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Authors	Devoy McAuliffe, Fiona;Kamidelivand, Mitra
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Modified Installation, Operations, Maintenance and Logistics model for Irish and Welsh wave and tidal technologies and locations

Work Package 8: Installation, Operations & Maintenance and Logistic models

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Authors: Fiona Devoy McAuliffe (MaREI, UCC) and Mitra Kamidelivand (MaREI, UCC)

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Abbreviations

CM	Corrective maintenance
EBA	Energy-base availability
LCOE	Levelized Cost of Energy
MC	Monte Carlo Simulation
O&M	Operation and Maintenance
OE	Ocean Energy
ORE	Offshore Renewable Energy
PM	Preventive maintenance
TBA	Time-base availability
TEC	Tidal Energy Converter
TRL	Technology Readiness Level
WEC	Wave Energy Converter
WES	Wave Energy Scotland
WW	Weather Window

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1 Summary

This report details the work of D8.5 within WP8 of the SELKIE project. It is linked to the three previous reports of WP8: D8.2, D8.3 and D8.4. The SELKIE project has developed an open-access Logistics and O&M tool for tidal and wave energy. A detailed description of the tool as well as methods and model logics are provided in D8.2. In D8.3 and D8.4, the O&M tool was employed to create scenarios of pilot, first array and first commercial scale projects for wave energy case studies based on an oscillating water column wave energy converter (described in D8.3) and for tidal energy case studies based on the Sabella D15 turbine (described in D8.4) in Wales and Ireland. This report provides the description of the sensitivity and scenario analyses of the first commercial scale wave and tidal energy projects studied in D8.3 and D8.4. The report aims to identify key areas in cost reduction and farm availability improvement. It considers different scenarios analyses, for example, the implementation of the weather restrictions for vessel operations, changes in failure rates, adapting a preventive maintenance strategy and the effect of mean time to repair. For each scenario, the impacts on OPEX, availability and energy production are discussed, and the results of optimal wave and tidal commercial case studies in Wales and Ireland are presented.

2 Introduction

Over the last decade, there has been a pronounced increase in support for marine energy through funding for projects to develop and scale up tidal stream and wave energy in Europe and across the globe. Europe plans to retain its first place as the leader in the ocean energy sector. In the Offshore Renewable Energy (ORE) strategy released in November 2020, the European Commission set a goal of 1GW of ocean (wave and tidal) capacity by 2030 which increases to 40GW by 2050 [1]. The ORE target for wave and tidal energy capacity is ambitious, and its implementation remains a challenge. Recent statistics published by Ocean Energy Europe [2] show that cumulative wave energy installation in 2021 reached to 12.7 MW, but only 1.4 MW is currently in the water. The installation capacity of tidal stream energy reached to 30.2 MW, and 11.5 MW is currently in the water. With few wave and tidal stream arrays in operation, support is needed for their widespread development to reach to commercial operational stage much more quickly.

The SELKIE project aims to lead research in the development of a streamlined commercialisation pathway for the marine renewable energy industry, especially in Wales and Ireland. SELKIE will create a set of multi-use technology, engineering and operation tools. The project will test and validate these tools on two pilot demonstration technologies for wave and tidal. The tools developed by SELKIE will be made open access. One of these tools is the O&M and Logistics model which was developed in WP8. The tool is available for download on GitHub including a system requirement and set up guide, as well as a 'How to Use Guide' and video providing a sample wave energy study¹. An overview of the SELKIE O&M and Logistics tool is shown in Figure 2.1.

¹ <https://www.selkie-project.eu/how-to-setup-and-use-the-selkie-om-and-logistics-tool/>

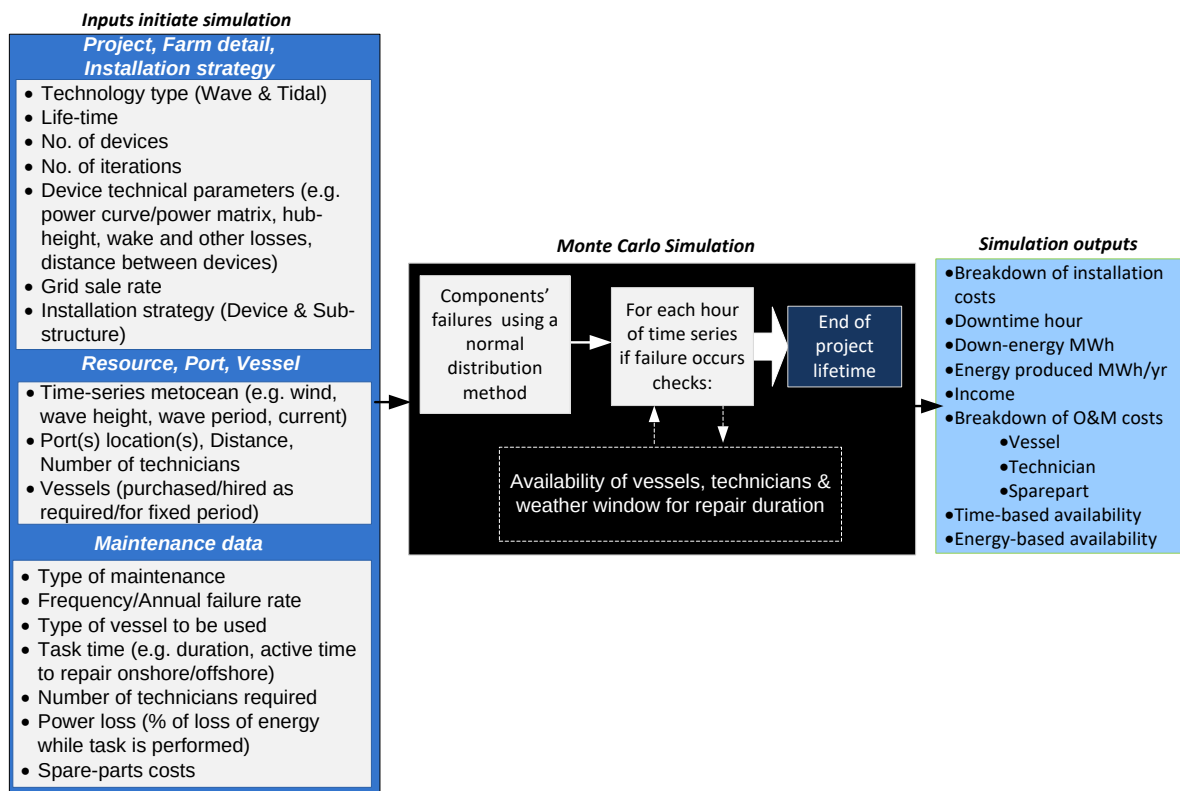


Figure 2.1 An overview of the SELKIE O&M and Logistics model.

