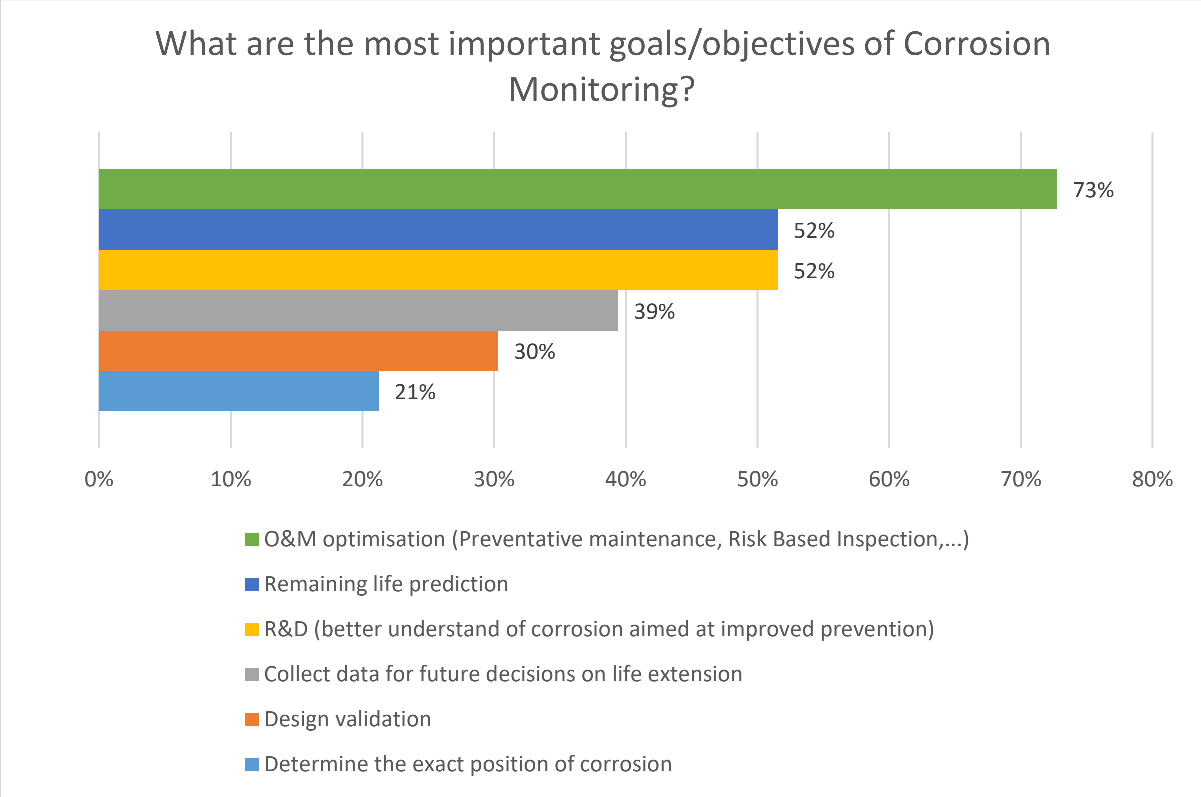
O&M needs and survivability of devices. This can in turn make it easier to convince potential investors.

- ***RUL, life extension and end-of-life***
    - Verify that the design life will be reached (in combination with load monitoring). I.e. estimating remaining capacity or fatigue life with the best information available, without the need for trying to identify the cause (of corrosion).
        - Validity of initial S/N curve after corrosion has manifested
        - Corrosion of foundation
        - Especially in the phase before CP is installed (typically in the range of a few months to a year for MP foundations)
        - During time of CP failure
    - Data from monitoring can also be used to extrapolate into the future when calculating possible life extension (i.e. what is the state at end of life (e.g. 25y), and how the state is expected to evolve. Continuous historical data of high quality is needed in order to reduce the uncertainties on this extrapolation. Fundamental insights in the corrosion mechanisms need to be obtained to develop prognosis modelling (possibly validated with laboratory testing).
    - Lifetime extension is more likely if the owner can demonstrate that the structure has been well maintained and monitored. Information from monitoring can be used to convince insurance companies as well.
    - In addition to life extension: provide information for end-of-life repowering, decommissioning and repurposing by knowing the exact condition at the end of the service life-time of the structure (optimal reuse of the steel)
- ***Reduce costs related to financial aspects***
    - A 'Philosophy of good documentation' is also valuable when it comes to closing contracts on insurance (which may be cheaper in case of good monitoring).
    - Reduction of the financial reserve to cover risks: There is always a risk involved and the money to cover that risk is reserved. This means that if monitoring decreased the risk, the money to be reserved can be reduced and otherwise invested.
    - In case of selling of assets (to another operator), having good monitoring data may yield a better price by reducing the uncertainty about the condition of the assets (if the condition of the assets are indeed good).
- ***O&M optimisation (OPEX reduction)***
    - Good monitoring in combination with lower safety margins to reduce overall costs.
    - Reduction of inspection costs by means of RBI (prioritisation of inspections and reducing the scope of inspections, leading to lower intervention cost and shutdown time)
        - Reduce the costs related to underwater inspections.
        - Increase the time between maintenance or detailed inspections, by updating probabilistic models, based on using corrosion information from monitoring and data with reduced uncertainties as compared to inspection data (see Value of Information in Chapter 6.1).

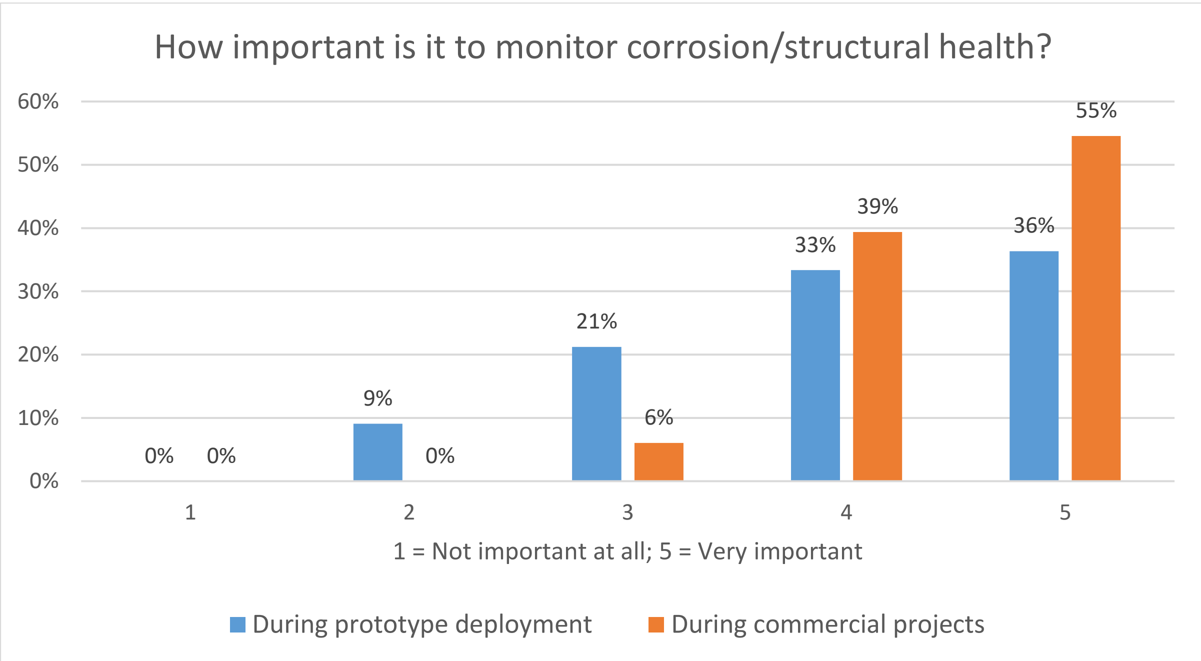
        - Avoid unnecessary inspections (can be very expensive, for example if floating structures are returned to port of submerged structures lifted from the seabed).
    - Easier inspection/monitoring of non-accessible or difficult to access zones/parts.
        - either difficult to reach locations on the device
        - or because devices themselves are difficult to access (remote, weather conditions, etc.)
    - Reduce costs of curative maintenance by applying Predictive Maintenance: By corrosion monitoring it is possible to know when maintenance is required, allowing a better planning, which reduces costs, time and spare parts storage.
    - Minimize risk of catastrophic failure.
    - Minimizing operational downtime
- ***Increased safety***
    - Prevention of accidents: monitoring can lead to a lower risk of accident by early detection of defects or monitoring of locations that cannot be inspected (avoiding falls, spills and other accidents due to structures/components in poor condition).
    - Reduced need for risky underwater inspections (divers).
- ***Reduced environmental impact***
    - Prevention of environmental accidents such as spills into the sea (peeling off of coatings, loss of parts/components, etc.).
    - Less pollution due to the use of ships for on-site inspections.
    - Longer structure lifetime also reduces environmental impact.

Many on-going corrosion projects are still part of R&D. Meaning that either research is ongoing on how corrosion monitoring can contribute to improved asset management, or the corrosion monitoring is not used to optimise operational tasks, but to better understand the ongoing degradation mechanisms and feed into optimising future generations of assets.

In the survey that was performed, the question was asked ***what are the most important goals/objectives of Corrosion Monitoring***. The answers shown below (multiple choice list) indicate that O&M optimisation is at the top of the list, with remaining life and R&D on the 2nd and 3rd rank. This is an important conclusion, as the state of technology (both sensor technology and data analysis) today is reaching a level where information for remaining life prediction and certainly R&D is possible, however an integration to realise O&M optimisation still requires quite some work. For remaining life prediction, a limitation today is the lack of technology to monitor pitting corrosion (see section 4.1.4). As a remark to the results of the survey, it should be noted that interviews with Fixed Offshore Wind asset owners over the period 2019-2020 had indicated that O&M optimisation was not on top of the list for corrosion monitoring, due to lack of knowledge on corrosion monitoring and a lack of sensor performance. In current projects, Corrosion Monitoring was mainly implemented for Design Validation and general R&D. ***Thus, the figure below rather shows the needs and not the current situation.***



From the answers to the question below, it's also clear that more importance is put on monitoring during commercial projects as compared to during prototype deployment. This is in line with the indication that the main (future) objective is considered to be O&M optimisation.



2.2 Monitoring Needs

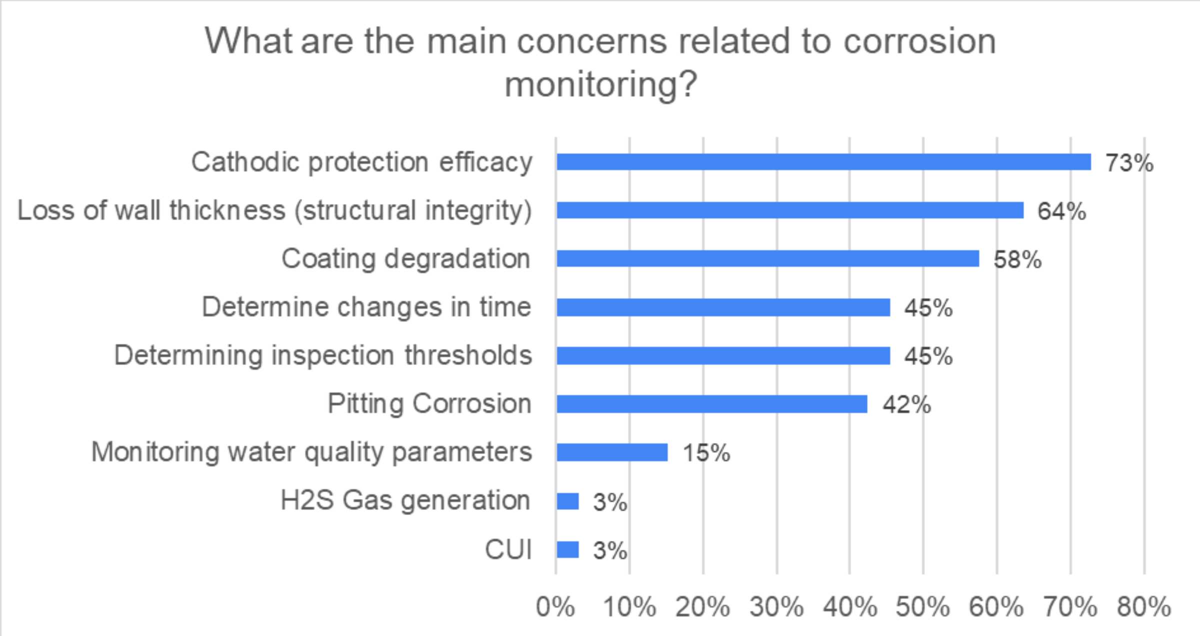
2.2.1 Parameters to be monitored

(The list below has been compiled based on written inputs from and interviews with research organisations and value-chain companies.)

- ***Uniform corrosion rate:*** to check effectiveness of CP systems, and as input to the amount of the corrosion allowance that is consumed (important for example for life-extension).
- ***Direct wall thickness monitoring:*** in contrast to using probes that measure corrosion rate on a steel element in the probe, direct wall thickness monitoring gives direct information on the structure itself rather than the aggressiveness of the environment.
- ***Pitting corrosion:*** Offshore wind operators are mainly concerned with the risk of pitting corrosion on their foundations (the size and shape of pits), because this has a large influence on fatigue life. This is however very difficult to measure (see section 4.1.4).
- ***Coating degradation:*** As long as the coating is intact, corrosion will not be an issue. The steel is only attacked once the coating is no longer protecting it. If the goal is to have no corrosion, it's not the corrosion rate that needs to be known, but the onset of corrosion, or thus, the moment when the coating is no longer protecting the steel. (Can be either due to 'natural' degradation of the coating, or mechanical damage to the coating.)
- ***CP protection level:*** All submerged structures have CP protection as a first or second line of defence. As long as the CP is operating as designed, it is typically assumed that no corrosion occurs.
- ***Electronics degradation***
- ***Environmental parameter:*** See section 4.3 for more information.
- ***Biological activity:*** impact on Microbiologically Induced/Influenced Corrosion (MIC)

In the performed survey, the question was asked what the main concerns are relating to corrosion monitoring, and thus what are critical parameters to measure. The results are shown below. The first seven options were available as multiple choice, the last two answers have been added by respondents.

