NeSSIE
North Sea Solutions for Innovation in Corrosion for Energy

Sustainability of Investment in Corrosion Mitigation

North Sea Solutions for Innovation in Corrosion for Energy

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The NeSSIE project (2017-2019) seeks to deliver new business and investment opportunities in corrosion solutions and new materials for offshore energy installations. The project aims to draw on North Sea regional expertise in traditional offshore sectors (i.e. oil and gas, shipbuilding) in order to develop solutions for emerging opportunities in offshore renewable energy sources (wave, tidal and offshore wind energy).

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AUTHOR

Leonore van Velzen (University of Edinburgh)
Shona Pennock (University of Edinburgh)

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Acronyms

ACS	Anti-Corrosion Solutions
AEP	Annual Energy Production
CAPEX	Capital Expenditure
CF	Capacity Factor
CP	Cathodic Protection
EC	European Commission
JRC	Joint Research Centre
LCOE	Levelised Cost of Energy
MSP	Marine Spatial Plan
ORE	Offshore Renewable Energy
O&M	Operation and Maintenance
OEM	Original Equipment Manufacturers
OPEX	Operating Expenditure
SME	Small to medium size enterprise
TRL	Technology Readiness Level
WP	Work Package

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Executive Summary

To confirm the medium-long term sustainability of investing in improved corrosion solutions, the potential impact on the Levelised Cost of Energy (LCOE) of tackling corrosion in offshore renewables is investigated. The study on the impact on LCOE of tackling corrosion indicates potential LCOE reductions ranging between 1% and 21% depending on industry input and optimistic scenarios. The sensitivity analysis affirms the need to understand the impact of corrosion on the performance and availability of ORE, which supports the recommendations to invest in training programmes, research and testing, and demonstration projects related to corrosion issues. These strategic investments will support the supply chains of applying anti-corrosion solutions (ACSs) to ORE.

1. Introduction

The NeSSIE project follows on the work and aim of the Vanguard Initiative (VI) for new Growth through Smart Specialisation, specifically the VI Energy Pilot action that is focused on making the EU the global leader in manufacturing robust high-integrity components for marine offshore energy applications. The Energy Pilot works with industry clusters, key companies and regional supply chains to identify common areas of expertise, common challenges and develops a network to support the development of innovative technologies and services to tackle these challenges which are too expensive for single regions and single companies. Through industry surveys, workshops and the development of the VI Energy Pilot Technology Roadmap, corrosion in water was identified as one of the main challenges for the existing supply chains to tackle with their expertise. The main ambition of these activities is the development of components to reduce the lifetime costs of the offshore renewables sector.

The aim of the NeSSIE project is to identify three offshore renewable energy (ORE) demonstration projects in the North Sea basin related to corrosion issues, building on existing supply chains and accelerating the deployment on ORE.

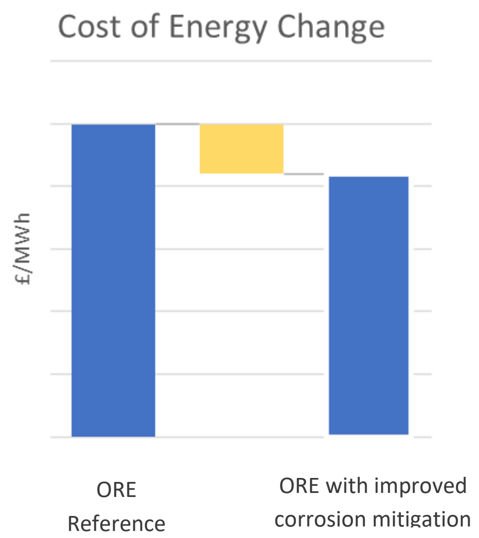


Figure 1 – Indicative cost energy reduction of ORE with the potential impact of tackling corrosion issues

This report, deliverable D3.3 of the NeSSIE project, discusses the sustainability of investing in corrosion mitigation to promote the supply chain of anti-corrosion solutions (ACSs) applied to the ORE sector. This is done by examining the impact of corrosion mitigation on Levelised Cost of Energy (LCOE) (see Figure 1). This is meant for policy makers to support decisions to shape the landscape, create a supportive environment for the growth of ORE and ACSs, and grow the supply chain in Europe. The scope of this report has changed from the NeSSIE project agreement from the ‘Investment Plan’ to ‘Sustainability of Investing in Corrosion Mitigation’ due to the difficulty in obtaining the data for an investment plan and the uncertainty of it; a more traditional investment plan was deemed to not add value to the NeSSIE project. Therefore, this report builds on the following a sentence in the NeSSIE agreement on D3.3: ‘The investment plan should guarantee that the assets and facilities developed will be sustainable in the medium-long term’. As mentioned, this was done through investigating the potential impact of tackling corrosion on the LCOE of ORE.

The next Section in this deliverable, Section 2, will elaborate on the required strategic investments for development of the sector. It gives a high-level overview of required investments in the current landscape to encourage the supply chain development. This is followed by the economic impact of applying ACS in the ORE sector in Section 3, where different scenarios are investigated. The report finishes with conclusions on which areas to support for the development of the ACS and ORE supply chain.

2. Strategic Investments

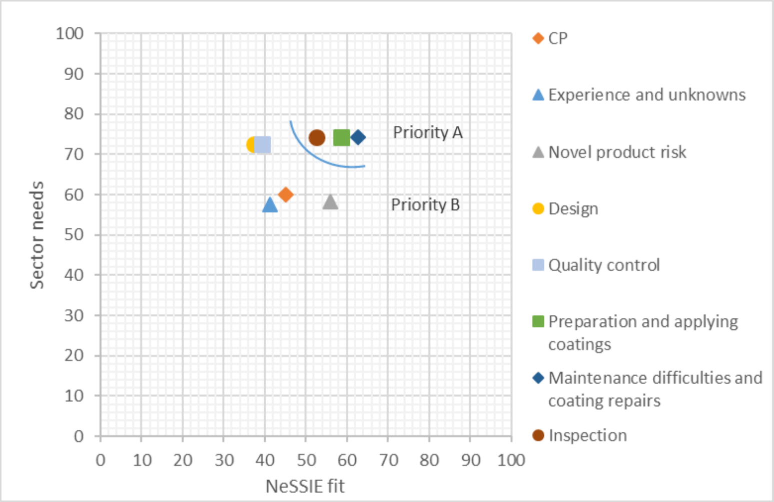
This Section provides recommendations for the investments to promote the supply chain of ACSs in the ORE sector. This is indicated here as the development opportunities, the required support to create an encouraging environment, the recommendations to ensure development, and finally the areas to invest in to realize the sector development.

2.1. *Opportunities*

Previous NeSSIE reports have provided an overview of the corrosion issues in the ORE sector, therefore indicating the focus areas to support market growth. Some examples of NeSSIE reports on which this report is building on:

- The non-technology challenges report [1] gives an overview or the current landscape.
- The report with the business and innovation needs [2] is based on discussion and feedback from industry.
- The Roadmap [3] identifies and prioritises the challenges related to corrosion in the ORE sector.
- The NeSSIE 'Assessment of Economic Opportunity Report' [4] gave an overview of the market potential of anti-corrosion solutions and novel materials applied to the ORE sector. Based on capacity projections up to 2050, the economic impact of applying improved ACSs to ORE projects was investigated for the ORE project developer and the ACS provider.

The identification and prioritisation of the ACS challenges in the NeSSIE Roadmap provides an overview of the key areas of improvement. This gives opportunities for the ACSs supply chain to provide solutions, coming from either existing solutions as applied to other sectors or novel solutions. The key challenges as identified in the Roadmap can be found in Figure 2.



NeSSIE Priority	ACS Challenge
A	Preparation and application of coatings
	Maintenance difficulties and coating repairs
	Inspection
B	Quality Control
	Novel Product Risk
	Cathodic Protection (CP)
	Design
	Experience and unknowns

Figure 2 – NeSSIE prioritisation of the identified anti-corrosion solution challenges [3]

After this first prioritisation, based on industry input, the NeSSIE project started the search for the demonstration projects in these three challenge areas. The process and the resulting projects are explained in the following Section.

2.2. *Development of anti-corrosion solutions*

To capture the market potential, policy initiatives need to support the development of ACSs as described in the NeSSIE report on 'Cross-Sector Knowledge Transfer' [5]. Different policy initiatives can provide a supportive environment for industry development, where key actors and collaborations are encouraged; regional assets are strengthened; and technology development is stimulated (Figure 3).