In two previous deliverables of WP8, the SELKIE O&M tool is used, and through scenario analyses, the reports examined the estimated energy production, installation and OPEX costs for a wave energy converter (WEC) (in D8.3), and a tidal energy converter (TEC) (in D8.4) for pilot, first array and first commercial scale farms in Wales and Ireland.

This report investigates the potential improvement to the availability and OPEX reductions of the first commercial scale WEC and TEC projects in D8.3 and D8.4. It looks at the following key areas affecting the farms' availability and OPEX of WEC in **Section 3** and TEC in **Section 4**:

- Weather restrictions
- Failure rates
- Preventive maintenance strategies
- Vessel purchased versus vessel rented scenarios
- Sensitivity of offshore operational durations

Based on these sensitivity and scenario analyses, the report proposes optimal commercial scale projects with viable potential solutions to achieve the highest availability and lowest OPEX for WEC (Section **Error! Reference source not found.**) and TEC (Section **Error! Reference source not found.**) farms in Ireland and Wales.

3 Sensitivity and scenarios analyses- Wave

3.1 Description of the wave base case study

From the previous report (D8.3), a potential 72 MW commercial wave project was modelled based on a theoretical 1.44 MW oscillating water column Wave Energy Converter (WEC) in

the Welsh (West Pembrokeshire) and Irish (West Wave) sites. The WEC uses the OE buoy power matrix [3]². A summary of the key input data from D8.3 is presented in Table 3.1.

Table 3.1 Summary of the O&M model input data from D8.3.

Specification of components and corrective maintenance			
Component	Annual Failure rate	Repair category	Spare-part cost
Minor mooring line	0.1	Type 1	10,000
Mooring replacement	0.2	Type 2	33,000
Turbine bearing	0.04	Type 1	6,700
Major structural	0.04	Type 2	1,700,000
Major mooring failure	0.04	Type 2	67,000
Minor structural	0.03	Type 4	10,000
Minor electrical	1.45	Type 1	6,700
Major electrical	0.04	Type 3	80,000
Generator	0.73	Type 1	6,700
Vessel specification			
Vessel type	Speed (knots) & fuel consumption (l/hr)	Daily cost & mobilization cost	Number
Multipurpose Workboat (MW)	18 & 100	4,000 €/day & 8,000€	6
2 Tugs (Tug)	8 & 100	10,000 €/day & 20,000€	6
Anchor Handling Tug Vessel (AHTV)	12 & 250	30,000 €/day & 60,000€	6
Other			
Base O&M cost €/yr	Other O&M cost €/yr	Number of technicians	A technician cost €/yr
250,000	10% of total	36	50,000

The potential facility ports, which were selected by WP4, were Pembroke Dock at 27 km distance for the West Pembrokeshire site, and Foynes port at 45 km for the West Wave site.

In D8.3, the time-based availability and OPEX (€/year/kW) of a first commercial scale wave project were compared to the minimum and maximum ranges in the literature [4], see Table 3.2 summary.

Table 3.2 Comparison of availability, OPEX costs of commercial tidal project with the literature range [8.3].

Parameter	Literature minimum range	Base-CS from D8.3: 72 MW commercial scale tidal project in West Wave	Base-CS from D8.3: 72 MW commercial scale tidal project in West Pembrokeshire	Literature maximum range
OPEX (€/year/kW)	65	63	69	340
Time-based availability	95%	83%	90%	98%

² While the reference device used is rated to 2880kW, it is assumed that a first commercial project device would be smaller. Therefore, the matrix has been divided by 2 and a device rated at 1440kW.

This report uses the wave 72 MW commercial scale project for West Wave in Table 3.2Table 4.2 as the 'Base Case Study' (Base-CS). This site was selected because it had the lowest availability but also the highest energy production suggesting that it

- a) may have the most potential if it can be optimised but
- b) has the most significant challenges to overcome

This report will focus on the availability and OPEX of the commercial wave array, examining OPEX per kWh to account for the impact of energy production offsetting estimated costs. It will conduct sensitivity analyses of some of the model inputs or considerations, and investigate their impacts on the relevant metrics, namely availability and OPEX³.

Based on the ranges of availability and OPEX in Table 3.2, an initial optimization target is to achieve a 95% availability (or maximum achievable availability) for commercial 72MW wave projects in West Pembrokeshire and West Wave. Sections 3.2-3.5 will examine key areas for reducing OPEX and improving availability identified in D8.3 including:

- Varying operational weather restrictions
- Increasing and decreasing failure rates
- Applying three different Preventive Maintenance (PM) scenarios, which reduce the overall failure of a turbine by 20%, 40% and 60%
- Varying operation durations
- Purchasing versus renting vessels

Following this analysis, an optimal scenario will be determined in section 3.7. The final optimised scenario will also be applied to the West Pembrokeshire site, providing a final comparison of the Irish and Welsh sites (section 3.8).

3.2 Weather restrictions

The Base-CS has a mixture of significant wave height (Hs) restrictions associated with different repair categories that depend upon the action required. These are summarised in Table 3.3. As a general rule, it was assumed that tasks requiring a long-time offshore will require calmer conditions. Wave period (Tp) is limited to 8 seconds and wind speed is limited to 12 m/s. These were set based on discussions with industry. It should be acknowledged that the wind speed is quite high however, no sensitive lifting activity at height is expected offshore in this case study. The wave period is quite a difficult parameter to select since operations may be able to occur in sea states with longer wave periods, although these will generally bring higher wave heights that may ultimately restrict operations. However, it was found that varying these conditions (wave period and wind speed) did not have a significant impact on results. Therefore, Hs is the key dominating factor and the focus of this section.

³ The tool can only model the turbine and substructure/foundation installation activities. Total installation cost in D8.3 is estimated as a percentage of the turbine and substructure installation cost using the literature data. For this report, the study will not perform sensitivity and scenario analysis of total installation cost.

Table 3.3 Weather operational Hs limits for Base-CS.

Repair Category	Vessel required	Operation duration offshore	Operation duration onshore	Hs limit for offshore operation
Type 1	Multi-purpose Workboat	6	n/a	1.5
Type 2	2 tugs	30	300	1
Type 3	2 tugs	30	240	1
Type 4	2 tugs	3	48	1.5

For simplicity, this section applies the same Hs restriction to all offshore O&M repairs and varies these from 1-3m in steps of 0.5m. The aim is to determine the scale of impact on availability and OPEX. Results are illustrated in Figure 3.1.