An interesting addition is monitoring of H_2S gas evolution, which can come from decaying organic matter in seawater filled structures or MIC. This gas can be fatal in very small doses and short exposures. Also other gases like chlorine gas and bromine gas can develop, as a result of the operation of CP systems, and result both in health/safety issues and have an impact on the corrosion itself.



2.2.2 Critical locations for monitoring

Location in terms of environmental conditions:

- ***Tidal and splash zones***
- ***At and below the mudline***
- ***Locations where the water flow differs from 'open sea' conditions:*** Increase water flow velocities in/around structural elements or vice versa, stagnant water conditions.

Location in terms of components/structural elements:

- ***Moving parts, moving chains, hinges, etc.:*** Typically for wave and tidal devices, where these moving parts can also be submerged. Monitoring corrosion of these elements can be particularly difficult and the degradation mechanism can be a combination of wear and corrosion.
- ***Corrosion of critical components exposed to seawater***: e.g. pumps and pressure accumulators
- ***Multi-material structures/connection:***
  - Dissimilar metal contacts
  - Locations where steel and composites are joined together. Corrosion issues can be expected there (galvanic corrosion with carbon fibres, crevice corrosion, etc.).
  - Steel/polymer interfaces, where cathodic disbondment/delamination can occur, leading to water ingress and corrosion.
- Structural steel welds
- Internal corrosion of seawater flooded structures: e.g. jacket legs, monopiles, J-Tubes and ballast tanks.
- Bolts and flanges: crevice corrosion occurring
- Mooring lines and hardware

- Difficult to access parts of hull structures

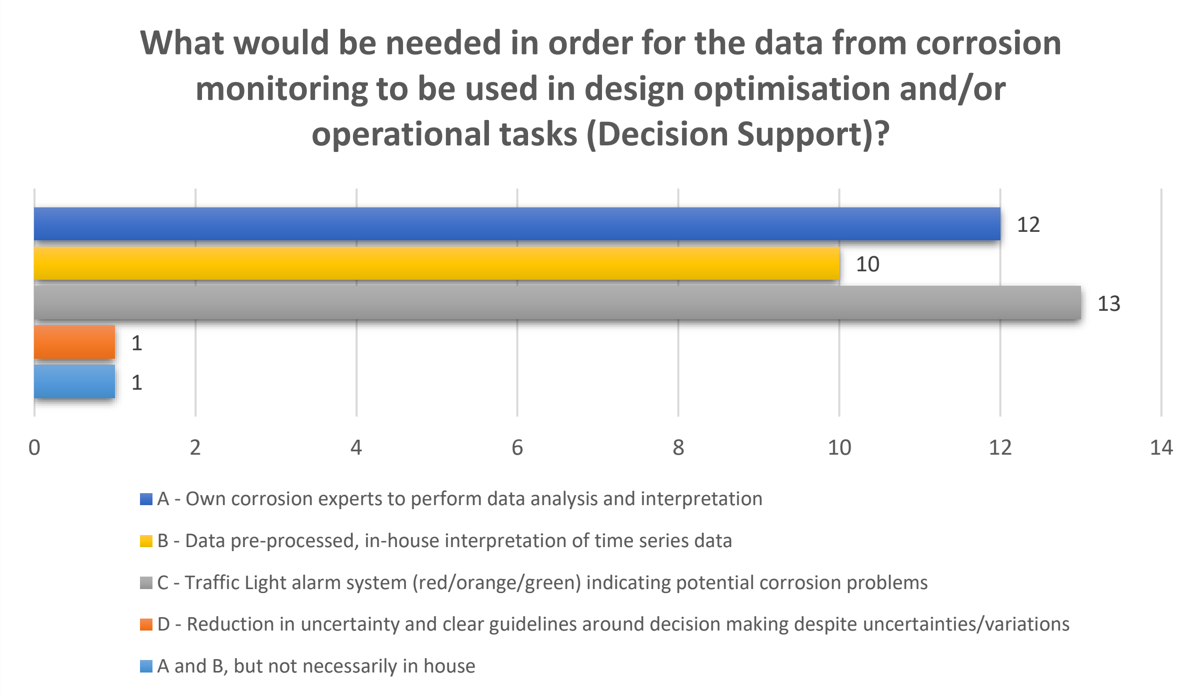
2.2.3 Other elements to be considered

- Often ***early detection of corrosion*** is required, especially when going through the effort of monitoring. In this case, accuracy of the measurement is critical. If the corrosion is only seen once it's in an advanced state, the monitoring is of no use. Especially early warnings are needed for areas of specific risk that can inform cost-effective planned maintenance.
- It is important that Corrosion monitoring of foundations can continue in a stage when no CP is installed yet, or during power outage, when CP is not active (as these are the periods in which most corrosion is expected). During these periods, there may be no power supply and/or data connection, which provides an additional challenge. Therefore, systems meant to monitor during these periods should be able to operate stand-alone.
- Uniform corrosion is typically a slow process and the corrosion rate due to exposure to seawater appears to be fairly constant. Therefore, some elements where the main added value of corrosion monitoring could be are:
    - Having high quality monitoring data as a reference for inspections.
    - Get information on periods without active corrosion protection (see above) or (unexpected) fluctuations in time (increasing water temperatures, increasing water flow, sudden changes in composition in the vicinity of river mouths, impacts of spills from ship accidents, etc.)
    - Locations with risks for higher corrosion rates (tidal, splash zones).
    - Monitoring of forms of corrosion like crevice corrosion, pitting corrosion or stress corrosion cracking (SCC) which can lead to rapid and sudden failure of metallic parts without clear visual indications.
- ***Cost of monitoring equipment*** is seen as an additional 'burden', especially because it's difficult to calculate the return on investment. In addition, while prototype developers might like to include it, their budgets are often very limited and focused on proving other aspects of their technology.

2.3 Implementation in asset management

When moving away from R&D related use of corrosion monitoring, the question comes up how corrosion monitoring could potentially be implemented in asset management. I.e. what is needed so that the information coming from monitoring can be used by operational managers?

In the questionnaire, the question shown below was asked to the respondents. The first three options were available as multiple choice, the other answers have been added by respondents. In total, 30 responses were received.



The answers show that the anticipated needs are evenly spread, and ranging over having own corrosion experts to simpler 'traffic light alarm' systems (warnings if certain values exceed normal acceptance criteria). Traffic light type system is indicated by 50% of respondents if looking only at asset owners and technology or project developers. In the survey, it was indicated that status reports should also include an estimate of remaining life in both the corrosion protection and structural integrity of component. Interestingly, one respondent also pointed out that the option of having 'own corrosion experts' doesn't necessarily need to mean having them in-house, but can be externally procured expertise.

In addition to being able to use corrosion monitoring for operational tasks, corrosion monitoring needs to be incorporated in the design and CAPEX. An example of this is monitoring below the mudline, where integration of sensors in the foundation can be considered (see also section 5.1.1).

There are also technical aspects to this. A measurement chain needs to be available that allows the data to be securely obtained, transferred, interpreted and subsequently analysed:

- The monitoring system must obtain data at a relevant frequency, especially if it is sensitive to other parameters like temperature, for example 4 times per day
- The system must be correctly calibrated and it must be possible to check the calibration of the system
- Measured data should be stored in a database, allowing to access historical measurements. In case of relying on external expertise, the database needs to be accessible by these external experts in a safe and controlled way.
- Data should be easy to visualise, with a combination of parameters as specified by the user. This makes it possible to perform a first evaluation of how variables are related and to easily observe sudden or long-term changes in the measured parameters.

- Lifetime evaluation would require integration over a long period of time and the possibility to make predictions towards the future. In addition, integration with other SHM should be possible, to combine corrosion info with load information, etc.

3 Current application of corrosion monitoring

Some monitoring is already being done in fixed offshore wind, with a clear focus on the foundation structures. Apart from CP monitoring, corrosion monitoring is not yet a mainstream activity. Most of the activities related to corrosion monitoring still seem to focus on R&D aspects (design validation and improvement, learning about the combined corrosion-fatigue behaviour of offshore structures).
Nevertheless, there seems to be a tendency to look more and more into the potential benefits corrosion monitoring can offer also to operational aspects. The business case for corrosion monitoring however still seems to be unclear, limiting widespread uptake. This is related to three main elements:

1. The value of corrosion monitoring being unclear
2. Existing questions with respect to sensor reliability and data analysis
3. The costs related to corrosion inspection and maintenance often being unclear, in turn making it difficult to build a business case for corrosion monitoring

The situation today can be summarised as follows:

- CP is typically a first line of protection for submerged parts of the structure. It is generally assumed that the structure will not corrode, as long as the CP system is operating as designed. CP monitoring is therefore standard for all devices that operate ICCP systems. Some monitoring is included in the ICCP set-up itself. Additional monitoring is often installed by operators in order to check potentials further away from the anodes. Current consumption data should typically be available through the ICCP system, but often not analysed, although this could provide a very valuable addition to the potential data. When sacrificial anodes are used, the potential of the structure is not always monitored. Systems to monitor the anode current output exist, but they are not installed as a standard.
- Corrosion rate monitoring:
    - There seems to be an increasing demand for monitoring using ER or LPR-probes (uniform corrosion rate), although still a very small number of foundations seem to be monitored. These seem to be quite reliable, although certain data features may require deeper analysis. The authors' are aware of one European asset owner where a large number of probes has been installed, which is currently still the exception.[2]
    - Mention has been made that LPR or EIS probes could also provide information on the tendency for pitting to occur. It seems that some operators may be experimenting with this.[3] However, the usefulness of these techniques to monitor pitting corrosion has not yet been proven (at least not publicly).
    - The sensors are often placed at three to 4 vertical levels, mud, bottom, halfway, and tidal zone.

[2] Information is not shared and kept confidential.

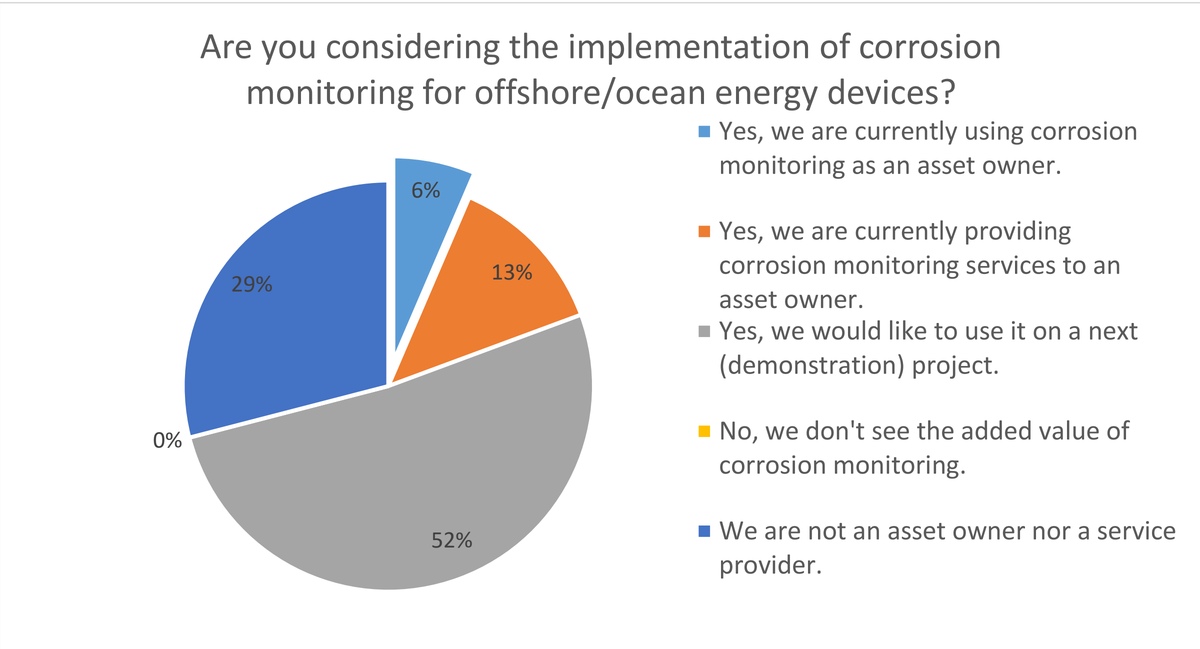
[3] N. Verkleij (Van Oord), Monitoring by Electrochemistry, Presentation during conference 'Corrosion Protection for Offshore Wind 2019', Bremen

- Environmental monitoring
    - temperature: very straightforward
    - water levels inside monopiles: to verify exchange of water through water refreshment holes
    - dissolved oxygen: critical parameter when it comes to corrosion
    - pH: problems with long-term reliability of sensors
- Coating degradation monitoring
    - Applied by some asset owner, typically still on witness plates rather than the structure itself

Generally, when monitoring any parameter (corrosion, stresses, deformations ...) only the most critical assets are monitored. This makes it possible to reduce the number of sensors and at the same time have the assets most susceptible to failure monitored. Another approach is to select a number of structures that are representative for the whole group of assets, where each may represent a subgroup with a typical design, installation location, etc.

The ***results from the performed survey*** indicate that the majority of Ocean Energy technology developers are not yet applying corrosion monitoring. Replies from the offshore wind sector indicate that CP monitoring is generally performed and to a lesser extent monitoring of environmental parameters. A minority of answers also indicate the use of corrosion (ER, LPR) and coating degradation monitoring.

The below responses from the survey clearly indicate that there is a strong interest in using corrosion monitoring, but that currently the active use of corrosion monitoring is still limited, with only 2 asset owners indicating that they are using corrosion monitoring (6%). Of the 16 responses (52%) indicating an interest in using it in a next project, 7 are technology developers or asset owners.