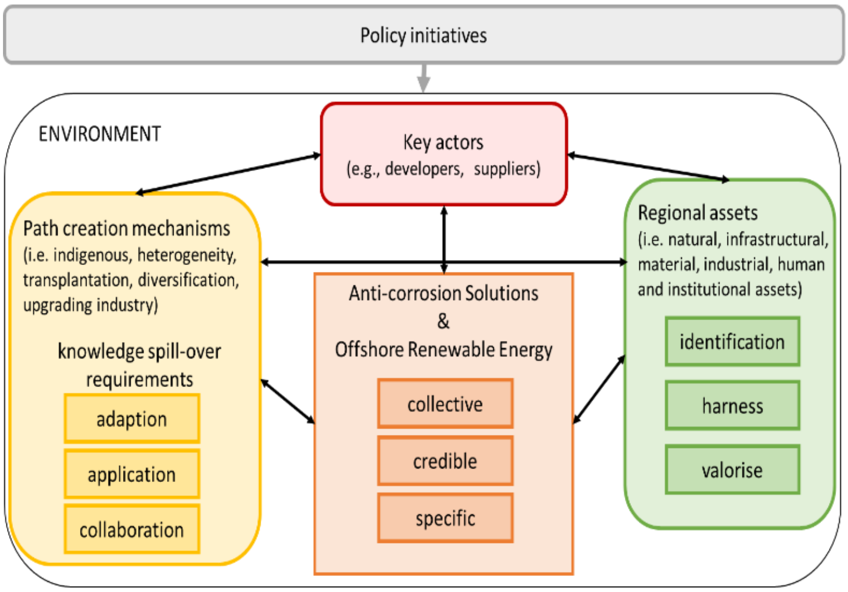


Figure 3 – Novel industry development based on knowledge transfer from established sectors as determined in NeSSIE's 'Cross-sector knowledge transfer' Report [5] , based on literature study [6] [7] [8]

Two examples of policy initiatives that can support the development environment for ACSs applied in the ORE sector are training programmes and collaborative centres and projects.

- Training programmes ensure awareness of corrosion issues and provide targeted knowledge transfer. This can strengthen the supply chains in the EU, by building on and expanding the existing expertise.
- Collaborative research and development can also have a strengthening impact on the supply chain through the engagement of different sectors and partners, industry issues can be tackled with a wide range of knowledge and resources. This can contribute to a collective vision for ACSs and ORE development.

The JRC report on the Future Emerging Technologies in the ocean energy sector [9], focussed on wave and tidal energy, also points out the necessity of an integrated systems approach and the potential of adapting higher TRL solutions from other sectors to develop wave and tidal energy technologies.

Recommendations for ACS roll-out in ORE

In the ‘Non-technical Challenges in developing Offshore Renewable Energy Projects’ report [1], NeSSIE has identified a list of challenges for the development of ORE in the current landscape in terms of market, finance, infrastructure and regulations. The NeSSIE Roadmap [3] was built on this landscape and the identification of the ACS challenges as applied in the ORE sector, it provides recommendations to support industry roll-out. These recommendations are as follows:

- Coordinate funding throughout the path towards commercialisation:
  The stop-start nature of financial support is considered as a hurdle for the development of the ORE sector, coordination and confirmation of suitable support throughout the development to market is required.
- Develop Marine Spatial Plans (MSPs):
  Many, from fisheries to leisure activities and wildlife, have the oceans as their home; MSPs can play a significant role to ensure suitable activities.
- Facilitate one-stop-shop consenting:
  Regulations and legislation can form a barrier, as there are many procedures in place, making consenting and licensing processes difficult.
- Targeted knowledge transfer:
  Application of best-practice is recommended as it encourages the development of ORE as well as strengthening the existing supply chains.
- Include corrosion at the design stage:
  A holistic design approach should be applied, to ensure issues such as corrosion are tackled at an early stage to avoid high cost at later stages.
- Capturing and sharing data:
  Reduction of uncertainties is of great importance with novel products, gathering data and transparency can support this.
- Research material interaction and novel materials:
  A very specific corrosion specific technology issue is the interaction of combining certain materials; research towards a deeper understanding of interaction phenomena is required.
- Long term testing of ORE devices, to investigate the impact of corrosion:
  Due to the relatively young ORE structures, the long term effects, such as on structural integrity or energy efficiency, can be assumed but are still to be determined.
- Ensure awareness of corrosion issues:
  Corrosion is a well-known issue, yet in the ORE sector sometimes overlooked with the focus on more immediate challenges. This relates to the above mentioned recommendation to include it in the design stage, actors need to be aware of it.
- Include corrosion mitigation in stage-gate metrics:
  Including mitigation measures in the stage-gate metrics can ensure corrosion is taken into account.

2.3. *Investment Focus*

Building on the previously mentioned studies, the overall focus points are to create awareness; to adapt a holistic and integrated systems approach; to collaborate and share knowledge and expertise; and to facilitate a supportive environment. This Section will describe the Strategic Investments to boost an environment that supports the economic and growth potential of ACSs applied to ORE.

2.3.1.Training programmes

As mentioned previously, training programmes can support the development of a sector. Considering training programmes in relation to the NeSSIE project, these programmes can ensure awareness of corrosion issues and provide targeted knowledge transfer. Programmes that focus on corrosion management knowledge strengthen the ability to tackle corrosion issues. It has been determined that monitoring of corrosion should be an active process, including proactive and reactive measures. Proactive measures, namely failure preventive actions, consist mainly of gathering data and corrosion checks at inspection and/or maintenance activities. Training programmes can elaborate the corrosion awareness and knowledge of inspection and maintenance crews. The mentioned proactive measure of capturing and sharing data, another recommendation of the NeSSIE Roadmap [3], can reduce the cost of corrosion by preventing significant failures.

2.3.2.Research and testing

Where corrosion is a well-known concept, the implementation of (novel) materials and new material combinations can result in unexpected material interactions and processes. Research and testing of material interaction as well as novel materials should be supported to develop the sector. Again, capturing and sharing of the data should be encouraged; transparency could avoid ‘reinventing the wheel’ and slowing down development.

2.3.3. Demonstration projects

Evidently, demonstration projects are meant to demonstrate a technology and move it further on the technology readiness level (TRL) scale. The TRL scale, as adopted by the European Commission (EC), indicates the status of a technology towards its commercialisation with a number between one (TRL1) and nine (TRL9), displaying ‘basic principles observed’ to ‘actual system proven in operational environment’ respectively [10]. It is important that a technology can find support and funding throughout all these stages of development, gaps in this process can lead to a loss of momentum and a halt in technology development. Therefore, there is a need to coordinate the funding at the different levels, another recommendation from the Roadmap.

A developing sector can often learn a great deal from experience in other (related) sectors. The NeSSIE report on Cross-sector Knowledge Transfer provides European examples of companies that have applied their expertise in a certain area to offshore renewables, such as Green Marine from the fishing industry to offshore services. Demonstration projects are an excellent base to investigate the market opportunities and apply experience from one sector to another.

The selected demonstration projects for NeSSIE are focussed on tackling the issues related to corrosion. They will investigate and apply potential solutions. Through the application of a technology, in these cases (improved) anti-corrosion solutions, the demonstration projects work towards the final aim to reduce the LCOE of ORE. Descriptions of the selected demonstration projects are given in the next Section.

2.4. *NeSSIE Demonstration Projects*

The approach of selecting the demonstration projects is divided in three stages [11]:

- In the first stage call, the project developers are selected with their corrosion challenges.
- The second call is aimed at establishing the potential anti-corrosion solutions.
- The third and final stage consists of the development of the business cases for the identified projects.

These projects identified different corrosion challenges, as discussed in the textbox below, and capturing multiple challenges as determined in the Roadmap.

Growth Opportunities – Key challenges in NeSSIE Demonstration Projects

The key challenges identified by NeSSIE developers can be broadly categorised as specific to either coatings, cathodic protection or novel materials

Coatings

- Protection for floating flanged joints which need to be opened for maintenance.
- Reactive paint or air/water-tight wrap solutions for boat landing fenders.
- Transition piece corrosion.
- Access hook-up locations.
- Corrosion at interfaces.

Cathodic Protection

- Standards for Cathodic protection (DNV-RP-B401) not enough for oxidised, aggressive tidal flow.
- Mitigation required for anodic effect of stainless steel.
- Better understanding of cathodic disbondment required (specifically related to CP on metal components bonded to carbon fibre blades.

Novel Material

- Better understanding of cathodic disbondment required (specifically related to CP on metal components bonded to carbon fibre blades.