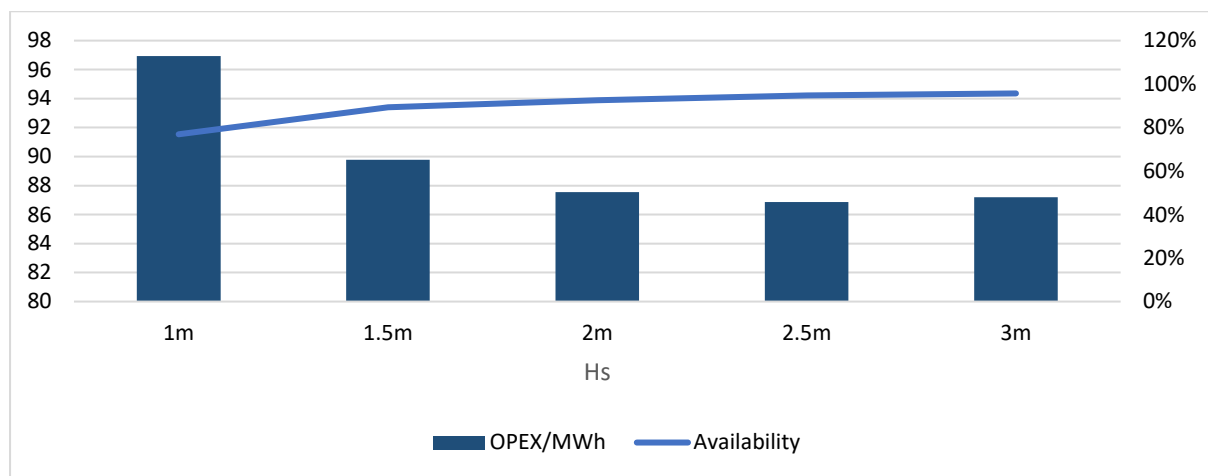


Figure 3.1 Impact of varying weather restrictions (Hs) on time-based availability at West Wave.

These demonstrate that even increasing all operational limits to 1.5m Hs would have a significant impact, increasing availability from the Base-CS (83%) to 89%. If operations could be undertaken in 2m Hs (93%), this would bring results much closer to the target of 95%. The most sensitive operation of transferring crew from small CTVS (crew transfer vessels) to fixed offshore wind turbines can currently be done in Hs up to 2m. Therefore, while it is dependent on the technology, design and O&M strategy chosen; it is theoretically possible that further technological advancements (e.g. increasing device stability during tow) and/or greater experience (repetition reducing uncertainties and risks) could increase the operational weather limits for wave energy farms as well. While 2.5 and 3m Hs successfully achieve availability $\geq 95\%$, it is unlikely that offshore operations can be undertaken in such conditions without significant changes in technology, O&M strategy and vessels (e.g. the use of larger more expensive DP vessels which would increase OPEX). Therefore, they are only presented for illustrative purposes.

3.3 Failure rates

The current failure rates applied are a mixture of experience from the current literature [5] [6] and discussions with industry for a theoretical oscillating water column WEC. Given that this study is theoretical, without actual real-life experience and data, the failure rates applied

are very uncertain. In addition, the same rates were applied for the base case pilot farm (1.44MW) as the commercial 72MW farm. In reality, it is likely that technological improvements would have occurred between these 2 deployments, improving device reliability. This section reduces and increases failure rates to consider the uncertainty of this input and the potential scale of the impact it could have, particularly the potential impact of technological improvements in improving reliability at commercial stage. Results are presented in Figure 3.2.

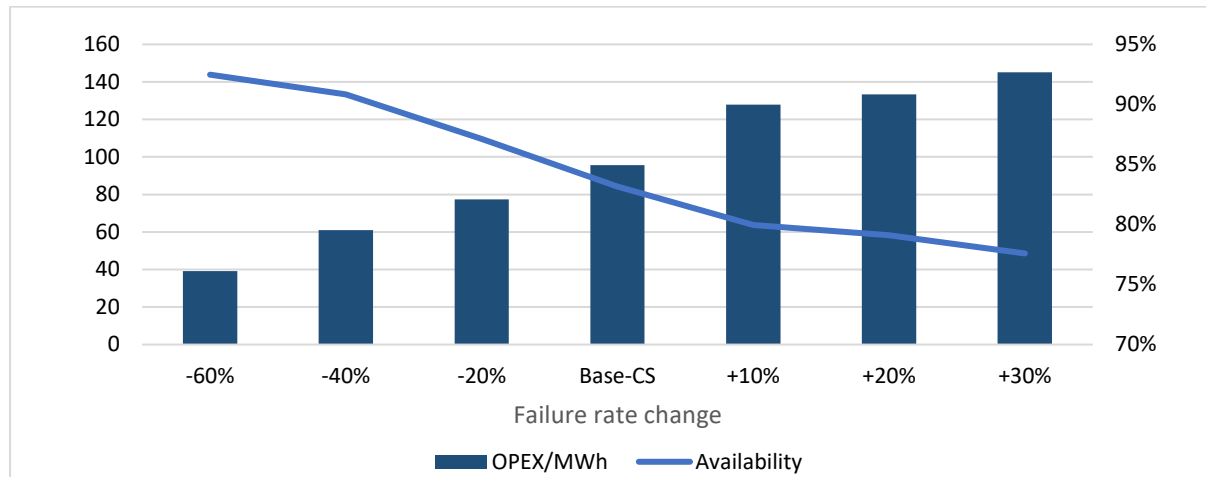


Figure 3.2 Impact of varying failure rates on Base-CS for West Wave site.

It is clear that the assumed failure rates have a significant impact on availability, and in turn, the energy production and revenue. Assuming improved reliability for a commercially deployed device and an indicative reduction of 20% in failure rates could lead to an availability of 87% (Base-CS 83%). Further real-life experience and data is needed to increase confidence in results. However, this study shows how the tool can be used to determine key bottlenecks to achieving targets and potential solutions.

3.4 Preventive maintenance

It is expected that some scheduled/Preventive Maintenance (PM) will also begin to be undertaken for a commercial farm. This section applies 3 PM scenarios which are presented in Table 3.4. For all scenarios, PM takes place every 2 years and occurs onshore. This study assumes that PM will actively improve the condition of the device. However, it should be noted that the tool does not have a link between PM and the health of the device i.e. scheduled maintenance does not reduce the likelihood of failure. Therefore, for each PM scenario, the failure rates are reduced by an indicative percentage that grows depending on the scale of PM (i.e. the PM duration onshore, cost and number of technicians). It should be remembered that while failure rates are reduced, increasing availability, the time required to undertake PM will also contribute to downtime. Therefore, this study is seeking the optimal trade-off between PM downtime and reduced failures.

Table 3.4 Preventive Maintenance scenarios.

Scenario	PM duration onshore ¹	Cost/PM/Turbine ²	Failure rate reduction	No. of technicians
PM1	50	10,000	20%	4
PM2	80	20,000	40%	5
PM3	120	30,000	60%	6

Results are presented in Figure 3.3 and demonstrate that the optimal scenario is PM2, assuming this will reduce failures by 40%. This achieves a high availability of almost 90% and the lowest OPEX of €88.81/MWh. While this is an indicative study, without real data, it demonstrates how the tool can be used to seek areas of optimisation in a scenario.