4 Monitoring methods and existing technology

In this chapter, an overview is given of the monitoring methods and existing technology known to the consortium of this Collaborative Innovation Group. The overview is split up in sections, according to the type of monitoring:

- Corrosion monitoring
- Coating degradation monitoring
- Environmental monitoring
- Cathodic Protection monitoring

An additional section shortly discusses the interpretation of measured degradation/corrosion rates vs. real degradation rates.

With all of the techniques discussed in this chapter for corrosion monitoring or coating degradation monitoring, it's important to realise that when using probes, the probes represent only themselves. That is to say, the corrosion rate measured is the corrosion of the steel element in an ER probe or calculated from a measured current in an LPR probes, etc. This is not necessarily the same as the corrosion rate of the structure itself. Even when using steel coupons, the corrosion rate of various coupons will never be exactly the same. It is therefore good to think of corrosion rate as a range rather than a single value.
The corrosion rate of the structure itself may also be influenced by other aspects. Galvanic effects may play a role, the presence of fouling, formation of deposits, etc. The corrosion rates obtained from measurement probe therefore should rather be considered as giving an indication for the aggressiveness of the environment.

Other techniques like ultrasound or eddy current inspection/monitoring can be used to get a direct measure of remaining wall thickness of the structure. Here it is important to realise that these are typically spot measurements (larger areas in case of for example phased array US).

4.1 Corrosion monitoring

In direct corrosion monitoring, a distinction can be made between physical methods and electrochemical methods. With physical methods, actual metal loss is measured, corrosion is estimated from images or other physical signals such as sound signals. With electrochemical methods, the occurring electrochemical reactions are measured in order to get information on the occurring corrosion. At some instances, cost indications are given. These are only rough estimates based on experience within this consortium. Next, a couple of specific points are covered: influence of bio-fouling on measurements, monitoring of pitting corrosion, MIC and concrete corrosion.

An important point of attention for all types of monitoring is to ensure that the probe element is exposed to the environmental conditions of interest (e.g., the same chemistry, temperature, flow regime, etc. as the structure being monitored). With sometimes strongly localised corrosive conditions, and sensors that are often point-sensors (i.e. measuring at only one point in space), this is not always straightforward. During design of the monitoring system, this point should be carefully considered.

4.1.1 Physical methods

4.1.1.1 Coupon method

The oldest method: Place a coupon in the area of interest, and of the same material as the structure of interest. Electrical connection between the coupon and structure of interest can be made to bring the coupon to the same potential as the structure.

Drawbacks:

- Need for retrieval to obtain data
- Slow response rate
- Only historical data are obtained, not real time data (while corrosion rates vary in time, i.e. coupons only give integrated data).
- Need to replace the coupon after acquiring data. Because development of oxide layers decreases the corrosion rate, estimating long term corrosion rates from subsequently installed coupons will give an overestimation (alternative is to start off with sufficient coupons to periodically retrieve one or a few of them and leave the others on-site, for long term 'monitoring' this either means a low sampling rate or a very large number of samples).

Advantages:

- Applicable to all environments: gases, liquids, solids / particle flow.
- Weight loss coupons can be made from any commercially available alloy.
- Very cheap.
- A visual inspection can be done.
- Corrosion deposits can be observed and analysed.
- Weight loss can be easily determined, making it easy to calculate corrosion rate.
- Localized corrosion can be identified and measured.
- The performance of inhibitor and other corrosion protections mechanisms can be easily evaluated.

Even if remote monitoring methods are applied, coupons should be installed as a reference and back-up solution.

4.1.1.2 ER-probes: Electrical Resistance probes

A fairly robust way of continuously monitoring corrosion, which has been used in the process industry to monitor pipeline corrosion is the use of ER-probes or Electrical Resistance probes. The measurement is based on the increase in electrical resistance of a corroding steel element.
The probe contains two elements: one corroding, one non-corroding. The electrical resistance of both is compared. As corrosion occurs on one of the elements, the cross-sectional area is decreased, and resistance increases. This increase is used to determine the corrosion rate. ER probes are often selected because of their relatively simple operations, relatively low maintenance, ease of data interpretation, real-time data collection and reliability.

- The main issues in utilizing ER probes include ensuring that the probe element is exposed to the environmental conditions of interest (e.g., the same chemistry, temperature, flow regime, etc. as the structure being monitored).

- Non-uniform corrosion, such as pitting, crevice corrosion, and stress corrosion cracking can lead to errors in measurement. These errors can be both in the form of underestimation and overestimation of the true corrosion rate.
- Where CP is applied, the formation of semi-conductive calcareous deposits on the probe surface may artificially increase the cross-sectional area which leads to underestimation of the corrosion rate.
- Cost for a single probe ranges from 500-800 euro, probes typically also require a transmitter, with one or multiple probes capable of being fitted to a single transmitter (cost range: 2000-3000 euro).

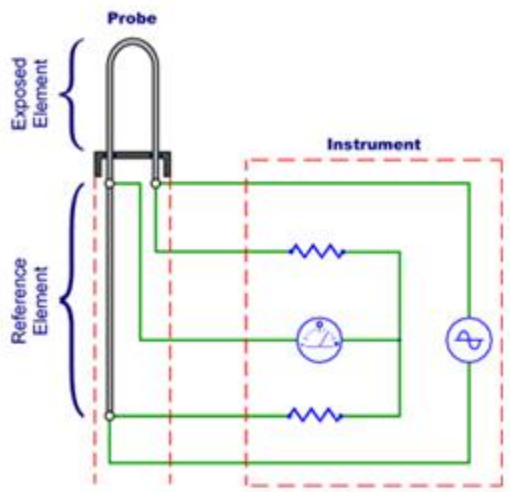


Figure 1: Schematics of a possible execution of an ER-probe. (http://www.alspi.com/erintro.htm)

- Response time and detection limit depend on element thickness. Thinner elements result in faster response times and lower detection limits, but also have a shorter lifetime.
- The corroding element of the ER probe can also be covered with a coating to evaluate the coating performance. (Under development at some suppliers, little info is being shared.) Remark: coatings typically fail at welds, due to damage, etc. If the element is coated under perfect conditions, it will likely experience failure much later than other critical locations on the structure.
- Probes typically only give good results until a certain % of the element has corroded (can be as low as 5%). Therefore, the probe has a limited lifetime and needs to be replaced several times over the lifetime of a wind farm. This will result in too high corrosion rates as the development of oxide layers decrease the rate. This needs to be taken into account when interpreting the data. Long term exposure of coupons can serve as a reference point.

There are also wireless sensors, totally passive energetically (without battery), small in size and inexpensive, and that can be integrated into structures: these sensors use RFID technology (Radio-frequency identification). Such sensors are currently under investigation at the Université Gustave Eiffel (UGE). They provide measurement of mass loss of a metallic element. The results obtained give access to the corrosion rate for uniform corrosion. They can also differentiate the corrosion mechanisms: uniform or localized with a number of distributed sensors on a structure. However, this technology system needs to be validated in situ.

4.1.1.3 Ultrasound monitoring

In ultrasound inspection a sound wave is actively introduced in the structure with a transducer and recorded again after interaction with the structure (typically reflection from a back surface, defects, etc.). This method is well known for inspection purposes (commercialised by for example Cygnus Instruments and Olympus), but less so for continuous monitoring, although some solutions are starting to be commercialised for continuous monitoring of pipelines.

- In inspection of wall thickness, one typically probes from the non-corroding side. If corroding from two sides, or preforming measurements from the corroding side, the surface needs to be cleaned (remove corrosion products) and for further monitoring this clean surface would need to be protected to maintain a good contact to transmit the sound waves. Cleaning and installation could be carried by a diver or an ROV.
- For continuous monitoring, probes can be glued to the surface or attached magnetically.
- Ultrasound inspection/monitoring in its most common form (longitudinal waves normal to the surface) is a local measurement. This implies that the monitored area should be well representative or the most critical areas of the structure.
- This limitation also means that the use of normally oriented longitudinal waves cannot be used to monitor external corrosion of for example pipelines, because the external sensor would cover the spot to be monitored and thereby influence the corrosion itself.
- The ***longitudinal waves*** can be used to measure wall thickness of samples corroding from one side. The sensor is then placed on the cleaned or non-corroding side. Then the wall thickness can be measured even without cleaning the corroding side (typically using a dual-element sensor, which is more suited for measurement with one side being a rough surface). To apply this approach to monitoring of offshore structures, a permanent sensor should be installed on a cleaned or uncorroded surface. This surface is then protected from further corrosion and the ***wall thickness reduction, resulting from one-sided corrosion is measured***.
- Another approach could be ***the use of Lamb waves***, travelling along the length of the steel plate/section (as compared to through the thickness and then reflected back). Using these Lamb waves, a separate transmitter and receiver could be used with some space between them. The speed of the sound wave and the dampening of the wave are correlated to the wall thickness. This approach allows the transmitter and receiver to be placed on the corroding side of the steel, and ***to measure the reduction in thickness of the steel section between the transmitting and receiving transducer***. To the authors knowledge, no commercially available system for marine deployment exists.
- It is unclear if commercial probes currently exist that can be used for ***continuous underwater deployment***. Systems that are capable of continuous monitoring exist that can be used for 'dry' applications, for example when monitoring from the inside. The high wall thickness in offshore structures may reduce accuracy of the measurement.
- Deterioration of the contact between probe and surface may be an issue for long term deployment of piezo-based transducers (either reduced coupling, or damage to the transducer itself due to mechanical vibrations, etc.). A solution might be the use of ***EMAT (Electromagnetic Acoustic Transducer)***, where no 'mechanical' surface coupling is required.
- Often early detection of corrosion is required, especially when going through the effort of monitoring. In this case, accuracy of the measurement is critical. If the corrosion is only seen once it's in an advanced state, the monitoring is of no use.
- There can be quite some uncertainty on inspections carried out using ultrasound (by divers/ROVS for submerged structures), see Figure 2. The uncertainty of measurements has been quantified according to a protocol set out by Boéro et al. (2012). See also section 6.1 for more information on the importance of 'uncertainty of measurement'.

Source: F. Schoefs (UNIVERSITÉ DE NANTES / CAPACITES SAS)

Figure 2: Steps of an ultrasonic underwater survey of a pile (cleaning, measuring, painting (blue areas top right) and post treatment) as sources of uncertainties

Another question that presents itself is whether ultrasound monitoring could potentially be used to detect **Pitting Corrosion**.

Theoretically this should be possible with guide surface waves or Lamb waves, and possibly also using phased array ultrasound. However, all these techniques may prove difficult to implement on rough and strongly corroded surfaces as often encountered in offshore structures. Also interference from the environment may prove a significant challenge (water surrounding the structures in case of submerged structures). The authors are not aware of such techniques being used in offshore energy structures for monitoring applications.

In summary, Ultrasound Monitoring could potentially be an interesting solution, however no off-the-shelf solution exists (to the authors best knowledge). This provides **an opportunity for future development**:

- To do monitoring using ultrasound, improvements in transducers may be required.
- Continuous monitoring in a real environment will likely require development in terms of data processing and the way in which the wave is send and recorded.

4.1.1.4 Acoustic emission (AE)

Acoustic Emission is by design a monitoring technique as the method consist in recording all acoustic waves coming from a structure and then analysing these signals. (For tank inspection, it is used as an inspection technique as well, where data is recorded for example for one or a few days to determine the current state of the tank.)

- The technique records all acoustic waves emitted by many sources and the challenge is to distinguish between background noises and corrosion in our case.
- The technique can also be used to ***detect forms of localised corrosion such as SCC and Pitting Corrosion***.
    - For pitting corrosion, it is not the pit formation itself that is detected, but the hydrogen bubbles bursts on pit walls.
- For monitoring pitting corrosion and SCC, the technique is currently used in several industries such as tanks in the process industry. The TRL in chemical industries is high (TRL 8-9), see for example providers such as Mistras Group or Vallen Systeme Gmbh.
- <u>**Opportunity for future development:**</u> Acoustic emission is currently used mainly to detect crack propagation in offshore structures, using it for the detection of corrosion (pitting /SCC) would likely require quite some R&D work. To the authors' knowledge, AE for detecting corrosion in offshore structures hasn't been tested yet. To be investigated:
    - the maximum distance of the sensor from the damage zone (attenuation of the AE signal)
    - signal analysis to identify signals related to corrosion (signature of corrosion events)
    - interference of background noise in a marine environment (sea animals, ships, waves, wind, etc.). However, the latter are likely low frequency noise, so it should be possible to discriminate them from the relevant source.
    - interference of other mechanical noises (from turbines, motion of the structure itself, motions of mechanical components, etc.)
    - corrosion resistance and durability of the sensor system itself
- In the Interreg project QUALIFY, the use of AE for monitoring of adhesive joints on ships is investigated. This could provide a starting point for corrosion monitoring on offshore structures. (https://www.qualify-euproject.com/)

Fibre optics sensors are under development at Université Gustave Eiffel (UGE). Fiber optic sensors offer attractive performance, derived from the special characteristics of silica: they are lightweight, chemically inert, and immune to magnetic interference. They also have high bandwidth, integrate easily into existing and new structures, and are resistant to high temperature, corrosive and hazardous environments. In addition, wavelength division multiplexing and compatibility with long-range optical communication systems, allow it to perform remote measurements at multiple points as well as fully distributed measurements with good spatial resolution using of a single optical fiber. Fiber optic sensors, such as Bragg grating sensors, for example, are commercialised by HBM, Technicasa, FBGS. ***Fibre Optic sensors for AE are still under development, and are currently being evaluated at UGE on prestressed concrete structures.***

4.1.1.5 Underwater imaging

Underwater imaging using RGB cameras, or even other spectral ranges, can also provide a means of corrosion inspection. This is not continuous monitoring, but can provide important information on the condition of offshore structures. Algorithms are being developed to automatically interpret images, making that underwater imaging is becoming quite promising. Image processing allows quantifying pitting corrosion (at least maximum length, area, …), however the surface needs to be cleaned from biofouling and corrosion products. An application with detection thresholds is available in Pakrashi et al. (2010) and methods are available in O'Byrne et al. (2013, 2014, 2015, 2018).