3. Economic Impact

In this Investment Plan, the economic impact is represented by indicating the change in Levelised Cost of Energy (LCOE). This Section will give an indication of the economic impact of tackling the corrosion issues as will be done in the NeSSIE demonstration projects. The calculation of LCOE is discussed, followed by the estimated impact of introducing improved anti-corrosion solutions to ORE through the investigation of three scenarios, namely 'pessimistic', 'stakeholder input' and 'optimistic'. These scenarios are based on literature and industry input. The uncertainty of this impact is examined with a sensitivity analysis.

3.1. *Levelised Cost of Energy*

The LCOE indicates the present value of electricity, if the total cost of the energy system (i.e. power plant, ocean energy array) is paid back over its lifetime. Hence, the LCOE gives the electricity price to break even over the project lifetime. It is calculated by taking the total cost and dividing this by the total energy production over its lifetime. Equation 1 provides the LCOE calculation applicable for offshore renewable energy.

Equation 1

$$LCOE = \frac{Cost\ of\ energy\ system\ over\ lifetime}{Energy\ production\ over\ lifetime} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t: Investments in year t [£];

M_t: Operation and maintenance cost in year t [£];

E_t: Energy production in year t [MWh];

r: Discount rate [%];

n: Lifetime [yrs].

The economic impact of tackling corrosion issues is represented as the percentage change to the LCOE. Some components of the LCOE are discussed below, including the potential impact of improving the anti-corrosion solutions in the ORE sector.

CAPEX

The Capital Expenditure (CAPEX) consists of the initial investment to build the project. With the aim of the NeSSIE project to support the development of three demonstration projects, additional corrosion management is applied. The additional measurements to introduce improved solutions can result in an increase in CAPEX, yet it could also result in an overall decrease in CAPEX due to the application of a novel material or reduction in underlying material.

OPEX

The Operational Expenditure (OPEX) relates to all cost from operation and maintenance activities; it also includes costs such as insurance. With the introduction with improved anti-corrosion solutions, the OPEX related to corrosion ($OPEX_{corrosion}$), and therefore the total OPEX, is expected to reduce.

AEP

The energy production is the Annual Energy Production (AEP); it indicates the total energy generated in one year of operation. This value is based on different components such as the load factor and the availability. The latter is based on the uptime of the devices, the time that the devices generate energy, which is dependent on reliability and maintenance/inspection. In terms of the NeSSIE project, the AEP is expected to increase due to a reduction in the downtime related to corrosion issues. In addition, corrosion and fouling issues are expected to influence the performance of wave and tidal energy. A reduction in corrosion could result in a lower impact on the performance, thus on the AEP.

3.2. *Impact Anti-Corrosion Solutions*

The International Measures of Prevention, Application, and Economics of Corrosion Technologies (IMPACT) study by NACE International [12] indicates the difficulty in measuring the potential cost savings of corrosion management, but indicates the positive effect by decreasing the maintenance costs, avoiding loss of production time, decrease in injuries, and increase in lifetime. The example of the automotive industry is given for potential cost savings by introducing innovative technologies and corrosion management strategies of 52% of corrosion related cost between 1875 and 1999. The NACE study states there are potential savings achievable of 15%-35%.

The cost reductions envisioned with tackling corrosion issues are expected at commercial stages of development, at points in time that the devices are in the water for longer periods in time. The current stage of marine renewables, makes it difficult to estimate the future corrosion related cost as there is no specific experience in dealing with extensive corrosion. Currently, corrosion issues are dealt with within other maintenance activities, and so assigning specific costs to these activities proves to be difficult. Mature sectors with corrosion experience, such as oil and gas, are taken as example to estimate the cost related to corrosion.

The demonstration projects will provide evidence for the potential impact of improved corrosion solutions for ORE projects. In this Section, an indication of the potential economic impact is given on the cost of energy when tackling corrosion. This report is not focussed on establishing an absolute LCOE value; it will give an insight in the potential reduction of LCOE when corrosion issues are taken into account at an early stage. The corrosion impact is determined by comparing a reference case ORE project, considering a 'business as usual' approach, with an ORE project that applies improved corrosion management.

Based on the knowledge gathered throughout the NeSSIE project from literature and industry practice, estimations are made for the effect of the improved corrosion solutions on the CAPEX, OPEX and performance of offshore renewables. These can be found in Table 1. The table indicates both an $\text{OPEX}_{\text{corrosion\_intial}}$ and $\text{OPEX}_{\text{corrosion\_change}}$, the $\text{OPEX}_{\text{corrosion\_initial}}$ indicates the percentage of total OPEX that is spent on corrosion (corrective corrosion). The $\text{OPEX}_{\text{corrosion\_change}}$ is the percentage of potential reduction in cost spent on corrosion, when applying improved corrosion management, based on the previously mentioned IMPACT study by NACE [12]. Therefore, $\text{OPEX}_{\text{corrosion\_change}}$ is taken as a percentage of $\text{OPEX}_{\text{corrosion\_intial}}$. The combination of both parameters results in the effect of tackling corrosion on the total OPEX, for example: considering an $\text{OPEX}_{\text{corrosion\_intial}}$ of 30% and an $\text{OPEX}_{\text{corrosion\_change}}$ of -35%, the $\text{OPEX}_{\text{corrosion}}$ becomes 30%*-35% = -10.5%. This calculation will be elaborated on in Section 3.2.1 Scenarios.

Table 1 – Impact of improved anti-corrosion solutions on the CAPEX, OPEX and performance of Offshore Renewable Energy

Parameters	Corrosion impact – range	Description	Source
CAPEX$_{\text{corrosion}}$ [% of total CAPEX]	+8%	The percentage of total CAPEX that goes to preventive anti-corrosion solutions	[13]
OPEX$_{\text{corrosion\_initial}}$ [% of total OPEX]	25% - 33%	The percentage of OPEX that is spent on corrective measures due to corrosion	[13]
OPEX$_{\text{corrosion\_change}}$ [% of OPEX$_{\text{corrosion\_initial}}$]	-15% - -35%	Potential savings in cost of corrosion through improved corrosion protection	[14]
Performance difference [avg. % difference over 5yrs]	0% - 6%	Performance difference between business-as-usual case and improved corrosion protection case over 5 years for wave and tidal energy, after which maintenance 'resets' the performance **(wave and tidal energy only)**	[15]

The next Section investigates different scenarios of corrosion impact based on the found ranges.

3.2.1. Scenarios

As mentioned in the previous Sections, the assumptions made on the impact of applying improved corrosion solutions on the cost of energy of ORE are often provided in a potential range of percentages; they contain uncertainties. This Section investigates three potential scenarios, namely a pessimistic, a stakeholder input and an optimistic scenario (Table 2). All scenarios are based on literature. The stakeholder input scenario considers the potential ranges from literature and based on estimations from ORE industry input. For each scenario, the change in LCOE is calculated due to the changes in parameter values, compared to a 'reference case' without improved ACSs.

To be clear on the impact of tackling corrosion on the OPEX, the OPEX$_{\text{corrosion}}$ parameter is introduced. This combines the effects of OPEX$_{\text{corrosion\_initial}}$ and OPEX$_{\text{corrosion\_change}}$. Based on the found range of OPEX$_{\text{corrosion\_initial}}$ (25%-35%), these parameter values for OPEX$_{\text{corrosion\_initial}}$ indicate a difference in expected cost related to corrosion. The assumption is made that the OPEX$_{\text{corrosion\_initial}}$ is 30% for the 'reference case', meaning that without improved ACS solutions the cost related to corrective corrosion is 30% of total OPEX. Thus, when considering different values in the scenarios for OPEX$_{\text{corrosion\_initial}}$ (Table 2), this also changes the overall OPEX. Therefore, the OPEX$_{\text{corrosion}}$ parameter is introduced to represent the combined effect of OPEX$_{\text{corrosion\_initial}}$ and OPEX$_{\text{corrosion\_change}}$ as percentage of total OPEX. With the OPEX$_{\text{corrosion\_initial}}$ for the 'reference case' assumed 30%, this results in an OPEX$_{\text{corrosion}}$ as in Equation 2.

Equation 2

$$\mathrm{OPEX}_{corrosion} = \left(\mathrm{OPEX}_{corrosion\_initial} - 30\%\right) + \frac{\mathrm{OPEX}_{corrosion\_initial}}{100\% + \left(\mathrm{OPEX}_{corrosion\_initial} - 30\%\right)} * \mathrm{OPEX}_{corrosion\_change}$$

$\mathrm{OPEX}_{corrosion}$: Percentage change to the total OPEX due to the combined effect of the OPEX$_{\text{corrosion\_change}}$ and the OPEX$_{\text{corrosion\_initial}}$ [% of total OPEX];

$\mathrm{OPEX}_{corrosion\_initial}$: Percentage of OPEX that is spent on corrosion related issues [% of total OPEX];

$\mathrm{OPEX}_{corrosion\_change}$: Percentage change of OPEX$_{\text{corrosion initial}}$ due to tacking corrosion issues [% of OPEX$_{\text{corrosion initial}}$].