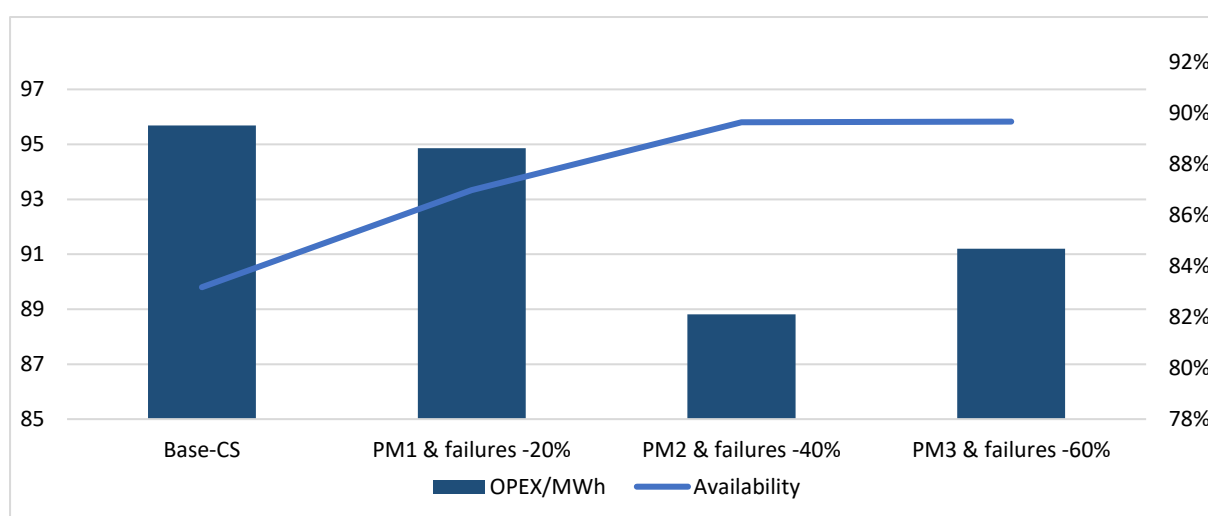


Figure 3.3 Application of Preventive Maintenance at the West Wave site

3.5 Vessel hired/purchased scenario

The model allows users to determine whether vessels are purchased or hired, and if the latter, the user can specify if they are “hired as required” or a rental period each year. The base case scenario assumes vessels are all hired as required. However, it may be cheaper for a large commercial farm to own their own vessels. Therefore 2 vessel purchase scenarios test the impact of purchasing vessels on OPEX costs: a) purchasing the Multipurpose Vessels (MPVs) and b) purchasing the 2 tugs (Tugs). Both are assigned an annual running cost of €10,000 for maintenance etc. Figure 3.4 presents results and demonstrates that there are potential savings in purchasing vessels for O&M. However, it should be remembered that the cost of vessels would need to be counted as part of the CAPEX and may ultimately negatively impact the overall cost of energy. Therefore, further work is needed to determine whether a vessel purchase scenario is optimal and this is beyond the scope of this deliverable.

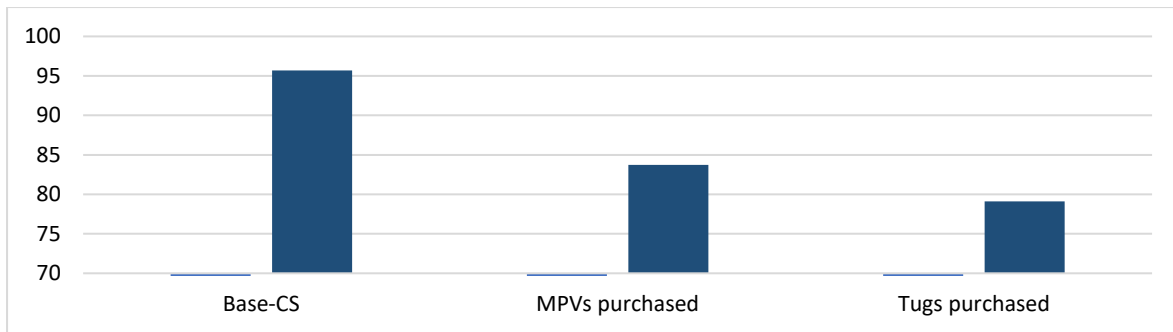


Figure 3.4 Vessel purchase/hire scenarios at West Wave site.

3.6 Operation durations

Another uncertain factor in the Base-CS are the assumed operation durations. This section varies this assumption to illustrate the scale of impact of these on results. Results are presented in Figure 3.5.

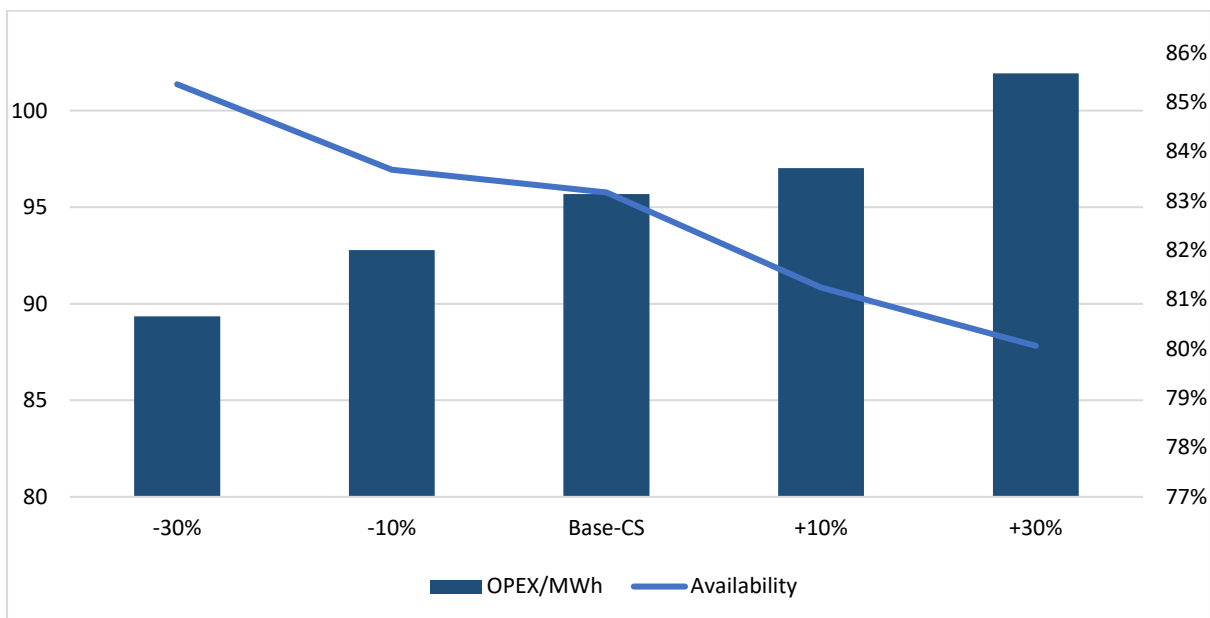


Figure 3.5 Impact of varying operation durations at the West Wave site

Results show that an increase of 30% reduces availability to 80% while a decrease of 30% leads to an availability of 85%. It is likely that experience would lead to some reduction in repair operation durations by the time WECs reach a commercial deployment. While reductions in task durations tend to have a lower impact on availability, streamlining operations may still prove important in an overall optimised scenario.