At Université de Nantes, work was done on visual inspection and data processing to inspect pitting corrosion. A protocol for divers was developed and the same is being developed for ROVs (how many pictures needed, distance to structure when making images, the lighting, etc.) to have the best repetition rate (starting from the detection rate, how is the best detection rate achieved?). Depending on turbidity, distance and lighting can be changed to have the best detection. This method can be used for measuring of bio-fouling. For measuring of pitting corrosion, the surface would first need to be cleaned.

The required software for this type of pitting analysis has already been developed. The technology is currently at TRL 5-6. It hasn't been proven yet that all pitting can be detected for all types of steel and structures (depends on type of corrosion products). The image analysis is based on colour and texture of the surface. Pitting corrosion is seen as a specific texture. The area of pitting corrosion can be measured and the number of pits and maximum length of pits determined. However, no info on the depth (0.7mm depth accuracy) is obtained using a standard, low cost RGB camera.

4.1.2 Electrochemical methods

4.1.2.1 Corrosion potential

By measuring the corrosion potential of steel exposed to an environment, information can be obtained about the tendency to corrode. The method indicates a modification of the thermodynamic conditions of the specimen that can be related to corrosion evolution. The SPCT probe commercialized by NKE Instrumentation (https://nke-instrumentation.com/produit/spct/) allows the monitoring of the potential difference between a coupon contained within the probe and a reference electrode, that corresponds to a corrosion potential. It is self-contained and designed for installation in a marine environment.

4.1.2.2 LPR probes: Linear Polarisation Resistance

With a LPR measurement, a linear sweep over a small voltage interval around the Open circuit potential (OCP) or corrosion potential is performed (typically +/- 10-30mV). During a full polarization measurement to determine the Tafel plots, a sweep over a +/- 600mV range is performed. To determine a corrosion rate from the small linear sweep performed during an LPR measurement, assumptions need to be made about the Tafel coefficients normally determined at higher potentials, which depend on the type of material and environment. If these coefficients are not adapted based on material and environment, a certain error on the corrosion rate can be expected. It is important to keep this in mind when using LPR probes in strongly fluctuating environments, or when using probes not adapted for the environment/material under study.

Drawbacks:

- LPR probes can only be used for immersed conditions.
- The downside to the LPR technique is that it can only be performed successfully in relatively clean aqueous electrolytic environments. LPR will not work in gases or water/oil emulsions where fouling of the electrodes will prevent measurements, due to low conductivity between the electrodes. Depending on the spacing between the electrodes, the main limitation of the LPR technique is that the resistance over the fluid (and electrode interfaces) has to be much lower than the polarisation resistance. This is not the case when a fluid is less conductive, for example in al <10% water containing oil, or when the electrodes are very far away from each other.

Advantages:

- Commercially available from for example C-Cube and COSASCO (and others) at similar cost as ER probes.
- It has a fast response rate when compared to physical probes like the ER-probe (there are fast response ER probes available, but these also have shorter lifetimes).
- It has a long lifetime
- Relatively easy in terms of data interpretation.

Opportunity for future R&D: In more sophisticated sensors, also mechanistic information can be derived, in order to enhance the precision and to provide data on pitting tendency. However, using LPR for measurements of pitting on carbon steel is not known so much. With the technique, the corrosion rates and the pitting tendency should be monitorable. Currently it remains unclear to what extent this is indeed possible and representative for actual steel structures.

On the use of LPR for measurement of pitting corrosion:
It is sometimes mentioned that LPR probes may provide an 'indication' for pitting corrosion based on the 'imbalance' between two electrodes of similar material. This imbalance appears to refer to fluctuations in the current between the electrodes. The probe suppliers stress that the imbalance should only be used as a first indication and not at all as a 'pitting rate'. Pitting corrosion can indeed be seen as fluctuations in current between pits and the surface outside of the pits. Actually measuring these seems to be moving into the field of ENM. The warnings of the suppliers that the imbalance should only be used as a 'tendency' indication is thus certainly well placed. It is yet unclear just how much value the information on imbalance really contains.
In contrast, dynamic polarization curves can be used to detect pitting corrosion. However, this measurement is destructive for the sample. Repetition of the measurement for monitoring is not recommended at all. In addition, for carbon steels, there is no a clear pitting potential as for stainless steels, which makes detection of pitting challenging (see also section 4.1.4).

4.1.2.3 ENM: Electrochemical Noise measurements

Electrochemical noise in corrosion refers to the naturally occurring fluctuations in corrosion potential and corrosion current. Adsorption/desorption processes on a metal surface, pitting, and crack initiation, etc., may be the sources of noise. The electrochemical noise technique is defined as the analysis of the spontaneous fluctuations of the electric current and potential of a corroding electrode.

According to literature, ENM is ***used for monitoring of both general and localized corrosion, especially pitting and crack initiation. The electrical resistance noise values are very important for analysis of the efficiency of protective coatings on metals.***

- A lot of development is still ongoing at universities, though on the part of practical application there are still many barriers.
- Very sensitive to background perturbations and analysis requires skilled staff.
- Uses advanced signal processing. It is based on differences in electrochemical events between two identical electrodes. High measurement frequency and Fast Fourier Transformation is needed to capture the right information. This means high demands in terms of equipment, data analysis and data storage due to high sampling frequency. Very small currents need to be measured (nano and micro amps), making it a sensitive technique which is currently still to be considered as more of a laboratory technique.
- Further development and application of the technology could in specific cases be very helpful, for example to evaluate pitting corrosion on carbon steels (which differs from pitting on stainless steels, see section 4.1.4).
- The hardware costs are also higher as compared to other more 'common' electrochemical techniques like LPR and EIS.

ENM is a technique coming from the process industry, ***to the authors' knowledge it has never been applied to monitoring of inspection of offshore structures.***

Despite the above discussion, ENM is mentioned in some commercial products, like the one from SensCorr BV (https://senscorr.com/industry/), where it is indicated that a pitting index can be determined according to ASTM G199 using the ENM technique. The pitting index is a value between 0 and 1. A value of 0.6 and higher means that the corrosion is more local (= pitting corrosion) than uniform corrosion.

4.1.3 Influence of bio-fouling

Biofouling is the growth of biological organisms on the steel structure under investigation. Growth of biofouling occurs in stages. First a biofilm develops, merely a thin layer of algae in which the larvae of hard fouling (shells, barnacles) can settle on the surface, and finally growth on the existing fouling. This last growth often occurs with the death of underlying species, and hence rotting material underneath.

On the inside of structures, the amount of hard fouling is typically lower, as there is less light and incoming water refreshment. Depending on the application chlorine gas evolution from the ICCP system can also reduce fouling. In situations where the steel is unprotected, MIC can be found, though, not all MIC induces a high corrosion rate. However, micro-organisms such as sulfate reducing bacteria typically contribute to corrosion and stress corrosion cracking. Recently, a very severe case of pitting corrosion due to MIC was observed in Zelzate, Belgium, where pitting depths up to 0.15-0.3mm per month were observed[4]. Additionally, the hydrogen uptake increases as well potentially leading to hydrogen embrittlement.

Consequences of bio-fouling:

- The development of a shielding of the cathodic protection, as the fouling can grow to 20cm thickness.
    - The growth of a fouling layer can also make an accurate measurement of the potential at the steel surface difficult.
    - Biofouling can change the interaction between CP and water and colonize differently the steel and the anodes, thereby having an influence on the measurement of the protection potential. There is no clear feedback about these effects.
    - Oxygen diffusion is also limited in some extend slightly reducing the current demand over many years.
- Behind the fouling skirt, the dead material can introduce active microbiologically induced corrosion, in short MIC.
- Biofouling can increase the hydrodynamic loading of structures, and amplify impacts of corrosion.
- Impact on sensors: biofouling can adhere to sensors and alter the signal they emit and/or receive. This will reduce the accuracy of the measurement, increase the uncertainty and sometimes make the sensor malfunction.
- Impact on visual inspections: Biofouling impedes visual inspection either using divers or ROVs. Biofouling may need to be removed in order to observed corrosion damage.

Possible solutions to prevent biofouling of sensors:

- UV LEDs
- Integrated brushes
- System to take a small water sample, measure and inject biocide to kill any fouling species that are present. This can be automated in a sensor. The use of biocides might be an issue. Maybe only take a sample every week to reduce the exposure to biocide.
- Flow cell to keep water flowing around the sensor
- Copper shield around sensor

4.1.4 Monitoring of pitting corrosion

Within the project consortium there is no known, commercially available, solution for monitoring of pitting corrosion on offshore structures. For process industry, Honeywell, Alspi and several other companies have developed sensors for detecting pitting corrosion, however the type of pitting corrosion that is of concern to offshore support structures is quite different.

Defining pitting corrosion

Pitting corrosion is typically known as the formation of deep pits with a small diameter to depth ratio. It generally occurs after local break-down of the passivation layer on for example stainless steels.

[4] Kris De Baere, Ongoing research by AMACORT at the Antwerp Maritime Academy (https://www.hzs.be/nl/onderzoek-expertise/onderzoeksgroepen/amacort-corrosie-en-fouling)

However, in offshore structures, where carbon steel is the main construction material, the shape of pits appears much more shallow than the deep penetrations ascribed to pitting in other sectors. ***It raises the question what pitting means for carbon steel in seawater? I.e. how to define pitting corrosion for offshore structures? And thus what is it that needs to be detectable by monitoring?***

The pitting in stainless steel in process industry is a different electrochemical mechanism than the pitting of carbon steel in offshore applications. The pitting of carbon steel offshore might be described as a kind of 'uniform pitting corrosion' or 'localised corrosion' resulting from heterogeneities in the environment on a local scale, i.e. the aspect ratio of these pits and the shapes are very different as compared to 'real pitting' of stainless steel (by breaking up of a passivation layer). For stainless steel, pitting corrosion is a well-defined electrochemical process with pinning of anodic sites at locations where the passivation layer has been broken. But is this also true for carbon steel in offshore? It is not always easy to identify where there is more general corrosion in a certain area and when it is a pit growing with time. The so-called pitting corrosion of carbon steel, is a local pinning of anodic reactions, still in the uniform corrosion mechanism. In addition, it is not well understood under what conditions pitting corrosion forms in marine conditions (e.g. under bio-growth).

The definition possibly has to be based on risk aspects, i.e. when does a pit result in a stress concentration that has an impact on the fatigue life? This is the type of pit that concerns offshore asset owners. A clear definition is required in order to know what we need to be able to identify and monitor (both from a physical and electrochemical point of view).

Opportunity for future R&D: The definition of pitting of offshore carbon steel could be part of a research project, where the mechanism is described and the causes determined. What is really happening, affecting parameters, verification of hypotheses, literature survey, etc.

Sensors for marine pit corrosion

To the authors' knowledge, no sensor are currently commercially available for measuring pitting corrosion in marine applications. One would also need to define what a pitting sensor needs to be able to measure. A basis could be some standards reported in Gomez et al. (2019) where the focus is on the number of pits and the extend (depth, maximal length). Also pit growth rate, or a 'risk' for the development of pitting corrosion could be useful parameters.

For most applications, not pitting in itself, but its consequences are of importance. This includes development of flaws, stress concentration, reduction of fatigue life, crack development, etc. Therefore, it would be beneficial if the same tools/sensors could be used to identify pitting, cracks, flaws, etc.

Possible approaches for the development of pitting corrosion sensors could be:

- Visual techniques with automated data processing (see section 4.1.1.5)
- ER-type probes with adaptations to detect pitting. Some ideas: thin wires, higher sensitive equipment, detection of liquid passing a corroding plate, etc.
- Ultrasound monitoring (guided wave, Lamb waves, see section 4.1.1.3)
- The use of AE (see section 4.1.1.4)
- In lab conditions, EIS and ENM can be used to identify pitting corrosion, this might be translated into a sensor system.
- LPR technique: see discussion in section 4.1.2.2

Opportunity for future R&D: It is clear that pitting corrosion is one of the forms of corrosion that can have the strongest impact on the lifetime of a structure. However, it also appears to be one of the most difficult forms to monitor. Research on the development of pitting sensors, either on the structure itself or based on coupons, could be extremely valuable for the sector.

4.1.5 Monitoring of Microbiologically Influenced Corrosion (MIC)

Other particular form of corrosion for which it has proven difficult to estimate risks and perform targeted inspections and/or monitoring is Microbiologically Influence Corrosion (MIC). This type of corrosion typically occurs near or below the seabed, but it is not necessarily limited to these locations.

- At C-Cube, methods to detect the MIC mechanism developing from an LPR measurement have been developed. The film formation can also be followed by EIS, though only in lab environments this has been done.
- Another way of monitoring the development of MIC could be to try to monitor local decrease in pH at the steel surface. This would however need to be done under the biofilm, i.e. a very thin/flat sensor that doesn't interfere with the biofilm formation itself. Such a development could prove very challenging.
- Also the development of biofilm sensors could provide information on the formation of MIC. Some work on this was done at Institut de la Corrosion in collaboration with NKE Instrumentation. A three-electrode potential and current measurement was performed. A drop in current density after addition of chlorine to kill living organisms shows that the influence of these organisms on corrosion is also detected. (E. Diler et al., 2014)
- MIC is a stochastic process. It is difficult to predict where exactly MIC will develop and thus where to place the sensors. The sensors also need to be placed without affecting the MIC behaviour itself.
- In the short term, different parameters like pH, potential, etc. of the steel could be monitored as an indication for the risk of MIC developing. Boundary conditions or risk parameters like nutrients in the water, the presence of bacteria, pH near/at the surface could also be used as input. However, quite some research effort would be needed in order to reliably link environmental parameters in different conditions to the extent of MIC corrosion developing. An AI-based approach might be envisaged here. (cfr. ongoing work in the SOCORRO project[5], the AI based approach followed there could possibly be extended to other forms of corrosion.)

An additional difficulty might be that sensors can be affected with bacteria before installation. If these bacteria lead to MIC, a high corrosion rate can be measured even if it doesn't come from the structure itself. Although for open water offshore monitoring, the impact of 'contamination' on a sensor may be expected to be very small.