The pessimistic scenario considers the lowest improvement of applying novel anti-corrosion solutions to the ORE projects. This scenario assumes an 8% CAPEX increase (+8%) related with the application of the improved anti-corrosion solutions. Simultaneously, the $\text{OPEX}_{\text{corrosion\_initial}}$ is the higher value in the range found in literature for OPEX spent on corrective corrosion, namely 35%. And the $\text{OPEX}_{\text{corrosion\_change}}$ is the lowest of the range (-15%), indicating the low impact of the ACS. Following Equation 2, the $\text{OPEX}_{\text{corrosion}}$ becomes 0%, thus the application of the improved ACS does not result in a change of the total OPEX.

The optimistic scenario attributes the most positive impact on the cost of energy when tackling corrosion issues. This means that the corrosion solution does not have any additional cost related to its application, therefore the $\text{CAPEX}_{\text{corrosion}}$ is +0%. The $\text{OPEX}_{\text{corrosion\_change}}$, in other words the cost reduction due to improved corrosion management, is the highest value in the assumed range as mentioned in a previous Section, being -35%. The $\text{OPEX}_{\text{corrosion\_initial}}$ is not taken within the range found in literature, the potential value of 5% was chosen for the most optimistic scenario based on industry discussions.

The Stakeholder input scenario considers an increase in $\text{CAPEX}_{\text{corrosion}}$ (+8%) with the additional corrosion management. The $\text{OPEX}_{\text{corrosion\_initial}}$ is taken as 10%, slightly less optimistic than the optimistic scenario, and the impact of the ACS is considered as the highest in the expected range (-35%), resulting in an $\text{OPEX}_{\text{corrosion}}$ of 27%.

Table 2 – Parameter values for the Pessimistic, Stakeholder Input and Optimistic scenario

Parameter	Pessimistic	Stakeholder input	Optimistic
$\text{CAPEX}_{\text{corrosion}}$ [% of total CAPEX]	+8%	+8%	+0%
$\text{OPEX}_{\text{corrosion\_initial}}$ [% of total OPEX]	35%	10%	5%
$\text{OPEX}_{\text{corrosion\_change}}$[% of $\text{OPEX}_{\text{corrosion\_initial}}$]	-15%	-35%	-35%
$\text{OPEX}_{\text{corrosion}}$ [% of total OPEX]	0%	-24%	-27%
Performance difference [avg. % difference over 5yrs] (wave and tidal energy only)	4%	4%	6%

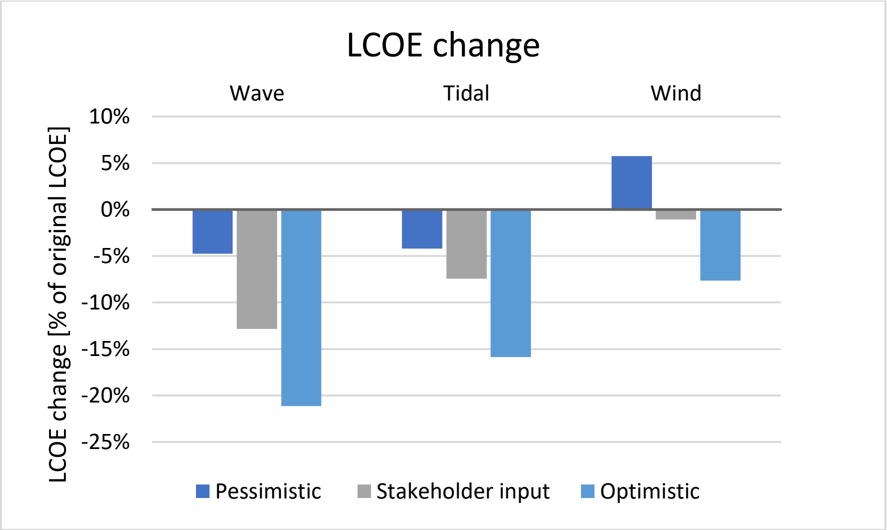


Figure 4 – LCOE change for the 'Pessimistic', the 'Stakeholder input', and the 'Optimistic' scenarios of the impact of tackling corrosion issues for wave, tidal and wind energy

Figure 4 shows the results of the three indicated scenarios. This shows that tackling corrosion issues for wave and tidal energy can potentially lead to significant cost of energy reductions, with LCOE reductions ranging from almost 5% up to 21%. The 2016 JRC Ocean Energy Status Report [16] investigated the effect on tidal LCOE of hypothetical cost reductions of 20% and 50% in different cost centres, namely 'civil and structural costs', 'mechanical and installation cost', 'capacity factor' (CF), 'OPEX' and finally the effect of combining all. Taking a 20% reduction on OPEX, the JRC study found a reduction of approximately 6% in LCOE. A 20% increase in CF, which is an indication of the performance of a device, gave a reduction in LCOE of 18%. Combining all four investigated variables, the JRC report found a reduction in LCOE of almost 20% for a 20% decrease in costs and a 20% increase in CF. For a 50% change in the variables, an LCOE reduction of almost 75% was found. As mentioned, the cost reductions in the JRC are hypothetical; the impact of tackling corrosion can be seen as one of the options to achieve these reductions. This NeSSIE study found a range of LCOE reduction of 5% to 21% effect of combining the variables (CAPEX increase, OPEX decrease, performance) with the different investigated scenarios. The potential cost increases and decreases of the variables investigated in the scenarios of this NeSSIE report consider realistic values based on literature and industry input.

For wind energy, Figure 4 shows that the stakeholder input and the optimistic scenario indicate a cost reduction of approximately 1% and 8%, respectively. The $\text{CAPEX}_{\text{corrosion}}$ does not increase for this optimistic scenario, thus the reduction in the $\text{OPEX}_{\text{corrosion}}$ leads to a reduction in the LCOE. For the pessimistic scenario, the increase in $\text{CAPEX}_{\text{corrosion}}$ is not outweighed by the reduction in total $\text{OPEX}_{\text{corrosion}}$, thus leading to an increase in LCOE of approximately 6%. As indicated in Table 2, no scenario considers a decrease in CAPEX (a negative value of $\text{CAPEX}_{\text{corrosion}}$). This study only assumes increases in CAPEX with the introduction of improved corrosion mitigation. A potential decrease in CAPEX, for example through a reduction of required underlying material or through the application of a cheaper and anti-corrosive novel material, is not assumed in this report.

The difference in results between wave and tidal energy on the one side and wind energy on the other can be attributed to the assumption of the impact of corrosion on the performance. This study neglects the influence of corrosion on the energy production of wind energy. Whilst for wave and tidal energy it is assumed that the energy production reduces when there are no improved anti-corrosion solutions, so for the base case. All wave and tidal cases apply a slower performance reduction due to the higher corrosion resistance, and thus have a higher performance than the base case.

It is important to note that the availability was not changed for any of the scenarios, due to the absence of information. The sensitivity study showed that the availability has significant influence on the LCOE. The impact of corrosion management on the downtime should therefore be studied, improved awareness of corrosion and therefore in corrosion monitoring can support this. By identifying the downtime associated with corrosion, there could potentially be larger reductions in LCOE when this downtime is reduced.

Safety is not taken into account in this study, for the pessimistic scenario the LCOE for wind energy might increase but corrosion issues for wind energy have been found around the access platforms. If these platforms are not compliant to safety standards (potentially due to corrosion), the increase in LCOE might not be an issue as safety is most important. If ACSs can reduce or eliminate some maintenance activities that may take place in a hazardous situation, this would also have a positive effect on safety.

To indicate the influence of the different variables on the LCOE, a sensitivity study is performed, which is discussed in the next Section.

3.2.2. Sensitivity analysis

As mentioned, the expected impact from the application of improved anti-corrosion solutions comes with uncertainty. This uncertainty is considered account by examining different potential scenarios, as was done in the previous Section. It is of interest to examine the effect of the uncertainty due to the difficulties in determining the exact cost of corrosion at the current stage of development of ORE. By means of a sensitivity analysis, this effect of the uncertainty of the parameters on the final results is examined. The sensitivity analysis investigates the impact of the different variables on the LCOE by changing the input values. Therefore, the analysis considers the uncertainty of the input values on the results. This is done by adjusting each variable whilst the other variables are kept consistent; this indicates the effect of each variable on the final results. The selected value changes are within a range that is considered realistic for this study, based on literature and industry feedback; these can be found in Table 3.