3.7 Optimized scenario - wave

Based on the above sensitivity analysis, this section compiles different optimised scenarios (Opt-CS) to determine whether it is possible to reach the target availability of 95%. The improvements made are summarised for each Opt-CS in Table 3.5.

Table 3.5 Optimised scenarios

Optimised scenario	Weather restrictions	PM & Failure Rates ⁴	Operation durations	Vessel purchase/rental
Opt-CS1	1.5m Hs; 10s Tp; 14m/s wind speed	PM1	-10%	All rented
Opt-CS2			-20%	
Opt-CS3		PM2		
Opt-CS4	2m Hs; 10s Tp; 14m/s wind speed			
Opt-CS5				
				MPVs purchased

⁴ See Table 3.4.

It should be noted that while varying wave period (Tp) and wind speed (m/s) operational limits did not have a significant impact on results, they were set higher for the optimisation studies to essentially remove them as a factor. This is due to the difficulty in selecting an appropriate limit for the wave period, and the lack of sensitive offshore lifting operations that would restrict wind speed (as outlined in section 3.2). It is also assumed that the significant wave height limit itself would ultimately limit actions to reasonable wave periods and wind speeds. As illustrated in **Error! Reference source not found.**, a wave height between 1-2m is likely to occur where there is only a moderate breeze (e.g. wind speed between 6-8m/s) and small but frequent waves. This is only a generalised correlation and cannot be taken as representative of all weather conditions and sea states. However, it provides a good overview of the likely relationship between wind speeds, wave periods and wave heights.

Beaufort number	Wind speed	Wave height	Sea conditions	Sea state photo
0	< 1kt	0 m 0 ft	Flat.	 BEAUFORT FORCE 0 SEA IS CALM, NO WIND VISIBLE
1	1 – 3kt	0 – 0.2 m 0 – 1 ft	Ripples without crests.	 BEAUFORT FORCE 1 SEA IS CALM, NO WIND VISIBLE
2	4 – 6kt	0.2 – 0.5m 1 – 2 ft	Small wavelets. Crests of glassy appearance, not breaking	 BEAUFORT FORCE 2 SEA IS CALM, NO WIND VISIBLE
3	7 – 10kt	0.5 – 1m 2 – 3.5ft	Large wavelets. Crests begin to break; scattered whitecaps	 BEAUFORT FORCE 3 SEA IS CALM, NO WIND VISIBLE
4	11 – 16kt	1 – 2m 3.5 – 6ft	Small waves with breaking crests. Fairly frequent whitecaps.	 BEAUFORT FORCE 4 SEA IS CALM, NO WIND VISIBLE
5	17 – 21kt	2 – 3m 6 – 9ft	Moderate waves of some length. Many whitecaps. Small amounts of spray.	 BEAUFORT FORCE 5 SEA IS CALM, NO WIND VISIBLE
6	22 – 27kt	3 – 4m 9 – 13ft	Long waves begin to form. White foam crests are very frequent. Some airborne spray is present.	 BEAUFORT FORCE 6 SEA IS CALM, NO WIND VISIBLE

Figure 3.6 Beaufort scale [7].

Results are presented in Figure 3.7.

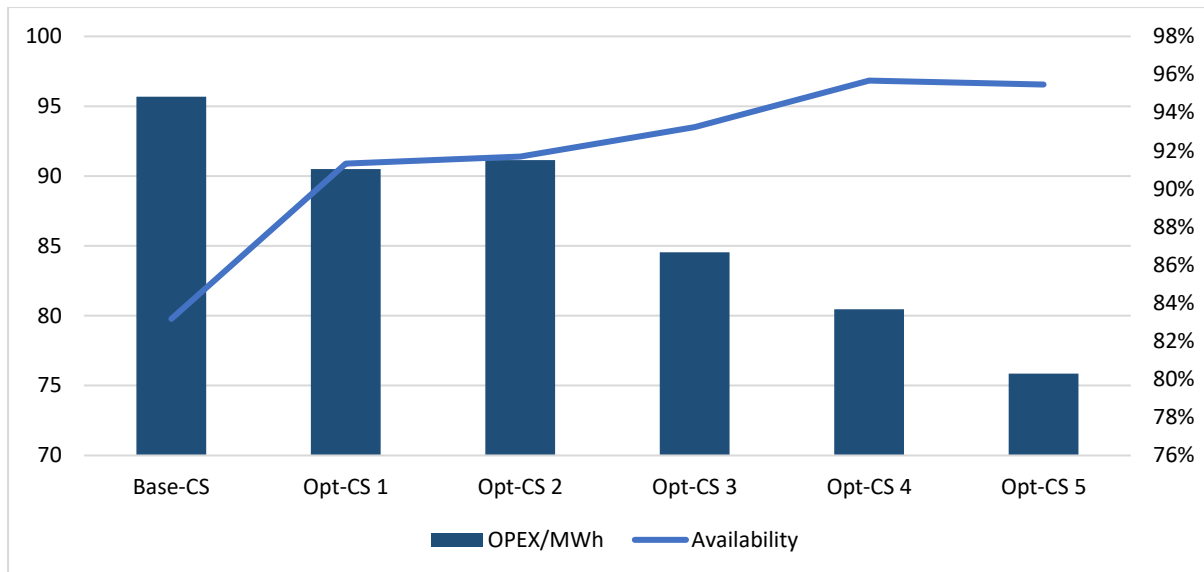


Figure 3.7 Optimised scenarios at the West Wave site

Opt-CS1 and 2 achieve a 10% increase in availability (>91%) and 5% reduction in OPEX. The implementation of PM2 in Opt-CS3, achieves a further increase in availability and reduction in OPEX. Opt-CS4 and 5 are optimal in terms of availability, achieving >95%. This is due to the increase in weather restrictions to 2m Hs. A further reduction in OPEX cost is found in Opt-CS5 when the MPVs are purchased. While all sensitivity studies were run for 10 iterations due to the computational time required; Opt-CS5 was run for 100 iterations as the best-case scenario.

3.8 Welsh and Irish site comparison

The WW_Opt-CS5 was applied at West Pembrokeshire (WP_Opt-CS6) to show potential improvements at the Welsh site. Results are presented in Figure 3.8.