Opportunity for future research: Development of MIC sensors. A particular difficulty could be corrosion by MIC below the mudline.

[5] www.SOCORRO.eu

4.1.6 Monitoring corrosion of concrete

Sensors embedded in concrete can be used to monitor evolution of the environment (ingress of e.g. chlorides) or the corrosion itself. Main challenges are choosing the right location to put the sensors and the durability of the sensors.

- Monitoring is often limited to the steel potential: normally there is a passive layer on the rebar, when the passivation is destroyed and corrosion begins, the potential will drop. This gives a good indication of corrosion risk.
- Often no direct monitoring of crack formation, etc. is performed
- Probes can be embedded in the concrete to monitor steel potential and conductivity. Measurements can also be done with sensors placed on the outside of the concrete, but then sensors are needed around the structure, in combination with modelling to extrapolate from measurement location to other positions on the structure.[6]
- Embedded sensors typically don't last for the full lifetime of a structure (e.g. >20 years). Therefore, a combined approach could be envisaged, with embedded sensors for validation on the short term and external sensors for long term monitoring.
- At Université de Nantes and Université Gustave Eiffel technology is being developed to monitor the permeation of Cl^- through the concrete cover.
    - At the time of writing of this report, development is at the stage of laboratory testing and almost ready for field trials.
    - Sensor are embedded in the concrete with sensing elements at various depths, allowing to determine a profile of chloride concentration vs. depth.

4.2 Coating degradation monitoring

There are corrosion sensors to monitor the thickness of a metallic coating or to detect the initiation of corrosion below an organic coating based on ***electrical resistance (ER) principle***.

- The AirCorr O sensor from NKE Instrumentation measures and records the evolution of the electrical resistance (ER) of a metallic coating applied to an insulating substrate. ER data can be converted into loss of thickness (mm), or corrosion rate (mm/year). Other companies are developing similar sensors (NanoCorr/Corr instruments, Xcorr series/Aginova,...) using the same measurement principle. The question of remote interrogation of these sensors (remote monitoring) and their durability (environmental aggressiveness, aging of the sensor etc.) is the critical point of these technologies.
- To monitor degradation of organic coatings, the corroding element in an ER-probe can be coated. If the coating degrades, the steel element will start to corrode and this is recorded by the ER-probe.

Electrochemical techniques can also be used to monitor coating degradation: At C-Cube sensors have been developed for periodic and permanent coating condition monitoring based on EIS measurements. The difficulties of the measurement and data interpretation are covered by the sensor design and analysis software. Data interpretation involves a standard procedure with internal calibration of the equipment. The more information/metadata is available (design, coating system,

[6] Elsyca NV (www.elsyca.com)

etc.), the better the prognoses of the degradation. The technique is currently applied at offshore asset owner, with testing of up to 36 different coating types on different locations using witness plates.

Advantages and drawbacks of the electrochemical technique are:

+ A lot of information is obtained about the coating and the substrate.
+ It is predictive (it can detect coating damage before it is noticeable to the naked eye)
- It requires the use of a Faraday cage.
- It requires an alternating power source.
- It is very sensitive to variations during the measurement (shocks, noise, vibrations, other signals ...)
- Interpretation of results is complex.

4.3 Environmental monitoring

Next to direct corrosion/degradation monitoring, the environment to which the structure is exposed can also be monitored. The advantage to this approach is that it provides information about the aggressiveness of the environment and therefore the risk to which the entire structure is exposed, whereas corrosion measurements are often spot measurements. Off course, there may also be local variations in the environmental conditions (for example in locations with little water refreshment or stagnant conditions). Selecting the critical locations for monitoring therefore remains a key element to a successful monitoring strategy. Combining environmental monitoring with direct corrosion monitoring, also provides a wealth of additional information that can help to interpret the measured corrosion rates and detect deviations from design assumptions.
Environmental monitoring is important since it is a precedes (first thing that can be monitored) potential changes in terms measured corrosion. It might trigger an alarm when certain values are exceeded, resulting in increased attention when checking the corrosion monitoring. For instance, a small change in corrosion monitoring (LPR, etc.) can either be ignored as statistical variation or given attention to when preceded by environmental changes detected by the environmental sensors.

Sensors for continuous monitoring exist for a large number of environmental parameters. The most common are Temperature (T), Dissolved Oxygen (DO), pH, Oxidation-Reduction Potential (ORP) and Electrical Conductivity (EC). However, monitoring solutions also exist for nutrients, ionic species, turbidity, chlorophyll, etc. Other values can also be derived from certain measured parameters, like for example salinity, which is derived from conductivity (it’s important to be aware of the assumptions made in such derivations).

In cases where it is expected that the environmental conditions change only slowly, periodic inspections instead of continuous monitoring may be preferred. Often, a project for this is conducted once per one or two years. This involves lowering a set of sensors together with a depth sensor, acquiring a depth profile of the parameters. However, if the cost of monitoring is the same total price as the periodic inspections (including all the transfer/personnel costs), monitoring is more beneficial. In cases where a faster response to changing conditions is needed, or where there are fluctuations in time which may go unnoticed with periodic inspections, monitoring also clearly brings advantages.
Therefore, in a situation where sensors need to be calibrate or inspected every year (which is the case with all commercial sensors currently known to the authors), it is not relevant to do monitoring, unless

the additional information on evolution of parameters over time (seasonal variations, etc.) provide important input for the corrosion monitoring or monitoring of CP. In that case one might chose continuous measurement, even if yearly calibration is required. It all depends on the value of information from monitoring data (see chapter 6.1).

Remark: environmental monitoring won't give information on types of corrosion like SCC which are mainly driven by the choice of material and mechanical conditions.

Below, a number of the most important parameters are discussed in more detail.

4.3.1 Temperature (T)

- Has a direct influence on corrosion rate, with a higher temperature leading to a higher corrosion rate.
- Also has an influence on other parameters like DO and EC and is therefore critical to correctly quantify these parameters.
- Easy to monitor, often included in other sensors like DO or EC.

4.3.2 Dissolved Oxygen (DO)

- Driving force for corrosion and one of the most critical environmental factors to monitor
- Oxygen is consumed in one of the major cathodic reactions. The concentration of DO therefore directly influences the corrosion rate, as this cathodic reduction reaction linked to oxygen is often the rate limiting factor. In that case, a higher DO leads to a higher corrosion rate.
- Can be especially important for closed spaces that rely on oxygen depletion or where the activity of microbial life is expected.
- Dissolved oxygen can be measured either with electrochemical or optical sensors. Optical dissolved oxygen sensors tend to be more accurate than their electrochemical counterparts and are ideal for long-term monitoring programs due to their minimal maintenance requirements. They should be able to hold a calibration for several months and exhibit little calibration drift.

4.3.3 pH

- Has a direct influence on the corrosion potential of exposed materials, although the influence is expected to be small within normal pH ranges (5-9).
- Can be altered in the vicinity of a structure (of inside a structure) due to the presence of cathodic protection (CP). In some cases, pH values as low as 4 have been reported, meaning a totally different environment, which do not correspond to the design rules assumptions.
    - The amount of calcareous deposit that is build-up on the surface due to the effects of CP depends on the pH of the surface (a pH of 8.5-9.0 is required for the formation of such deposits, while the seawater typically has a pH of around 8.2). CP leads to the steel surface becoming more alkaline, with the increase in pH at the surface depending on the CP current.

    - On the other hand, CP can reduce the pH of the water around the structure considerably due to the formation of O_2 (ICCP), H_2 (ICCP outside of design operation) or Al-hydroxides (SACP based on AlZnIn, hydrolysis of Al-ions)[7]. This should normally only occur in situations where there is almost no water renewal (closed monopile designs, ballast tanks, etc.). If the pH drops too low, the protective calcareous layer on the surface can be broken down.
- pH measurements are predominantly conducted with pH-sensitive glass electrodes.
- The potential of cells containing glass electrodes often drifts slowly with time.
- Accuracy in the range of 0.1 would probably be appropriate for most corrosion related monitoring.
- pH sensors often don't work well in real world conditions and need frequent re-calibration. However, recent (2010's) developments are opening the way to solid state pH sensors which could be cheaper, more stable and robust compared to traditional pH sensors. (https://www.mdpi.com/journal/sensors/special_issues/PH)
    - It's assumed that they can be made cheaper. However, the experience is that they are typically still more expensive than electrode based sensors.
    - Notwithstanding their potential, so far no proof has been seen that these sensors would last longer and require less calibration.
    - Typically have a somewhat lower accuracy than the glass electrodes
- If pH cannot be measured accurately, the pH could theoretically be reconstructed from the measurement of other parameters in the carbonate system in seawater (pH, CO2, dissolved inorganic carbon DIC, alkalinity). The practical feasibility of this approach has, to the authors' knowledge, not yet been investigate for marine environments.
- Cost: 400-1000 euros

4.3.4 Oxidation-Reduction Potential (ORP)

- ORP is a measure for the oxidation or reduction tendency of the water. A positive value means oxidating, negative reducing. A higher oxidating tendency means that corrosion is more likely to occur. However, there is no 1-on-1 relationship between ORP and corrosion rate.
- In the industry, it is often used as a proxy for corrosion in certain chemical/cleaning processes, where a threshold in terms of mV is set and when ORP becomes higher, corrosion can be expected to occur.
- The ORP measurement is typically included in pH electrodes.

4.3.5 Electrical Conductivity (EC) & Salinity

- Salinity is derived from the EC, under the assumption of a known and stable water composition.
    - In seawater, chloride concentration is the main component in the salinity.
- Two types of sensors exist: Electrode Conductivity sensors and Inductive (Toroidal) Conductivity sensors. The former is the most common and requires calibration every few months. Electrodes need to be cleaned in case of fouling. The latter is seen in process industry,

[7] Source: Elsyca

has a large measurement range and is quite robust. (Need for calibration of the latter not known to the current authors.)

4.3.6 Formation of corrosion products and other deposits

- Corrosion products have a tendency to reduce the corrosion rate over time.
- Calcareous deposits: important in combination with CP, which can result in the formation of these deposits, as they decrease the corrosion rate (and CP current requirements).
    - In this regard, monitoring of the Ca/Mg balance would bring important information about the formation and stability of the calcareous deposits.

4.3.7 Chloride content and other chemical compounds in the water

- Higher chloride contents increase the EC and with it the corrosion rate.
- Higher chloride contents will also increase the likelihood of pitting corrosion.
- For offshore structures, it is expected that the composition of the water is relatively constant, in which case measuring the EC can give a good estimation of chloride content. (Periodic water sampling can be performed to confirm this.)
- Monitoring the presence of sulfur and nitrogen species in water can give an indication about the activity of MIC.
- Two main types of monitoring solutions exist: Ion Selective Electrodes (ISE) and Analysers
    - Ion Selective Electrodes operate according to the same principle as a pH electrode. They exist for a wide range of species: Ammonium / Ammonia; Chloride; Nitrate; Fluoride; Iodide; Bromide; Calcium; Magnesium; Potassium; Sodium; Lithium; Cupric ($Cu2+$); Silver. The accuracy of ISEs is often limited to several %. They also need frequent recalibration. And it is know that for example ISE sensors for chloride don't work well in seawater.
    - Analysers are automated probes that perform chemical analysis, either by reacting a sample of water with a reagent that changes the colour depending on concentration or by performing spectroscopic analysis. The former are more likely to be deployable in offshore conditions. Storing and refilling of reagents means that the number of measurements that can be performed is limited, but there are systems that can perform > 2000 measurements. Recent developments in this field are for example from https://www.clearwatersensors.com and https://2swater.com. Also companies like https://www.ysi.com/ offer this type of solutions.

4.3.8 Gasses

Inside foundations, protected by CP, gasses can built up like bromine, chlorine and hydrogen gasses, affecting the environment. The effect of these compounds, mainly in the E0 of steel (the own electrochemical potential of the steel, i.e. the corrosion potential of the steel in the environment changed by the presence of bromine, chlorine, etc.) are not taken into account in the design. This can also result in overprotection of the steel, the fast degradation of coating underneath the Airtight platform, the corrosion of the vent system, and chlorine and bromine fumes exiting into for example the tower of wind turbines, resulting in attack of the electronic devices, and human health and safety, let alone the environmental issues.

4.3.9 Bio-fouling affecting sensor reliability

- In marine conditions, fouling of sensors presents a significant problem.
- Especially pH sensor are sensitive to drift, even after short exposure times (1 month or less).
- Solutions exist to limit fouling and drift (brushes to automatically clean sensors, UV-light, biocides in combination with a flow pump, etc.).
- However, even with such solutions, issues were reported after 4-6 months (Schoefs, 2021), making it necessary to go on-site for cleaning every 3-4 months (see Figure 3 and Figure 4). This clearly indicated that further development in these sensors is required to make unmanned operation for periods up to 1 year possible.
- The cost of anti-fouling systems (often on multi-sensor probes) can be quite high compared to the cost of individual sensors. In addition, it is unclear to the authors if a 6-month maintenance interval can be achieved even with these types of solutions.

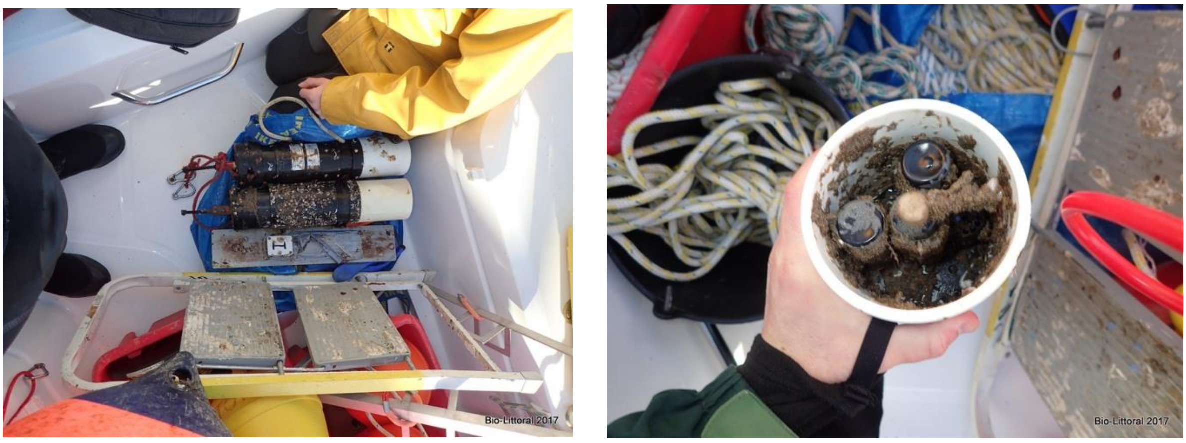


Figure 3: Typical multisensory probe (see 4.3.10) with an internal colonization after 4 months even in presence of a brush. © F. Schoefs-Université/Capacités.