Table 3 – The parameter values investigated in the sensitivity analysis

Parameter	Corrosion impact – base case	Sensitivity analysis range	Source
$\text{CAPEX}_{\text{corrosion}}$ [% of total CAPEX]	+8%	+0%; +3%; **+8%**; +13%	[13]
$\text{OPEX}_{\text{corrosion\_initial}}$ [% of total OPEX]	10%	5%; **10%**; 30%; 35%	Industry input; [13]
$\text{OPEX}_{\text{corrosion\_change}}$ [% of $\text{OPEX}_{\text{corrosion\_initial}}$]	-35%	-15%; -25%; **-35%**	[12]
Performance difference (only for wave and tidal energy) [avg. % difference over 5yrs]	4%	0%; **4%**; 6%	[15]
Change in availability	+0%	-5%; -1%; **+0%**; +1%; +5%	-

The sensitivity analysis is performed considering the ‘corrosion impact – stakeholder input’ in the previous Section as the base case. The results of the sensitivity study are found in Figure 5, Figure 6 and Figure 7. Appendix I contains the LCOE change results of the different parameter values.

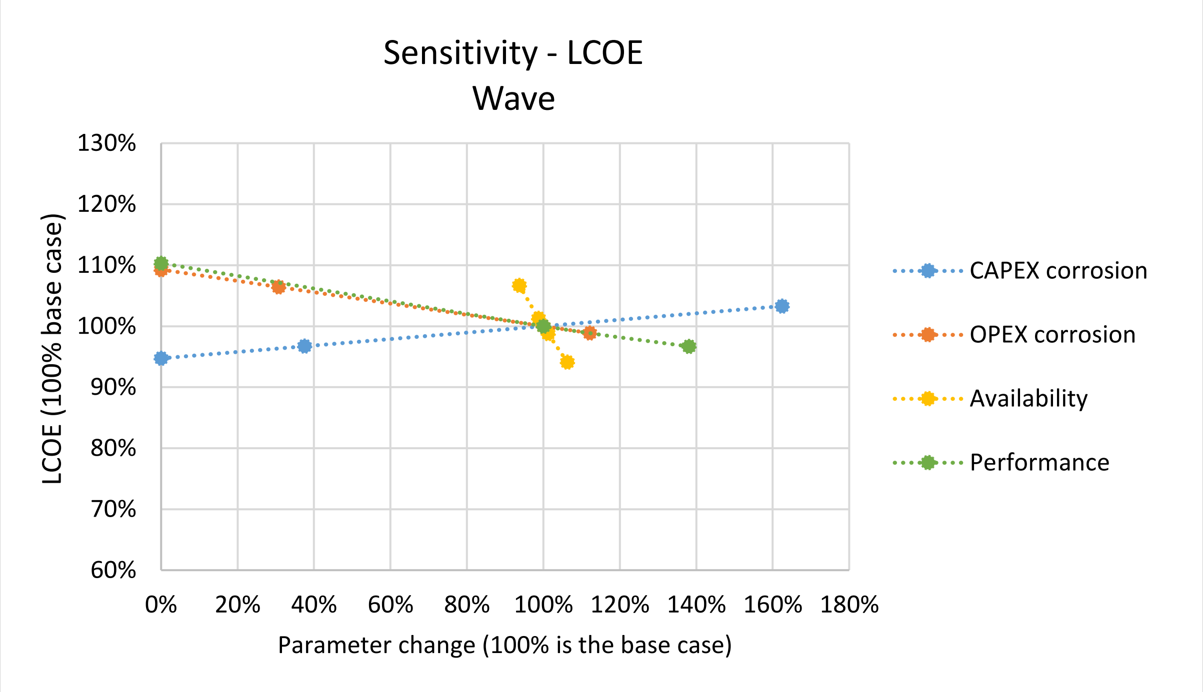


Figure 5 – Sensitivity analysis for wave energy, with the 'Corrosion impact – base case sensitivity' in Table 3 as the base case (parameter change 100%; LCOE 100%)

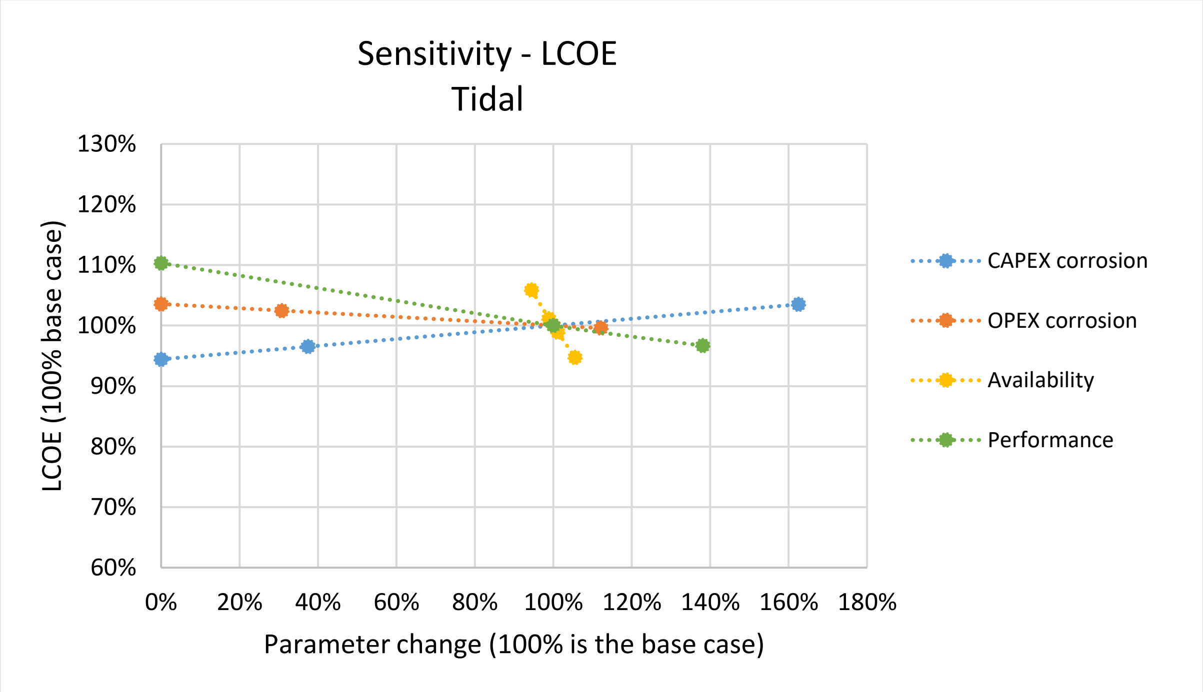


Figure 6 – Sensitivity analysis for tidal energy, with the 'Corrosion impact – base case sensitivity' in Table 3 as the base case (parameter change 100%; LCOE 100%)

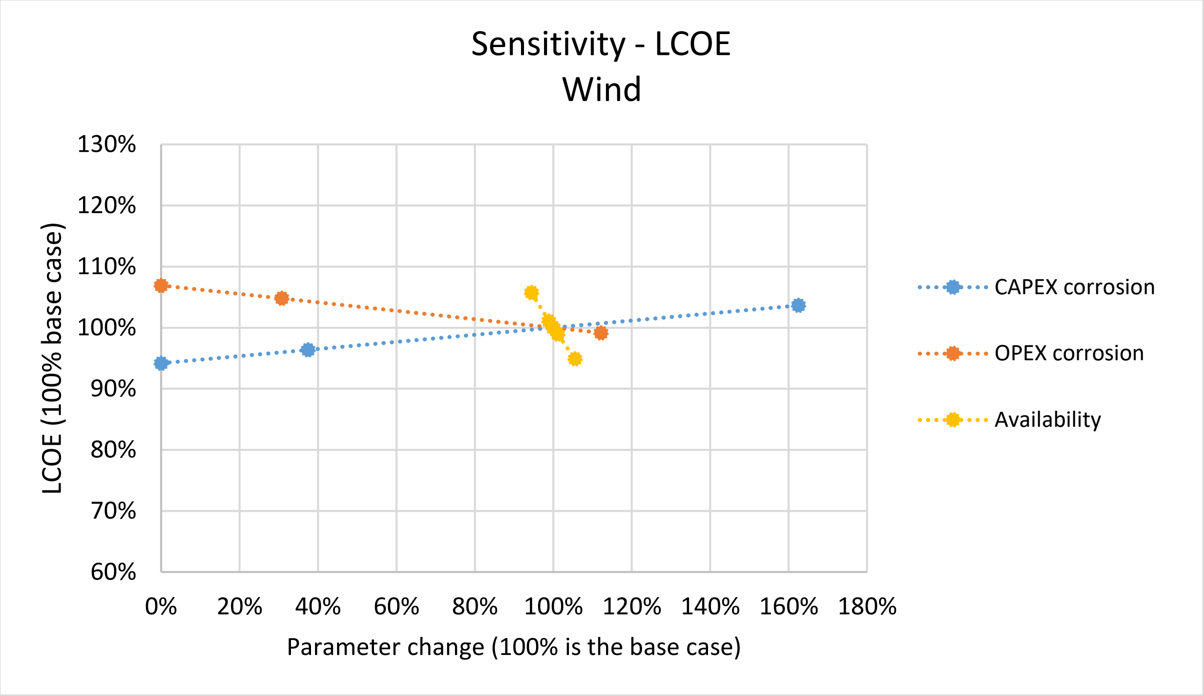


Figure 7 – Sensitivity analysis for offshore wind energy, with the 'Corrosion impact – base case sensitivity' in Table 3 as the base case (parameter change 100%; LCOE 100%)