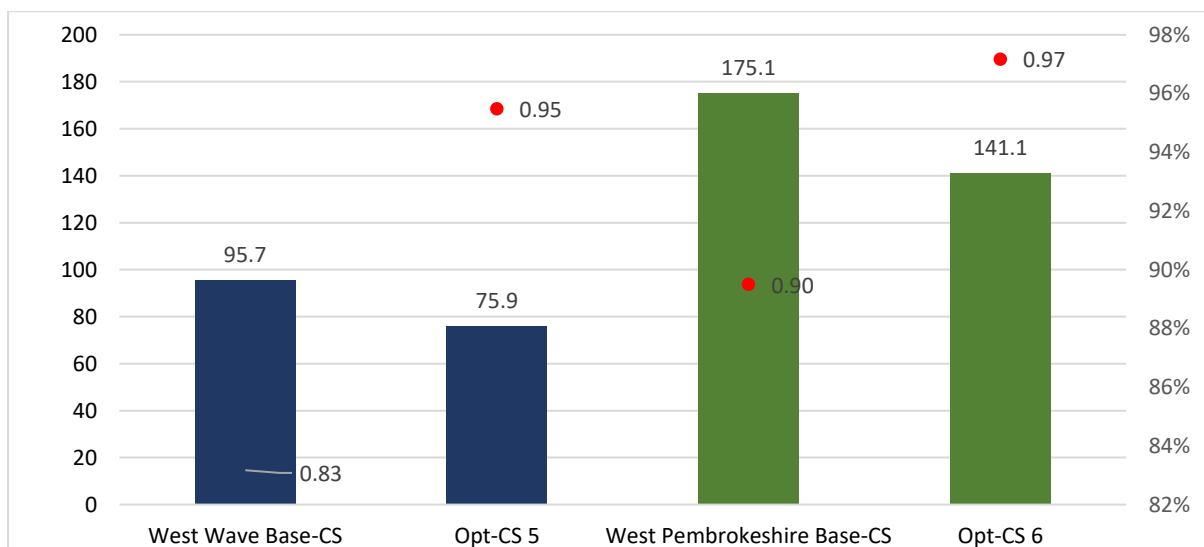


Figure 3.8 Comparison of Base-CS and optimised scenarios at the Irish and Welsh site.

Optimisations result in an 8.57% increase in availability to 97% and a 19.44% reduction in OPEX at the West Pembrokeshire site. Comparison between the Welsh and Irish site

demonstrate that West Wave still has more potential with the lower OPEX despite a lower availability i.e. produces more energy and revenue to offset costs. This is assuming that the suggested optimisations and target availability can be achieved.

3.9 Concluding remarks- wave case study

This report investigates potential improvement to the availability and OPEX reductions of the first commercial scale WEC projects in D8.3. It looks at key areas affecting the farms' availability and OPEX such as weather restrictions, failure rates, operational durations, maintenance strategy and vessel purchased versus vessel rented scenarios. Based on the sensitivity and scenario analyses, the report proposes optimal commercial scale projects with viable solutions to achieve the highest availability and lowest OPEX for WEC farms in Ireland and Wales.

The key optimisations include

- Increasing operational weather restrictions to 2m Hs; 10s Tp; and 14m/s wind speed. This assumes real-life experience has helped streamline operations and reduce risks making it easier to undertake activities in higher wave heights and/or there have been design improvements that increased the stability of the device during offshore maintenance and/or tow to shore.
- Applying the PM2 scenario with PM every 2 years, reducing failure rates by 40%. It is assumed this reduction also accounts for potential increases in device reliability due to improved technology by the time a design reaches commercial deployment.
- Reducing operational durations by 20%, assuming real life experience has streamlined operations.
- Assuming that MPVs are purchased since these are the smaller of the vessels required and undertake most of the minor repairs. Tugs will still be rented.

Results are presented in Table 3.6.

Table 3.6 Optimised case-study results.

Scenario	OPEX/year/kW	OPEX/MWh	Average Annual Energy (MWh)	Availability
West Wave Base-CS	63	95.69	47,167	83%
WW_Opt-CS5	59	75.86	55,749	95%
West Pembrokeshire Base-CS	69	175.13	28,175	90%
WP_Opt-CS6	60	141.08	30,759	97%

This deliverable identifies the scope and scale of improvements needed in order to achieve an availability of 95-97% and to further reduce OPEX costs. When comparing the Irish and Welsh sites, although the availability is still higher at West Pembrokeshire than at West Wave; the higher energy production offsets costs. This suggests that there is more potential for a commercial WEC deployment at the Irish site in this instance. Further optimisation could examine whether economies of scale can be found when increasing the farm size (e.g.

increasing to 100MW farm), seeking the most cost effective farm capacity and whether this can be best achieved by either increasing the number of WECs with the 1.44MW device or increasing the individual WEC capacity with fewer devices.

4 Sensitivity and scenario Analyses – Tidal

4.1 Description of the tidal base case study

From the previous report (D8.4), a potential 50 MW commercial scale tidal project was modelled based on the 500 kW Sabella D15 tidal turbine in the Welsh (Morlais) and Irish (Wicklow Head) sites. The potential facility ports, which were selected by WP4, were Holyhead port at 8 km distance for the Morlais site, and Dublin port at 12 km for the Wicklow Head site.

A summary of the key input data for a first commercial scale tidal project (50MW) from D8.4 is presented in Table 4.1.

Table 4.1 Summary of the O&M model input data from D8.4.

Specification of components and corrective maintenance			
Component	Failure rate %	MTTR ¹	Spare-part cost
Nacelle Body Major	2.7%	69	35,000
Support Structure Major	1.4%	509	200,000
Blade Minor Repair	1.9%	16	10,000
Pitch system Major	0.8%	53	8,000
Pitch System Minor	37.6%	15	3,000
Gearbox Major	0.9%	54	70,000
Drivetrain Major	9.7%	69	45,000
Generator Major	0.5%	149	25,000
Generator Minor	10.1%	14	10,000
Control System Major	0.2%	54	4,000
Power Converter Major	0.4%	14	15,000
Power Converter Minor	30.0%	70	7,000
Electrical System Minor	3.7%	59	3,500
Subsea Umbilical Major	0.1%	14	100,000
Vessel specification			
Vessel type	Speed (knots) & fuel consumption (l/hr)	Daily cost & mobilization cost	Mobilization time (hr)
Multipurpose dynamic positioning (DP)	12 & 300	20,000 €/day & 50,0000 €	48
Other			
Base O&M cost €/yr	Other O&M cost €/yr	Number of technicians	A technician cost €/yr
250,000	300,000	8	50,000

¹ Mean time to repair of all components except ‘subsea umbilical’ includes the offshore operation time of 9 hours for the turbine retrieval and 9 hours for turbine reinstallation.