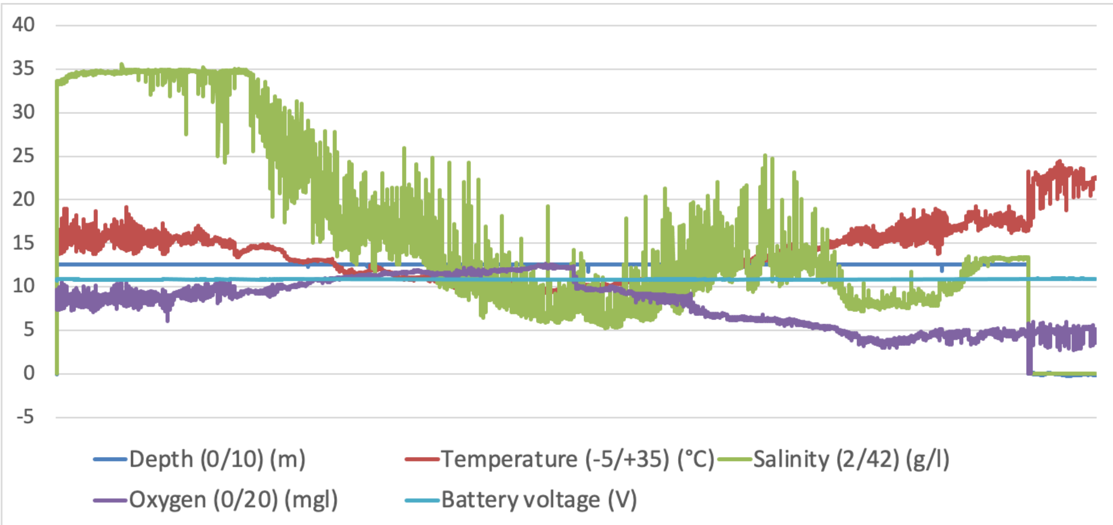
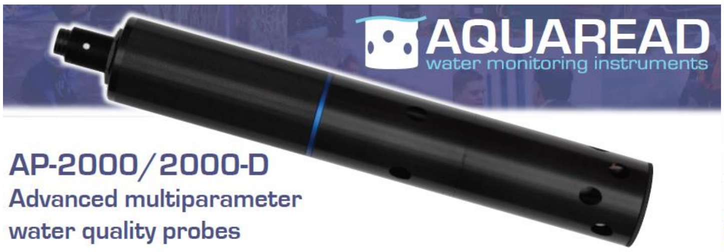


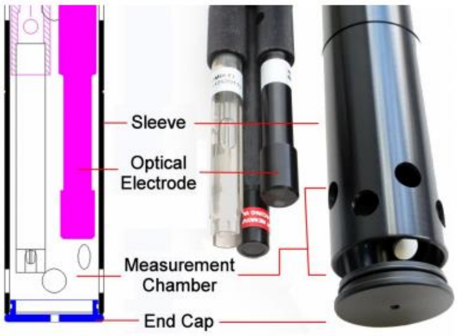
Figure 4: Deviations of parameters (salinity) measured by a multisensory probe after 7 months without maintenance. © F. Schoefs-Université/Capacités.

4.3.10 Multisensory probes

The range of sensors available on the market is very large. The range in cost easily spans an order of magnitude (from a few 100 to thousands of euros). There is also a choice to be made between using single probes (that each measure one or two parameters) or using multisensory probes (A single probe body that contains all required sensors). The latter seem to be the most suitable choice and have typically been designed for monitoring of ocean water, surface water, ground water, aquaculture, etc. (Although not for the long periods of unmanned operation typically required in offshore energy structures.)

An example of such a system is shown below[8]:





- Most of the types of measurement discussed above can be integrated, in a multisensory probe except for concentration analysers.
- Can also be used as hand-held meters for manual inspection.
- Systems with anti-fouling solutions to reduce need for cleaning exist
    - systems using a brush (cheapest anti-fouling system)
    - systems using UV light (good feedback from these systems[9])
    - systems using a flow cell (with/without biocides)
- Huge price range: 4k to 39k euros, depending on number of sensors, anti-fouling options, data storage/transmission options, etc.
- A number of known suppliers are (non-exhaustive list): Aquaread, YSI, Seabird Scientific, AML Oceanographic, Eureka Water Probes, NKE, Anhydre

4.4 Cathodic Protection monitoring

One of the most important forms of corrosion protection for submerged structures is cathodic protection. Monitoring the effectiveness of the cathodic protection is therefore also critical. In effect, the electric potential of the structure needs to be known.

There are two main ways to monitor CP systems:

- Direct measurement of the potential, typically using reference electrodes

[8] https://www.aquaread.com/

[9] FLANDERS MARINE INSTITUTE, www.vliz.be

- Measurement of anode currents (can be done both for sacrificial anode systems and impressed current systems)[10]

Other way of monitoring the functionality of CP systems could be:

- ER/LPR probes connected to the steel structure
- Bromine and chloride gas development: The overpotential of the ICCP system is a driving force for redox electrode reactions (anodic reactions), first oxygen (hydrolyses: $2H_2O$ -> $O_2 + 4H^+$), followed by chlorine and eventually bromine gas development. So, with increasing overpotential this ladder of evolution develops. Monitoring the evolution of gasses could thus possibly give information about the operation of the ICCP systems, however it is not expected to lead to a real qualitative assessment of the protection level of the structure.

CP systems are often designed using advanced computational models. Monitoring of environmental conditions (boundary conditions) could be used to further fine tune modelling assumptions (not just water composition, but also flow velocities, presence of (abrasive) particles that can degrade protective layers being formed, etc.).

Although the design of CP systems is covered by design standards, they don't cover the influence of local flow velocities, DO, T, salinity, etc. These parameters influence the electrochemical reactions of the surface of the structures to be protected. A solution has been developed by NKE Instrumentation (SCPC sensor) to measure in-situ the current density necessary for the protection of a submerged metallic structure, and thus the size and quantity of sacrificial anodes (or the current supply power of the cathodic protection system). Elsyca can also perform CFD simulations to determine the seawater flows and velocities in and outside the monopile, providing input for the CP design. The corrosion models developed by Elsyca, potentially backed-up with available field data, can be used to design CP systems, optimised for local conditions and structure design.

Opportunity for future development: A particular question is also the potential of the surface below bio-growth. This potential is often unknown and cannot be measured accurately, resulting in uncertainty about the corrosion protection of the structure. The same is true for the potential of the surface below the mudline, which is a critical area both in terms of mechanical loading and highest risk of under-protection.

4.5 RFID sensor systems

For ***RFID sensors (Radio-frequency identification)***, the principle is to have many low cost sensors with a good durability (no electronic devices in it). The measurement probe can be humidity, deformation or thickness loss by corrosion. For passive RFID tag, the method is based on the remote interrogation by a reader of a passive tag on which are placed an antenna and a chip. The radio frequency wave emitted by the reader is received by the chip of the tag and allows it to collect energy and return information to the reader. To some extent, it can therefore also be seen as a kind of inspection

[10] Example of a probe to measure anode activity: https://stoprust.com/products-and-services/efg-probe/
Example of a sensor allowing to monitor the current needed to protect 1 m² of steel: https://stoprust.com/products-and-services/dr-2-cd/

technique rather than continuous monitoring. ***At the Université Gustave Eiffel a research project is currently ongoing with this technique to detect damage of anticorrosion layers on steel offshore structures, as well as for detection of uniform corrosion rate and locations of more localised corrosion.***
There are some references for civil engineering structures (I. El Masri et al., 2020; R. Khalifeh et al., 2016), but not yet for offshore, as the domain of offshore structures is under development. The TRL is low for the moment (laboratory stage). Only passive sensors can be developed with this technique: an ER sensor is possible, however it is unclear if sufficient power could be transferred for techniques like LPR and EIS.

5 Sensor integration, data analysis and monitoring strategy

Effectively monitoring corrosion comes down to more than a selection of the most reliable sensors. Decisions need to be made on how many sensors to use, where to use them and what parameters to monitor. The sensors need to be incorporated in the structures so that monitoring on the most critical locations becomes physically possible. They also need to be integrated in IT systems, data transfer needs to be arranged and the sensors themselves also need to be included in maintenance schedules. Finally the collected data needs to be combined with other available data from design, inspections, other sensor data, etc. and analysed. The analysis needs to lead to outcomes and conclusions that provide added value for O&M programs, design optimisations, etc. (see chapters 2 and 6.1).

In this chapter, some of the challenges this presents are looked at in a bit more detail.

5.1 Sensor integration

5.1.1 Installation of the sensors

A distinction can be made between retrofit solutions and installation of sensors on new builds. In ***retrofit solutions***, the possibilities to accurately position sensors are often limited if a cost effective solution is sought after, especially if the use of divers/ROVs is to be avoided. For example in the case of monopile foundations, sensors on the inside of the MP are often hang-off from the work platform. In some cases, magnet systems can be used to fix sensors against the structure itself. This type of approach could also be used on the outside, where water flow, waves, etc. can push sensors around if they are not securely fixed in place.
For ***new builds***, options can be explored to attach sensors to the structure prior to installation. Corrosion Monitoring sensors are now typically added as an add-on after manufacturing (and often after installation). This can be done much more efficiently when installation of sensors would be taken into account in the design stage (which is rarely done). Attachment points can be foreseen, cable routing for the sensors can be integrated with other elements of the structure, etc. Sensor placement could be foreseen in such a way that the measuring surface of the sensor is level with the actual steel surface instead of stick-on or hang-off, thereby being more representative for the structure itself. The sensors themselves could also be redesigned in order to make optimal integration possible. It might even be possible to attach sensors to the structure prior to installation, on the conditions that the sensors, cabling, etc. themselves survive the installation procedures.
A particular problem is ***monitoring of corrosion and environment below the mudline***. With retrofit solutions, it's virtually impossible to install sensors below the mudline. Although an options using a

full-length corrosion coupon has been presented in an article by Force Technology in 2016 (Mathiesen T. et al., 2016). This is essentially a steel pipe driven into the seabed and retrieved after a certain period. If sensors could be integrated on structures prior to installation, and survive installation (pile driving in the case of MP foundations), monitoring below the mudline could perhaps be realised. An additional difficulty is the impossibility to perform maintenance on the sensors, meaning that they should be robust enough to remain operational for at least a couple of years.

Additional remarks from the survey:

- In some cases, a system that does not require separate power can be beneficial. (Lack of power on some (test) sites.)
- Corrosion monitoring of foundations can be especially critical in a stage when no CP is installed yet, or during power outage. This means systems meant to monitor during these periods should be able to operate stand-alone.
- Real-time data should be available, or at least status updates at reasonable times intervals depending on the application and criticality of the component and conditions (e.g. once a day, once a week,…).
- Passing of cables through the hull to accommodate sensors on the outside can be an issue.
- Cable failure can be an issue.
- Underwater installation is difficult and expensive.
- Installing sensors at the critical locations can be very challenging.

5.1.2 Sensor performance and maintenance

As has already been covered in chapter 4, many existing sensors are not robust enough for long-term marine deployment. There can be problems with bio-fouling on the sensor, but also mechanical damage to sensors, especially if they are installed on the external surfaces of offshore structures. Cabling of sensors can also be long and difficult to attach properly to the structure to avoid damage from seawater movement.

In order for continuous corrosion/environmental monitoring to truly become widespread in offshore energy applications, the period between sensor maintenance should be at least of the same magnitude of the period between required structure/system inspections. Unless the value of information is large enough to offset the costs for sensor maintenance (see chapter 6.1). Ideally, sensor maintenance can be planned alongside normal operations. For offshore wind structures this typically means that maintenance should be limited to once a year. At commercial stage, wave and tidal devices should also not be maintenance intensive anymore to be cost competitive, so the same limitation would likely apply in this sector.

5.1.3 Data collection and transfer

Because most offshore energy structures are not visited regularly, local data logging is not a good solution and automated data transfer to shore is required. A number of options for data transfer exists. If a network connection is available, data transfer via GPRS/4G/5G is a good option. This has the advantage that sensor systems can be made completely stand-along. Especially for retrofit solutions this makes integration easier. The advent of offshore 4G/5G networks, for example in offshore wind-farms makes this an attractive option.

Another approach is to transfer data to shore using existing data cables running from the offshore structures. As an example, the company 24Sea has an integrated DAQ design to which many types of sensors can be added and data being transferred over LAN networks. This makes available simple communication of the data. The data is often not seen as strategic, and has their own gateway to shore. The communication of the older wind farms is often more difficult, not having internet.
Another solution, applied for example in projects of the Université Gustave Eiffel is Lora (https://lora-alliance.org/). Lora was used to communicate data from a structure situated offshore to the coast. This may be carried out only for structures close to the coast (approx. 15 km). The number of industrial examples of usage of this technology is however limited.

5.2 Monitoring strategy

In order to set up an efficient monitoring system, the monitoring strategy needs to be clearly defined. This includes a definition of where sensors need to be placed, how many sensors are required and what parameters need to be measured.

5.2.1 Definition of monitoring strategy (concept) – points to be considered

Defining an effective corrosion monitoring strategy, should start from knowing very well what the requirements/needs are for the application under considerations. I.e. it should start from the considerations in chapter 2.