The sensitivity analysis shows that the following variables have the highest impact on LCOE, which are the variables with the steepest graphs in Figure 5, Figure 6 and Figure 7:

- Availability has a great impact on the LCOE. In this report, the availability is kept constant between the reference case and the different investigated scenarios, due to the absence of information on the downtime (and therefore availability) of corrosion maintenance. It is of interest to investigate the potential impact of reducing the downtime, thus increasing availability, due to corrosion maintenance when corrosion management is improved.
- The performance, and its link to the AEP, also has a great impact on the LCOE. Similar to the availability, it is important to investigate the impact of corrosion on the performance of wave and tidal energy devices. The assumptions in this report on performance are based on a biofouling study, therefore knowledge on the specific impact of corrosion on the performance on wave and tidal energy. In addition, the performance was assumed to stay consistent for wind energy, thus assuming there is no effect from corrosion on wind energy performance.

4. Conclusions

It is important to understand the effect of anti-corrosion solutions on the ORE sector, to determine the economic impact with more certainty. This study has shown there are significant cost reductions expected when applying improved corrosion solutions, ranging between 1% and 21% decrease in LCOE depending on different investigated scenarios. On the other hand, in some cases the increase in initial cost did not fully offset the operating cost reductions, due to a reduction in corrosion related maintenance. This suggests that such solutions would not be adopted unless other reasons, such as safety, would call for it.

The sensitivity study in this report displayed the significant impact of the performance and availability on the LCOE. It is therefore important to further understand the impact of corrosion in the performance and availability of the energy source.

In conclusion, to promote the existing corrosion supply chain applied to the ORE sector strategic investments in training programmes, research and testing, and demonstration projects are required. These focus points can provide a better understanding of corrosion issues as well as support tackling these issues, potentially leading to significant cost reductions as shown in this report.

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Appendix I – Sensitivity Analysis

I.1 Wave Energy

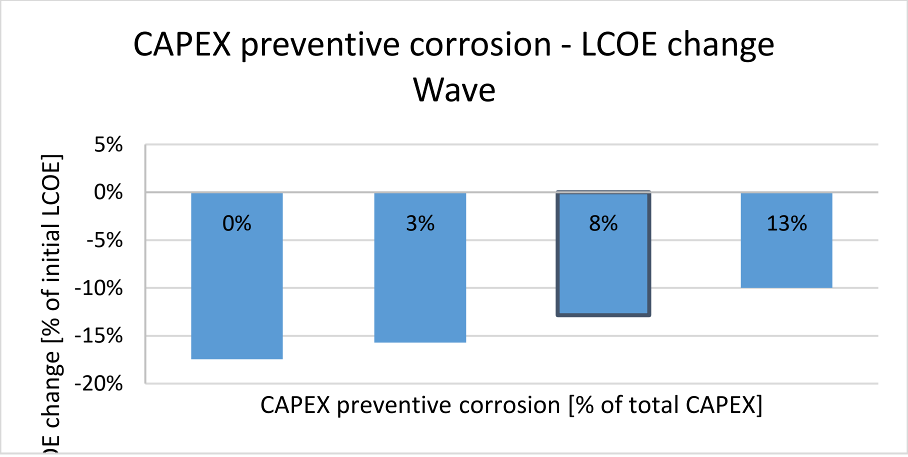


Figure 8 – Effect of CAPEX value on the LCOE for wave energy, investigating CAPEX$_{corrosion}$ of 0%, 3%, 8% and 13% of total CAPEX. The sensitivity base case value is indicated with the dark border (CAPEX$_{corrosion}$ 8%).

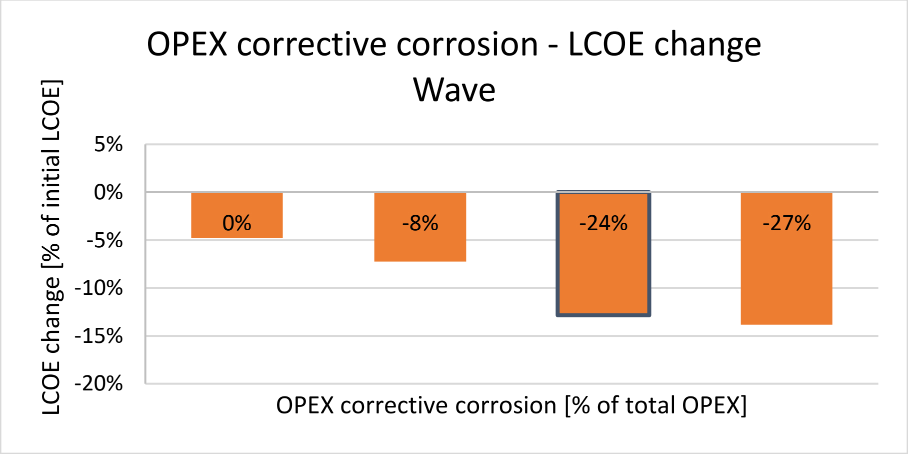


Figure 9 – Effect of OPEX value on the LCOE for wave energy, investigating OPEX$_{corrosion}$ changes due to adjustments in OPEX$_{corrosion\_initial}$ and OPEX$_{corrosion\_change}$ (OPEX$_{corrosion\_initial}$, OPEX$_{corrosion\_change}$) of 0% (35%, -15%) , -8% (30%, -25%), -24% (10%, -35%) and -27% (5%, -35%). The sensitivity base case value is indicated with the dark border (OPEX$_{corrosion}$ -24%).

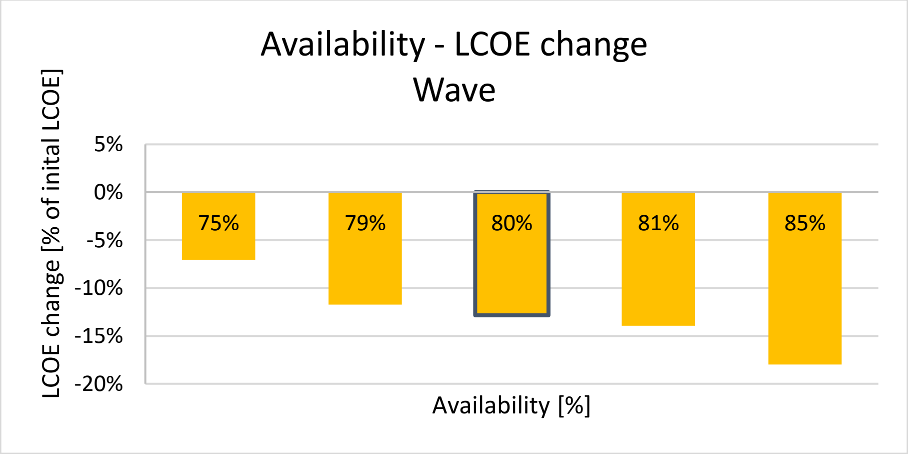


Figure 10 – Effect of changes to the availability of wave energy on the LCOE, investigating changes to availability of -5%, -1%, 0%, +1%, +5% compared to the sensitivity base case value, which is indicated with the dark border (availability 80%).