In D8.4, the time-based availability, €/kW OPEX and €/kW installation costs of a first commercial 50 MW tidal project were compared to the minimum and maximum ranges in the literature [8], see Table 4.2.

Table 4.2 Comparison of availability, OPEX and Installation costs of commercial tidal project with the literature range [D8.4].

Parameter	Literature minimum range*	Base-CS from D8.4: 50 MW commercial scale tidal project in Morlais and Wicklow-head	Literature maximum range*
OPEX (€/kW)	80	323	360
Installation (€/kW)	470	555	800
Time-based availability	92%	96%	98%

* Values are reported to two significant figures from D8.4.

This report uses the tidal 50 MW commercial scale projects in Table 4.2 as the ‘base case studies’ (Base-CS) in Wicklow Head and Morlais. It focuses on the OPEX and availability of the commercial tidal array. It will conduct sensitivity analyses of some of the model inputs or considerations, and investigate their impacts on the relevant metrics, namely availability and OPEX⁴.

Based on the ranges of availability and OPEX in Table 4.2, an initial optimization target is to achieve a 98% availability (or maximum achievable availability) and €80/kW OPEX (or minimum feasible costs) for commercial 50 MW tidal projects in Morlais and in Wicklow Head.

Following the descriptions of weather restrictions in Section 4.2, key areas for reducing OPEX and improving availability of optimal tidal energy projects in Morlais and Wicklow Head will be discussed in Sections 4.2 to 4.6 through the following scenarios:

- Sensitivity of the turbine failure rate reduction on the availability and OPEX.
- Adapting three different preventive maintenance scenarios which reduce the overall failure of a turbine by 20%, 40% and 60%.
- Further O&M reductions by considering one purchased vessel.
- Sensitivity analysis of changing the offshore operation time on the farm availability.

4.2 Weather restrictions

In the O&M activities, vessel types have significant roles in the costs and availability outputs of the tidal farm. Based on consultation with the industry, a multipurpose DP vessel equipped with a crane was considered for the O&M activities for the Sabella tidal device. The DP vessel has high accessibility as it can operate in Hs of ≥ 2 m and at wind speeds up to 20 m/s which results in an availability of about 96% in both locations. Therefore, for the tidal case study in

⁴ The tool can only model the turbine and substructure/foundation installation activities. Total installation cost in D8.4 is estimated as a percentage of the turbine and substructure installation cost using the literature data. For this report, the study will not perform sensitivity and scenario analysis of total installation cost.

the report, the vessels' weather window limit is optimal for the two sites. However, it is likely that the weather limit would restrict offshore maintenance operations for example if the device is required to be towed back to the shore, as may be the case for floating tidal turbines. This section will provide more information about the impacts of weather condition limits on the project's OPEX and availability.

A summary of the weather window waiting time for the two sites, at different wave height is presented in Figure 4.1. The mean waiting time to have acceptable weather for at least 10 hours varies substantially with the H_s limits. Ten hours is chosen as it is the time required for the vessel transit (to and from ports) plus time to retrieve (when collecting the turbine) or to reinstall (when returning the turbine to operation after repair).

The results in Figure 4.1 show that, as the weather restrictions increase, there will be longer weather window waiting time for vessel operations in the Morlais site compared to the Wicklow Head site. For example, decreasing the vessel wave height limit to 1.5m H_s , could increase the mean weather window waiting time to 277 hours (i.e., 3.2% less availability) in Morlais while it is 77 hours (i.e., 0.9% less availability) in Wicklow Head. In summertime (and wintertime), this could result in 0.9% (and 5.3%) average less availability of the Morlais site compared to 0.2% (and 1.5%) in the Wicklow Head site.

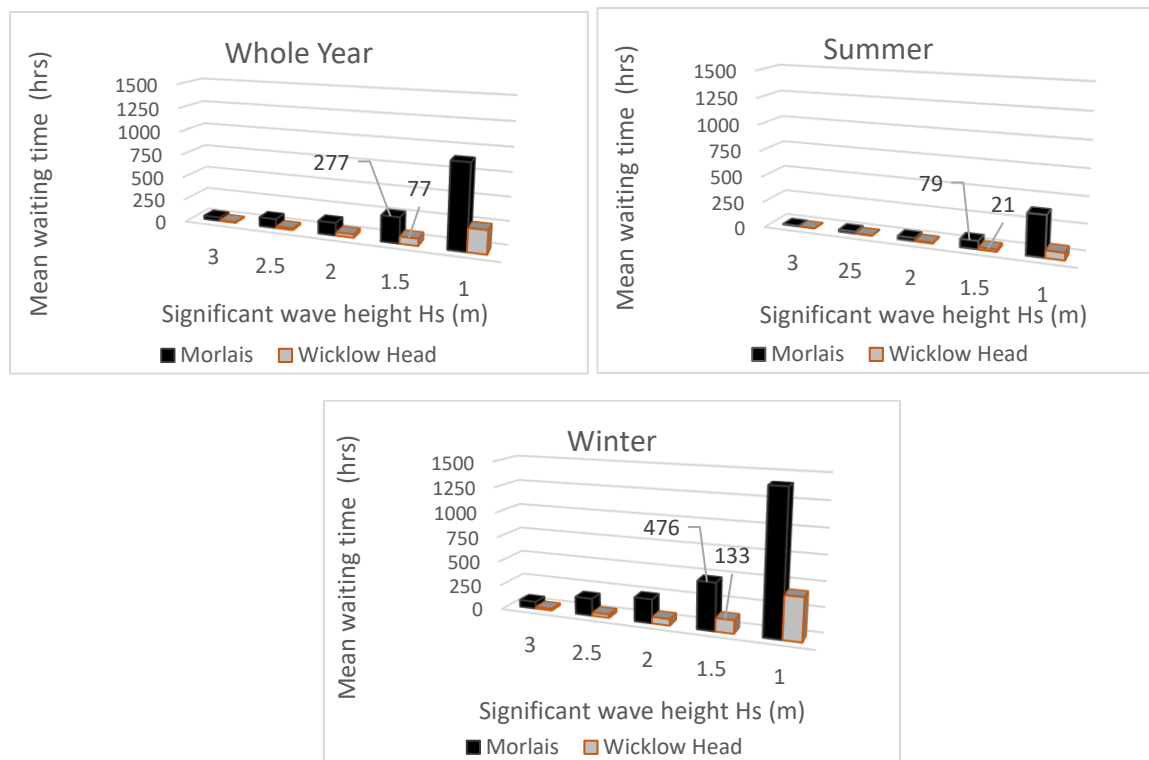


Figure 4.1 Mean weather window waiting time to have minimum 10 hours good weather for the offshore O&M activities in the Morlais and Wicklow Head sites.

The effect of the weather window waiting time on the project downtime is case-study-dependent, and is a result of the failure rate, port distance, type of vessel and location. Specifically for the analysis of the two projects in Wicklow Head and Morlais, these variables are the same with respect to the type of vessel used for the O&M activities and for component

failure rates, but the weather conditions of the two locations and the port distances are different.