The most interesting parameters to measure are typically corrosion rates and protection potential (in case of CP). Knowing the location and extent of corrosion would in addition allow to act to mitigate corrosion in a more effective way. In addition to direct corrosion monitoring, it would be interesting to monitor the environmental parameters that influence corrosion (see under section 4.3), in order to be able to obtain a correlation between environmental and corrosion parameters that allows better estimates to be made for the future.[11]

A corrosion monitoring strategy should evolve from the risk inventory during the planning of the windfarm or other offshore energy structures. Questions to be asked are:

- What location on the structure are considered most critical?
- What corrosion mitigation strategies will be applied and can their effectiveness be monitored?
- Are all structures exposed to an equal risk or are some structures in a higher risk zone?
- What are the expected inspection and maintenance costs?
- Are all risks accurately known or is further analysis during first years of deployment required?

Also, the vision and scope of the farm is important. If the financial loans are paid off in 25 years, and monitoring can help to prove that the remaining technical lifetime of the structures is another 15 years, this would mean monitoring can provide a lot of value, even if O&M costs are not reduced by the monitoring. ***An important element in determining the monitoring strategy is therefore to define the goals of the monitoring campaign.***

Many corrosion probes don't measure the structure itself, but an element in the probe. Therefore, these probes can be considered more as measuring the aggressiveness of the environment than

[11] Work on this topic is being done in the European project SOCORRO (www.socorro.eu)

corrosion of the structure itself. The measured corrosion rates are therefore an approximation of what can be expected for the structure. Other techniques that could be used to monitor the actual structure, like UT and AE are not (yet) developed for continuous maritime deployment. Monitoring certain environmental parameters and aggressiveness of the environment can however be used as markers for what is going on with the structure itself.

5.2.2 Critical positions/elements for monitoring

The sensors must be placed in the most critical points of the asset to be monitored. In order to define a good monitoring strategy, a good insight is needed in what these locations are, which may be very application dependent. Critical points in reference to corrosion include: welds, crevices, grooves, areas that accumulate water (with poor drainage in case of above water structure), areas with stagnant water conditions for submerged structures, intertidal areas, below the mudline, splash zone and areas that are difficult to inspect (safety reasons, accessibility). Information obtained from the survey is contained in section 2.2.2.

Computation models (digital twin principle) can be used to determine strategic locations where to install sensors. The expected location dependent corrosion rate of the structure can be determined by modelling the structure and the corrosion taking place. In addition, the protection potential resulting from a CP system can be calculated. Al this information can be used to decide what parameters to monitor in what locations and how many sensors are required.[12]

- During a project on offshore jacket structures, Université Gustave Eiffel identified the two most critical locations as the intertidal area, and the area in contact with the soil: Mud zone. This is where interfaces exist between 2 different environments, which accelerates corrosion.
- Exposed areas (tidal, splash zones) have to be monitored in priority as the corrosion rate can be very high. In these areas, there is a critical combination of high oxygen levels, wetting/drying, mechanical damage and inefficient CP. Corrosion can potentially also be less predictable in these areas and vary more from one site to another or from one period to another (as the conditions also vary more as compared to continuously submerged parts of a structure). The splash zone is a critical zone in terms of highest expected corrosion rate, but typical sensors for submerged application cannot be used here (i.e. electrochemical methods are not feasible).
- Pitting corrosion results in the formation of additional stress concentrations. Near the connection between components, where there is already a structural stress concentration and therefore enhanced risk of fatigue, the additional impact of pitting should be quantified.
- A critical level of pitting corrosion that needs to be detectable should be defined based on a risk analysis:
    - If fatigue due to additional stress concentration is the expected failure mode, the minimum depth and length to be detected have to be known.
    - If water ingress in a component due to perforation of a wall is the expected failure mode, the minimum depth to be detected has to be known.

[12] Source: Elsyca, company specialized in modelling of electrochemical processes, including corrosion

In the development phase of devices/structures, attention should already be paid to where corrosion or other degradation phenomena are observed, even if only indications after short term deployment, as this can provide valuable information to develop an efficient monitoring strategy for long term deployment.

5.2.3 Virtual sensing and fleet leader concepts

Opportunity for future research: Applying the principle of virtual sensing, which is mature for fatigue, to corrosion is not straight forward. As for the case of fatigue, validation of the digital twin and virtual sensing is required, using actual field data from monitoring and inspections of the fleet leader(s). In addition, minimal 'triggers' are required from existing data on the other foundations (SCADA, SHM, etc.) that are representative for the occurrence of corrosion events/high corrosion risk. It is unclear what these 'triggers' could be. Perhaps current consumption of anodes could be used, but this is also influenced by damage to anodes, changes in the CP configuration, etc. Therefore, additional input or validation is required based on inspections, known system changes, etc.

5.3 Data analysis

A lot of work is still needed in terms of optimising and automating data analysis. This could include the following steps:

- Comparison to known values for environmental parameters, corrosion rates, etc. for the location under study.
    - For environmental parameters, in Belgium, the monitoring data from VLIZ can be used as a reference. Values like temperature, pH, oxygen, etc. has been monitored for years using a research ship. There is also a buoy located at the C-Power windfarm that monitors water parameters. The data is available on request (https://www.vliz.be/en/request-data).
- Automated recognition of sensor malfunction (for example detection of sensor drift).
- Computation models can be used to monitor the corrosion health of a structure. Local sensor data could be extrapolated to calculate the corrosion rates on the entire structure, based on current distribution. (www.elsyca.be)
- Models to link environmental parameters to expected corrosion/degradation rates (for example as being developed in the SOCORRO project, www.socorro.eu).
- Interpreting data from probes to understand what this means for the actual structure itself (representativeness of for the structure).

Some typical corrosion rates are given in the table below. It is however important to realise that actual corrosion rates may be strongly location dependent. The corrosion is not a monotonous phenomenon and the corrosion rate should be linked to a lifetime. Data are available in Schoefs et al. (2020), based on 30,000 measurements of corrosion during more than 30 years in French seas.

Environmental zone	Corrosion rate (mm/y)
Buried in soil	0.06-0.10
Submerged zone	0.10-0.20
Intermediate zone	0.05-0.25
Splash zone	0.20-0.40
Atmospheric zone	0.050-0.075

Source: J.P. Ault, The Use of Coatings for Corrosion Control on Offshore Oil Structures, J. Prot. Coatings Linings. 11 (2006) 42–46.

An important aspect is also ***how the results of monitoring are reported to asset owners***.

- In the best case the asset owners themselves know how they want the data. But, in general, data has to be converted in the form of notices and actions to take. Such as remaining life of assets, requiring maintenance, high corrosion rates,...
- Data from corrosion monitoring is also expected to contribute to an optimised O&M plan. Data analysis should therefore allow to update O&M plans, to set inspection priorities, etc. Even short-term data can already play an important role here.
- The raw data will not be comfortable or understandable for all asset owners. When it is requested to report data (after analysis) as an 'expected remaining lifetime', it is important to realise that, to come to such a value a fair number of assumptions needs to be made. The main assumptions and conditions under which the 'remaining lifetime' is to be used thus also need to be reported and made clear to the end-user.

In terms of reporting, an important distinction is between short-term and long-term data. With the short-term mainly feeding into setting inspection priorities, raising alarms, etc. And the long-term feeding into management decisions on life extension, design changes for future plans, etc. In section 2.3 the results from the performed survey give insight into what is expected in terms of reporting (ranging from traffic light based to own interpretation of raw data).

6 Economic evaluation of corrosion monitoring

To the authors' knowledge, no real economic evaluation of the potential benefits of corrosion monitoring for offshore energy applications has been done before. A major issue is that application of monitoring solutions may have a significant CAPEX cost, and it is difficult to calculate the return on investment. In this chapter, a methodology to approach this challenge is first described, followed by the limited input related to costs that could be obtained.

6.1 Quantification of the benefits/objectives of corrosion monitoring

The expected economic and non-economic benefits/objectives of corrosion monitoring have been discussed in chapter 2. It is often suggested that Corrosion monitoring will allow better planning of maintenance. This means performing maintenance and inspection tasks only when necessary and avoiding unnecessary storage of spare parts. It will also avoid the need to repair assets, being able to take the appropriate actions to prevent failures when necessary. Other potential objectives/benefits can be found in the field of design validation, financing, end-of-life, philosophy of good documentation, etc.

Although monitoring will increase CAPEX to some extend due to the need to purchase and integrate sensors, an increase in CAPEX (and potentially OPEX) is argued to be acceptable if the value of information obtained from monitoring is higher than the CAPEX and OPEX costs related to the monitoring itself. The meaning of this value of information and how this can be evaluated/quantified is described in the following. The main advantage of a structured methodology to quantify the value of monitoring is that it can be used to decide in what cases and for what objectives monitoring provides an improved solution as compared to the current reference scenario and what the Return on Investment is.

Method for value quantification

The added value or benefit of a monitoring system is to be linked to the specific objectives envisaged (lifetime extension, maintenance costs reduction,…). These objectives are required in order to write the cost function and all the parameters that affect this function. A benefit Bformula and associated costs functions used in the quantification of the monitoring added value of a wharf (Schoefs et al, 2021), is given as:

$$\mathrm{B} := C_{\mathrm{T},SDT} - C_{\mathrm{T},SHM}$$

where $C_{T,SDT} := E(c_i\, N_i + c_p\, N_p + c_c\, N_c + c_f\, D_f N_f)/T$ and $C_{T,SHM} := E(c_0 + \tilde{c}_i\, t + c_p\, N_p + c_c\, N_c + c_f\, \overline{D_f} N_f)/T$

with $C_{T,SDT}$ the optimal cost (in terms of time between inspections) with a usual inspection policy based on Semi Destructive Testing (SDT) only and $C_{T,SHM}$ the cost with SHM only, N_i *and* c_i the number and cost of inspections, N_p *and* c_p the number and cost of preventive replacements, N_c *and* c_c the number and cost of corrective replacements, $\overline{D_f}$ the mean duration spent the curative zone multiply by N_f the number of sequences in in this zone.

Once the cost function is known, a list of potential actions can be drafted (type of inspection, type of conditional repair,...), for which the costs need to be known to serve as input for the cost function/model. The list of actions that serve as input for the cost function, should also account for all the available policies: for example, if the objective is to reduce maintenance costs, strategies and costs of preventive and curative maintenance should be known. Also potential value related to environmental benefits may be considered.

Usually, a monitoring strategy is compared with a strategy with inspection only (see equation above). The latter is the reference scenario that allows computing the benefit (positive or negative) of the use of a monitoring strategy. The uncertainty of data makes the comparison to the reference scenario very difficult, often resulting in both a positive AND negative economical outcome for structure monitoring being possible. Due to the effect of uncertainties on the costs (bad decisions) all the uncertainties on the collected data and all the performances should be known. If not, a parametric study can be carried out. It should be noted that the uncertainties on data can differ significantly when comparing monitoring data to inspection data, depending on the technology used, procedures followed, measurement conditions, etc. It is not a-priori known whether monitoring or inspection provides the larger uncertainty (see 'Value of information').

Value of information

To calculate the cost/benefits of monitoring, the value of information from monitoring needs to be quantified. This value of information is quantified through the benefit (see equation above). It may be higher from monitoring as compared to inspection, due to a reduction of the uncertainty of measurement (due to operator-related uncertainty, location uncertainty (measuring on different location), time variation uncertainty). It should be noted that this will only be true if the sensors used for monitoring are accurate, reliable and robust enough in order for monitoring not to introduce additional uncertainty. This currently still seems to be a technology gap, as indicated earlier in this report. However, if uncertainty can be reduced, this would increase the value of the data. As described above in the cost functions, this benefit is also highly dependent on the cost of the actions (especially curative maintenance) and the cost of failure.

The value of information can also be used to rationally calculate the level of monitoring that should be employed (only CP, direct corrosion monitoring, environmental parameters) and the density of monitoring (how many structures, how many locations on a structure, etc.).

The basic scenario problem

In most cases, the basis scenario or reference scenario is inspection. For offshore wind, the base scenario is often what is mandatory in the DNV guidelines and other regulations (Bureau Veritas, ABS) but these guidelines do not give detailed descriptions of the inspection program. Corrosion monitoring is not mandatory apart from ICCP systems.

In addition, in the case of corrosion of offshore structures, the value of the data coming out of inspection, as well as the costs related to this are not fixed. The value of a sensor is difficult to prove onshore, because cost of inspection is not very high. But the scenario is very different for offshore structures.

Inspection in the basic scenario could be manual inspections using drop cells, ultrasound monitoring, divers, etc. However, the use of divers is very costly, strongly depends on weather (both cost and planning) and has safety risks associated with it (especially for floating structures). In addition, diver inspection may lead to bad decision due to large uncertainty of measurement when not in a comfortable situation. Therefore, also the use of ROVs could be a basic scenario. At Université de Nantes[13] it is know from experience that the uncertainty of measurement can be very high in case of diver inspections. For both divers and ROVs, uncertainty is also introduced due to presence of fouling, bad light/visual conditions, etc.

Knowledge gap: What is the basic scenario? What inspections are done, how frequent and what is the cost of inspection? (If monitoring is not performed.)

The impact of sensor performance

The theoretical performance of a sensor is usually quantified by: accuracy (uncertainty aroung the target value) and precision (bias from the target value). The practical performance considers also, the lifetime of sensors, need for maintenance, calibration, etc. which are all critical information to make an accurate cost calculation, which again feeds into the cost/benefit comparison between monitoring and inspection. The performance of sensors will also have a direct impact on the uncertainty of data, i.e. is the measurement still accurate, and thereby on the value of information. Sensor performance thus has an impact on both the cost and benefits part of the calculation.

[13] Université de Nantes, Interview with Prof. Schoefs on 18/03/2021

Knowledge gap: The lifetime and need for maintenance and calibration of current sensors for long term maritime deployment is unknown.

Required input from industry:
Determining the Value of Information requires various inputs: (1) the costs of actual practices based on inspection only, (2) the cost of failure, (2) the cost of preventive and curative maintenances and (3) the cost of monitoring system optimised for a certain design and in line with a clear objective (see beginning of Chapter 2).