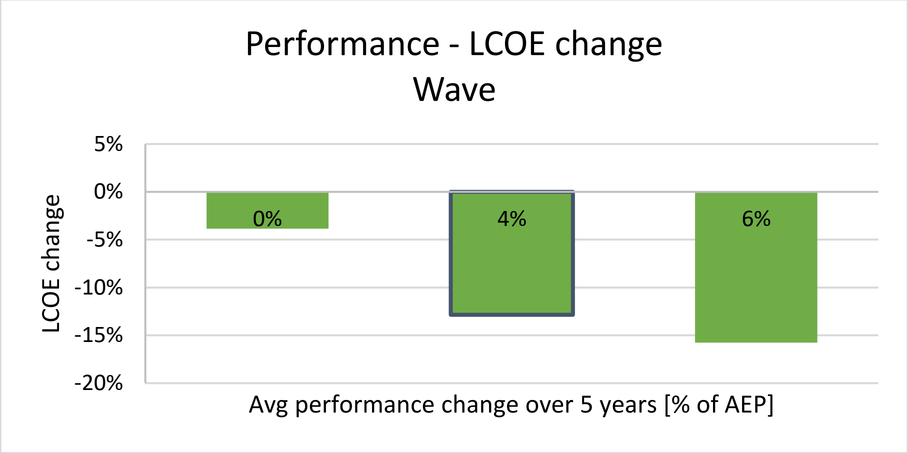


Figure 11 – Effect of performance of wave energy on the LCOE, investigating the average performance difference over 5 years between the business-as-usual case and the application of improved corrosion mitigation of 0%, 4% and 6% of total AEP. The sensitivity base case value is indicated with the dark border (performance difference 4%).

I.2 Tidal energy

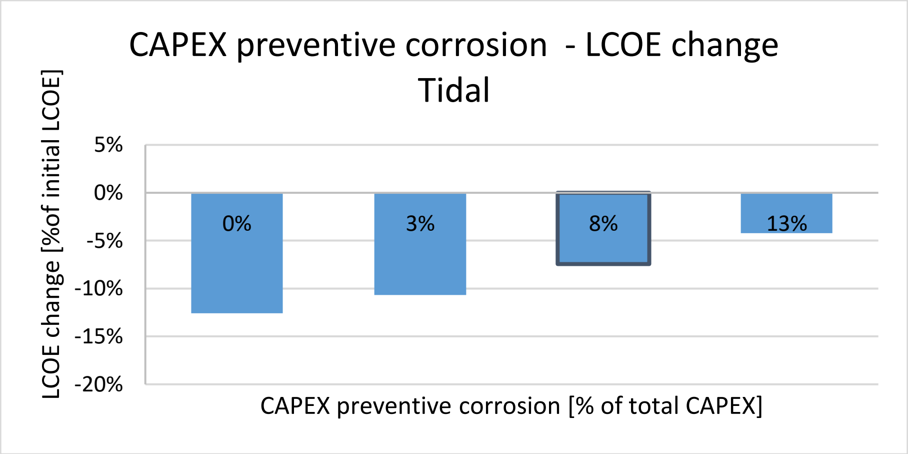


Figure 12 – Effect of CAPEX value on the LCOE for tidal energy, investigating CAPEX$_{corrosion}$ *of 0%, 3%, 8% and 13% of total CAPEX. The sensitivity base case value is indicated with the dark border (CAPEX*$_{corrosion}$ *8%).*

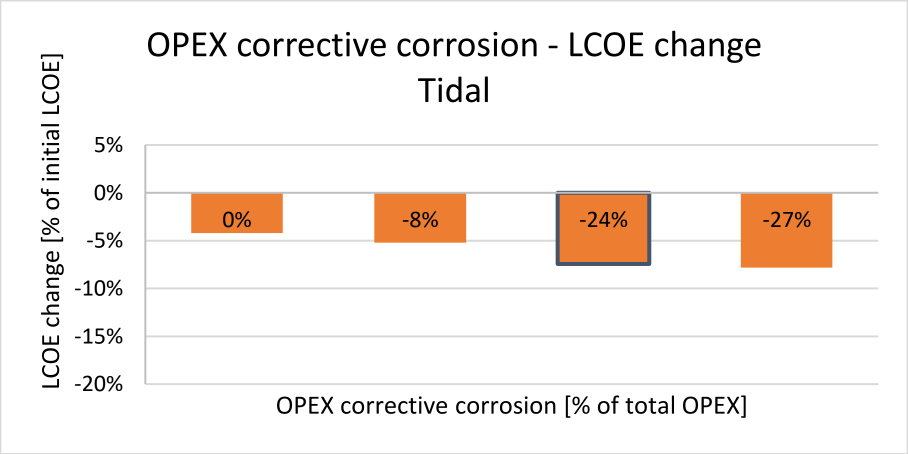


Figure 13 – Effect of OPEX value on the LCOE for tidal energy, investigating OPEX$_{corrosion}$ *changes due to adjustments in OPEX*$_{corrosion\_initial}$ *and OPEX*$_{corrosion\_change}$ *(OPEX*$_{corrosion\_initial}$*, OPEX*$_{corrosion\_change}$ *) of 0% (35%, -15%) , -8% (30%, -25%), -24% (10%, -35%) and -27% (5%, -35%). The sensitivity base case value is indicated with the dark border (OPEX*$_{corrosion}$ *-24%).*

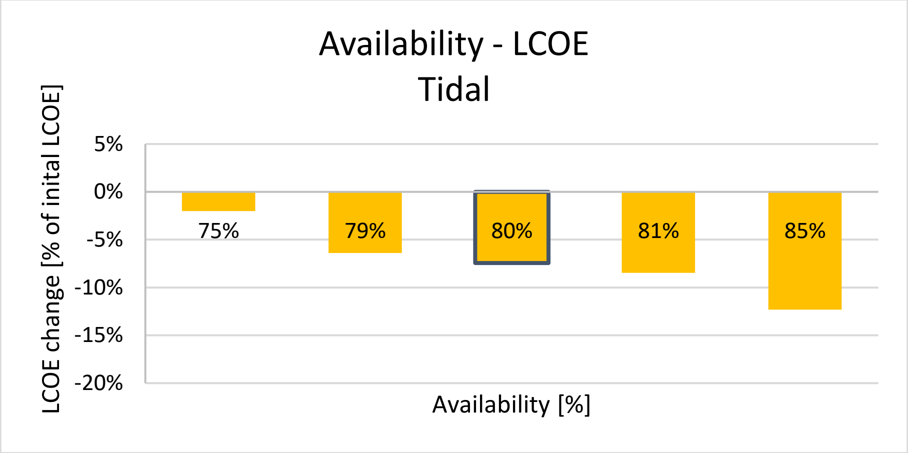


Figure 14 – Effect of changes to the availability of tidal energy on the LCOE, investigating changes to availability of -5%, -1%, 0%, +1%, +5% compared to the sensitivity base case value, which is indicated with the dark border (availability 80%).

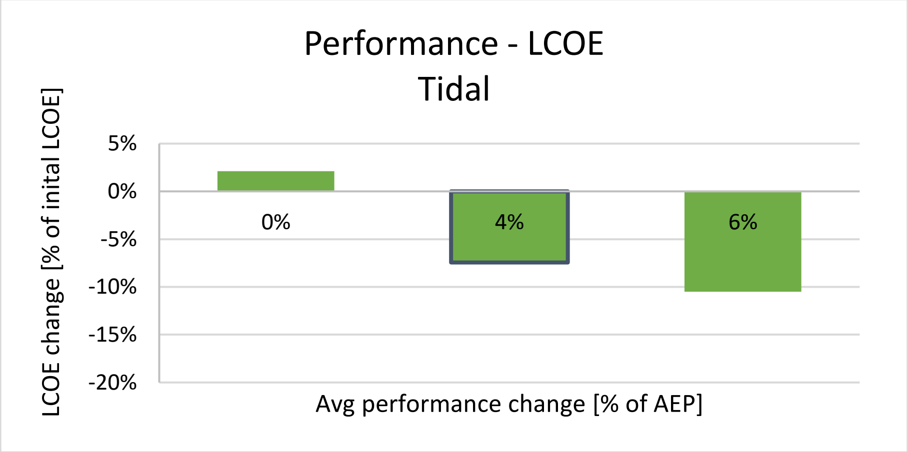


Figure 15 – Effect of performance of tidal energy on the LCOE, investigating the average performance difference over 5 years between the business-as-usual case and the application of improved corrosion mitigation of 0%, 4% and 6% of total AEP. The sensitivity base case value is indicated with the dark border (performance difference 4%).