Additional parameters which should be known:

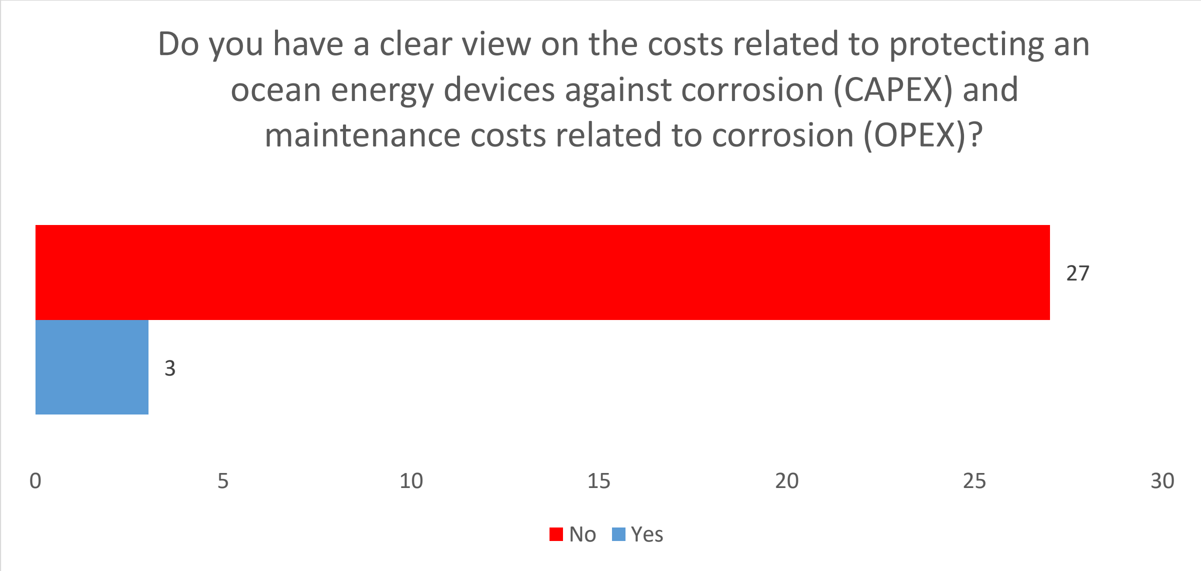
- The overall performance of the monitoring system must be known: accuracy, sensitivity, life-time, maintainability, the lasts two being usually not provided. Some of them could be an output of the optimization strategy (i.e. minimum life-time of the monitoring system) others could be an input (required sensitivity).
- The costs of maintenance related to corrosion prevention, without monitoring.
- What is the cost of corrosion inspection without monitoring?
- What is the cost of monitoring? (Depends on coverage, amount of sensors, choice of parameters to monitor, etc.)
- What is the period over which monitoring is required (5yrs, 10 yrs, 25 yrs)?

Knowledge gap: Most of the input parameters for calculation of the value of information are not known. Even companies working in the sector often don't have a good overview of the costs related to corrosion. In addition, the potential value of the benefits is also not known.

6.2 Inputs on costs of corrosion and their relation to the implementation of monitoring

A major issue in defining the business case for corrosion monitoring is that the 'reference scenario' is not known. From the performed survey, this is clearly illustrated with the answers received to the question 'Do you have a clear view on the costs related to protecting an ocean energy devices against corrosion (CAPEX) and maintenance costs related to corrosion (OPEX)?'. Out of 30 answers, only 3 answered positively. However, of these 3, 2 deduce it from general numbers in other sectors or general reports like the NACE reports. Even if only the answers from technology developers or asset owners are considered, only 1 out of 10 respondents had a good idea about the costs related to corrosion. The one positive answer comes from a fixed offshore wind asset owner, indicating that the costs related to corrosion are 1-2% of the total costs (CAPEX & OPEX combined). In a report from the NeSSIE project, the costs related to corrosion were estimated to be up to 11% of OPEX[14].

[14] NeSSIE project, Assessment of Economic Opportunity, Feb 2018 (http://www.nessieproject.com/library/reports-and-researches)



Some general remarks can however be made with respect to costs:

- For corrosion management of offshore structures, the balance between CAPEX to OPEX is typically greatly towards OPEX, as the costs related to offshore inspections and corrective actions are very high. Offshore paint repair is 10-100x more expensive than repair in paint shop.
- In a globally expanding market like the offshore wind market, one should also consider geographical variations in corrosion related costs. As an example, China can be considered: Given the fact that China has quite unique coastal characteristics, turbines installed in such areas are subjected to corrosion issue which may reduce turbine availability. Therefore, in order to expand the lifetime of OWF in China, anti-corrosion solutions are necessary to meet the geographical and climate conditions in China, causing extra cost of turbines.
- Variations between technologies also lead to completely different corrosion related costs.
    - For example Tidal Energy structures which are completely submerged and may have moving or other parts that need frequent inspection, need either diver/ROV inspection, or need to lift the structures out of the water. With both approaches, very high costs are associated. Here costs related to corrosion monitoring would have to be offset by being able to do less diver/ROV inspections.
    - Also distance to shore has a very big impact on the cost of inspections.

All respondents to the survey expect that corrosion monitoring will reduce OPEX. Nevertheless, it is indicated that it is unclear just how big the reduction in OPEX can be, and that a significant development effort is still required to achieve this OPEX reduction with corrosion monitoring. As discussed earlier, it is also indicated that corrosion monitoring, next to decreasing OPEX could lead to more insights and better design verification which eventually could lead to lower costs, as well as life-extension (see chapter 2 for more information).

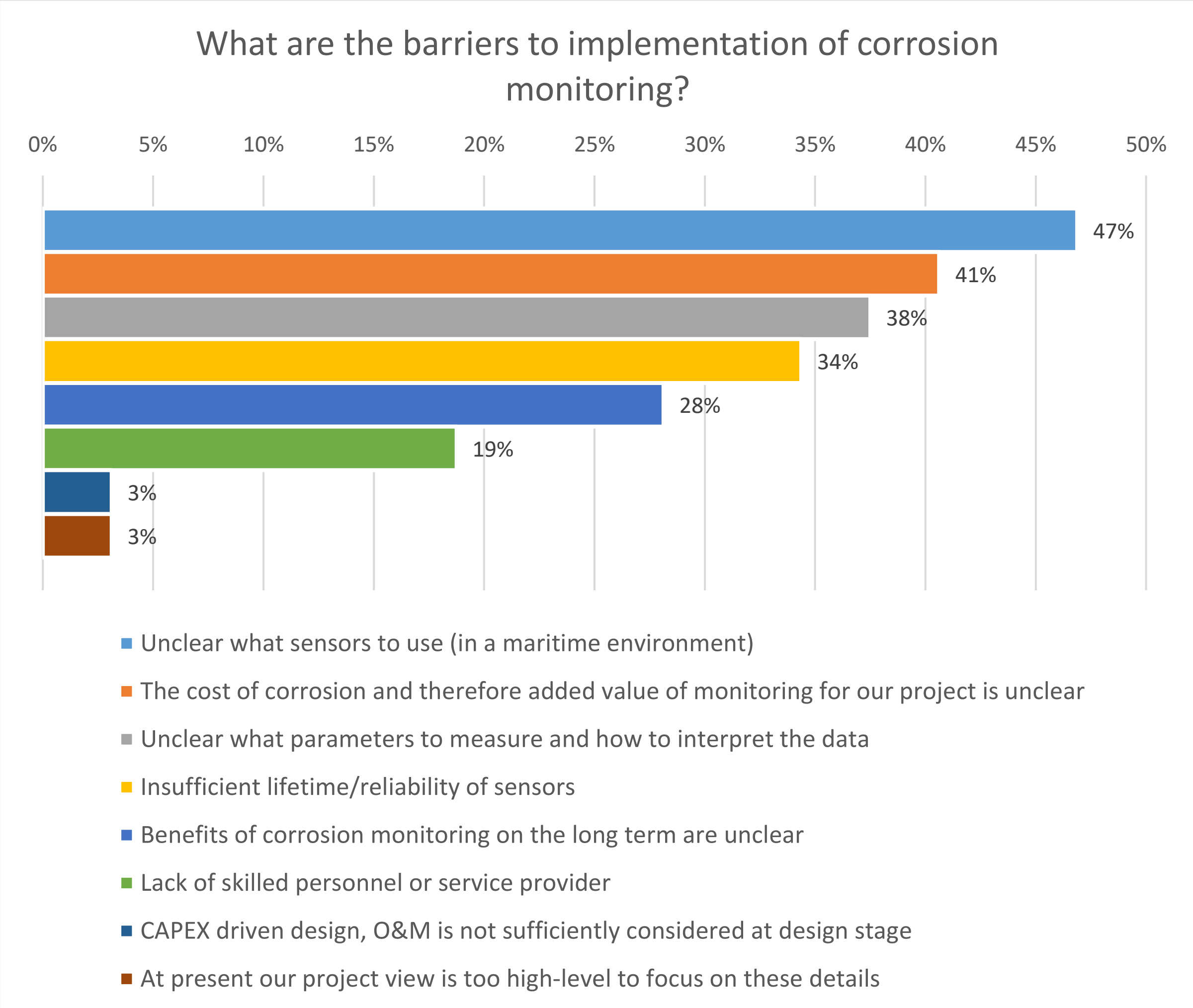
Input parameters that need to be known to determine an effective corrosion monitoring strategy and the appropriate sensors are (both a reference scenario and scenario with monitoring):

- Expected time between (top-side) visits to a structure and cost of such a visit

- Expected time between diving/ROV inspections and cost of inspection
- Cost and frequency of above LAT corrosion inspections
- Cost (including post-treatment, data storage, …) and performance (including life-time) of a sensor
- Maintainability of the sensor
- Type and cost of maintenance due to a given critical level of corrosion
- Consequence and cost of failure

7 Gaps and barriers preventing implementation of Corrosion Monitoring

A subset of largely non-technical barriers that might exist was presented to the respondents of the survey (see below). The first six responses were part of the multiple choice answers, with answer 7 and 8 having been added by the respondents in the 'others' section.



This illustrates that for a large percentage of the respondents, non-technical barriers are very important. This can be combined in two major roadblocks:

1. It is unclear what monitoring techniques should be installed to make a good assessment of offshore structures (including corrosion, coating degradation, etc.) possible. I.e. there is a lack of knowledge to define an effective, application dependent monitoring strategy.
2. The business case for corrosion monitoring is unclear.

The second point starts from the fact that the current cost (CAPEX and OPEX) of corrosion is not known and varies from project to project (prevention, inspection, maintenance, repair). I.e. what is the return on investment (long vs. short term)? It can be used for R&D (design validation, etc.), but does it also present sufficient advantages to justify more widespread use for O&M optimisation and lifetime extension?

Below is a list of identified gaps and barriers that are more technological in nature.

- Robustness, reliability and long term stability of sensors.
  - Specifically for environmental monitoring
  - Time between calibration/maintenance should be at least 6-12 months
- Cost of Monitoring
  - Cost of sensors (high cost, uncertainty about result in aggressive environment)
  - Installation and maintenance costs of sensors (addition of sensors complicates the maintenance program: additional devices that need to be maintained; installation should be aligned with construction works and damage should be avoided)
  - A recent report (July 2020, Floating Wind JIP, Carbon Trust[15]) indicates that most monitoring systems have a negative return on investment.
- Difficulties related to installation and integration of sensors
  - Installation of sensors on existing structures may be difficult, no easy and cost effective installation solutions exist for 'test projects' (areas difficult access, sensor difficult to attach to existing structures, alteration of the structure to install the sensors required, etc.)
  - Installation of sensors should already be considered at the design stage, which is almost never done.
  - The sensors themselves can change the local environment, thereby influencing the measurement (e.g. water flow, development of fouling and rust layer). This should be avoided.
- Monitoring of localized phenomena
  - Existence of 'micro-climates' in/around structural elements difficult to identify and monitor. The occurrence of local phenomena cannot be excluded, but by monitoring the environment, at least a 'general' idea can be obtained of whether some 'risk factors' are present or not.
  - Monitoring of larger areas not possible (typically 'spot' measurement), meaning that localised occurrences are not observed if not monitoring in the right spot.
- Access to expertise to define system requirements and develop a specification
- Trained people

[15] https://www.carbontrust.com/our-projects/floating-wind-joint-industry-project/floating-wind-jip-phase-ii

- Data interpretation: no generally accepted framework
    - Wide variation of markers/parameters measured
    - Currently ad-hoc interpretation
    - Lack of access for benchmark experiments (corrosion often a slow process and thus long benchmark experiments required, making this extra difficult)
    - No automated data processing/interpretation procedures available
    - Data interpretation can be high sensitivity to specific deployment conditions
    - Tools for easy interpretation of measurement data by end-user are lacking
- Specific sensor technology for relevant corrosion processes or protection systems
    - A recent report (July 2020, Floating Wind JIP, Carbon Trust) indicated that "There is a technology gap for monitoring of corrosion on both topside structure and subsea mooring."
    - Monitoring of pitting corrosion, crevice corrosion, SCC
    - MIC/biofouling monitoring
    - Monitoring at/below the mudline
    - Techniques for direct monitoring of the structure (for example based on UT, AE, Eddy Current, etc.)
    - Monitoring corrosion of electrical component
    - Rapid and detailed electrical potential mapping[16]
    - Systems to monitor CP below the mudline and below bio-growth (potential of the steel surface needs to be known)
    - Cost-effective and easy to implement corrosion monitoring of bolts and flanges
    - Monitoring of corrosion in the splash zone
- Lack of accessible information on corrosion of past (prototype) projects from which it can be learned what are the critical corrosion phenomena, critical locations, how fast corrosion proceeds, what the associated costs are, etc. More evidence bases should be created (see for example https://ultir.github.io/, O'Byrne et al. 2018).

[16] It should be noted that Electrical Field Gradient Mappings can be performed by ROVs (for example FiGS® from Force Technology). Current distribution can be determined and technique can be used to check CP efficiency; this technique is relatively fast, but not cheap.

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(in bold, members of the OPIN Group):

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