I.3 Wind energy

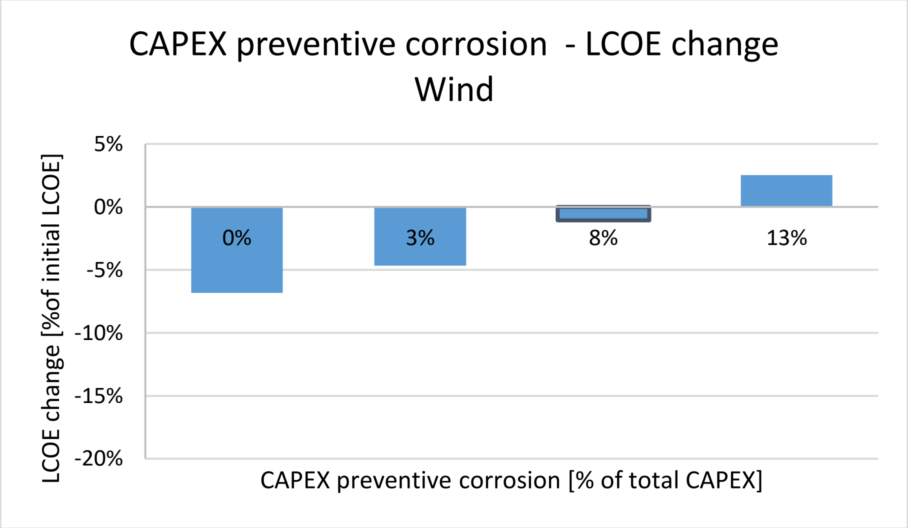


Figure 16 – Effect of CAPEX value on the LCOE for wind energy, investigating CAPEX$_{corrosion}$ of 0%, 3%, 8% and 13% of total CAPEX. The sensitivity base case value is indicated with the dark border (CAPEX$_{corrosion}$ 8%).

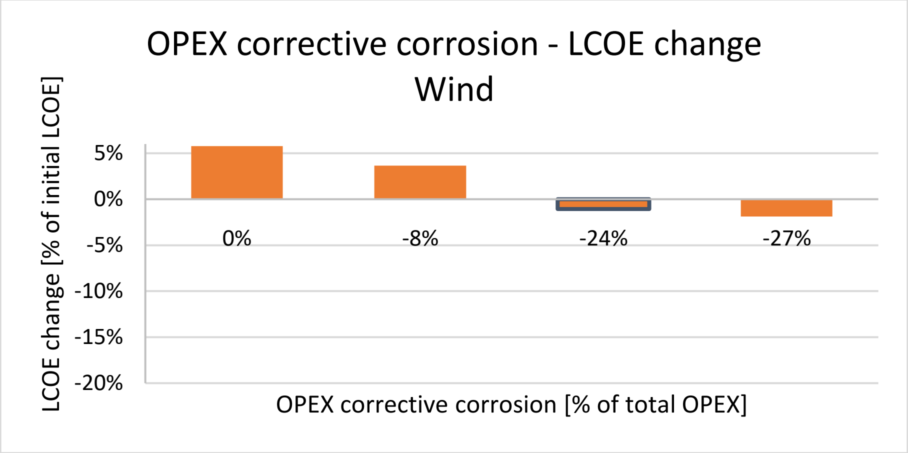


Figure 17 – Effect of OPEX value on the LCOE for wind energy, investigating $OPEX_{corrosion}$ *changes due to adjustments in* $OPEX_{corrosion\_initial}$ and $OPEX_{corrosion\_change}$ *(*$OPEX_{corrosion\_initial}$*,* $OPEX_{corrosion\_change}$ *) of 0% (35%, -15%) , -8% (30%, -25%), -24% (10%, -35%) and -27% (5%, -35%). The sensitivity base case value is indicated with the dark border (*$OPEX_{corrosion}$ *-24%).*

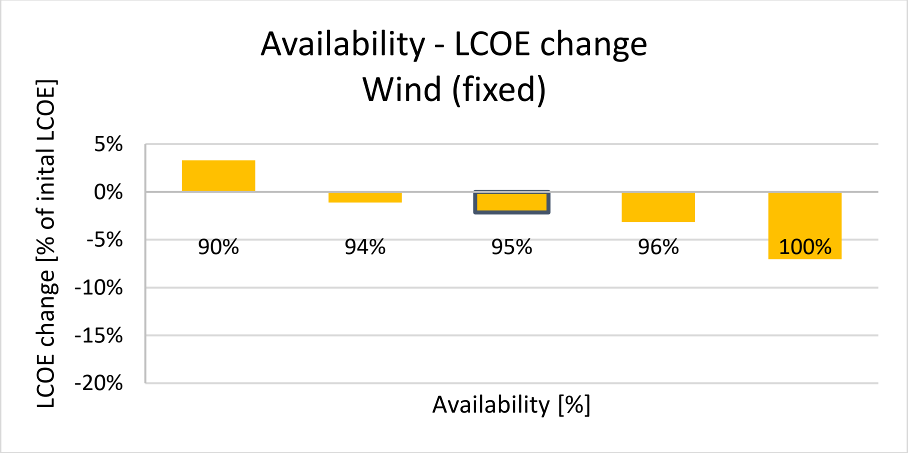


Figure 18 – Effect of changes to the availability of fixed wind energy on the LCOE, investigating changes to availability of -5%, -1%, 0%, +1%, +5% compared to the sensitivity base case value, which is indicated with the dark border (availability 95%).

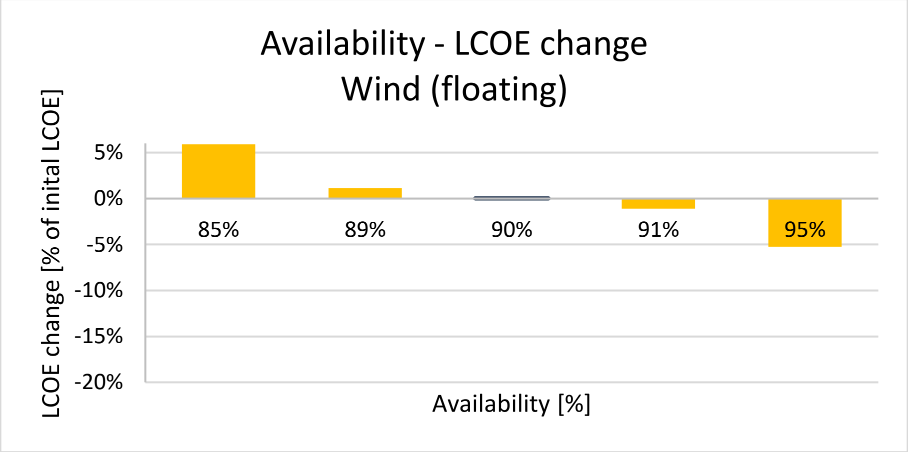
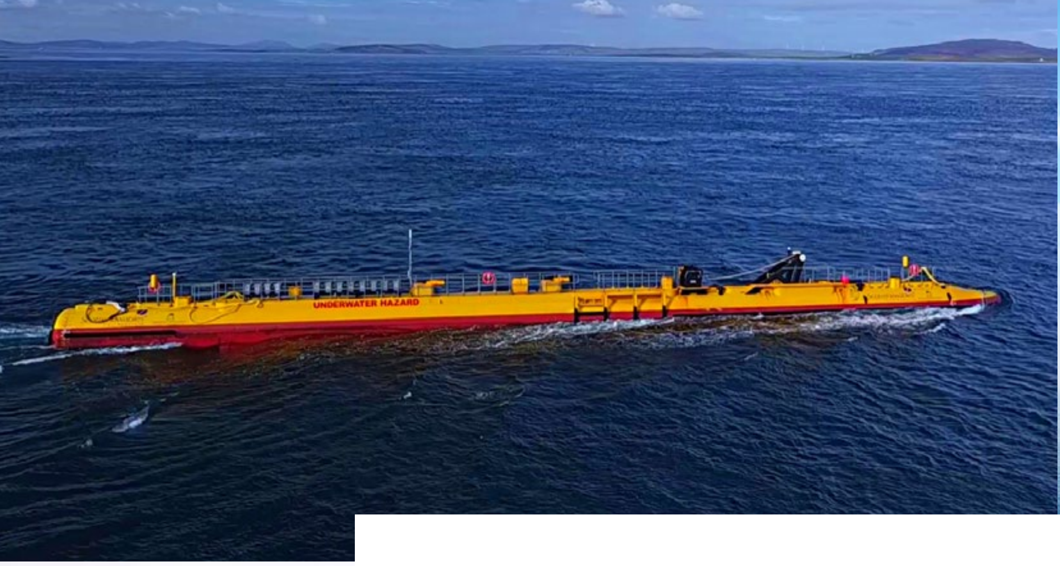


Figure 19 – Effect of changes to the availability of floating wind energy on the LCOE, investigating changes to availability of -5%, -1%, 0%, +1%, +5% compared to the sensitivity base case value, which is indicated with the dark border (availability 95%).



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