The impact of port distance, in particular for high weather restrictions, will not be negligible as it extends the length of time required by the weather window. For the Morlias site, the distance of Holyhead port is 8 km which is around 33% less than the 12 km distance from Dublin Port to the Wicklow Head site. This shorter port distance for the tidal project in Morlais reduces, but does not remove, the impact of the harsher environment on availability and OPEX compared to Wicklow head as can be seen in the sensitivity results in Figure 4.2.

The sensitivity results show that there will not be a significant difference between the availability and OPEX of the two tidal projects in Wicklow Head and Morlais for the wave height limits $\geq 2\text{m}$. However, for the wave height limits of 1m and 1.5m, the availability of tidal project in Morlais will be lower by around 4% and 2%, respectively, compared to the project in Wicklow Head. At these wave height limits, the availability of the tidal farm in Morlais will reduce to ~88% (for 1m Hs) and 93% (for 1.5m Hs) which are significantly lower than the availability of ~96% for the Base-CS. For the project in Wicklow Head, availability will be 91% and 95% at Hs 1m and 1.5m, respectively.

Compared to the Base-CS, there will be an increase in OPEX (€/kW) of 8% and 6% in Morlais and 7% and 5% in Wicklow Head when the wave height limits reduce to 1m and 1.5m.

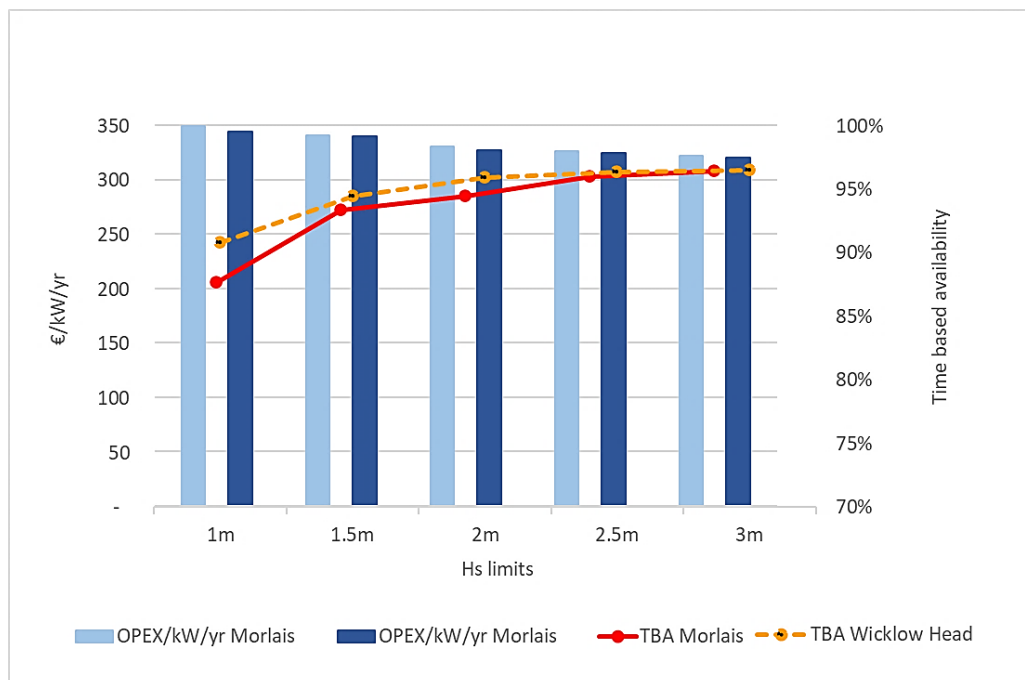


Figure 4.2 Sensitivity analysis- change of wave height limits on availability and OPEX.

4.3 Failure rates reduction

A tidal turbine consists of different components, and the operation of each of these components is necessary for the whole tidal system. For the tidal case study, an overview of the components' failure modes (e.g. minor or major) in Table 4.1 shows that minor failures

account for around 83% of the total failure of a turbine; the pitch system, power converter, generator and drivetrain form the majority of this. The repair costs and loss of revenue during the repair time has a huge impact on the project from a business point of view. In a sensitivity analysis, the effect of failure reduction at 10% intervals until achieving 98% availability on annual O&M costs and availability is investigated in Figure 4.3.

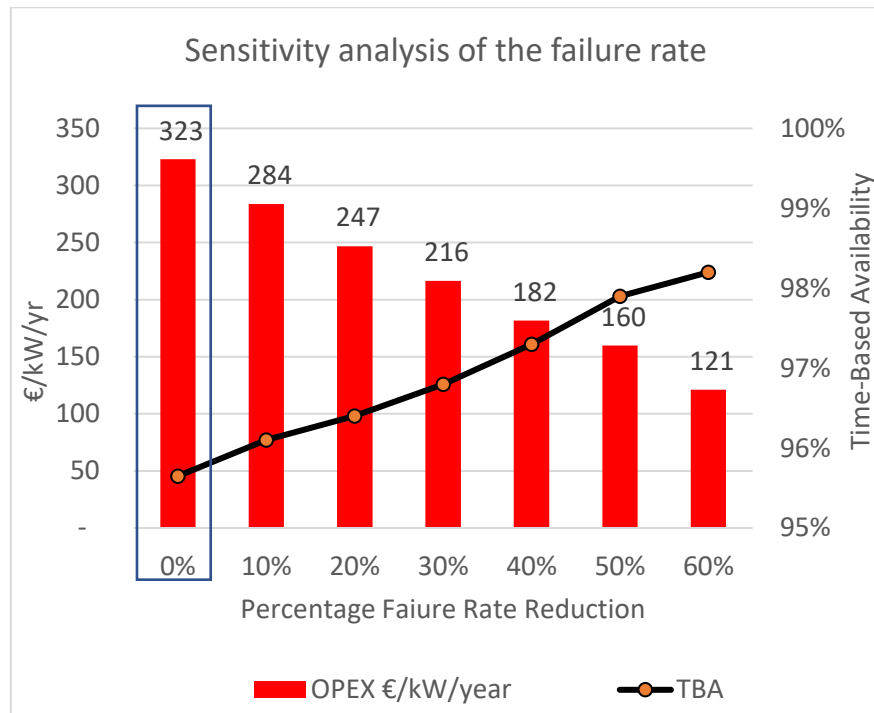


Figure 4.3 Sensitivity analysis- decreased overall failure rates on availability and OPEX.

The failure rate sensitivity analysis in Figure 4.3 indicates that every 10% reduction in the device overall failure rate can increase, on average, the availability by 0.4% and reduce OPEX by 15%. A 60% reduction of the overall failure rate will result in achieving 98% availability and 63% reduction in the OPEX compared to the Base-CS.

Technology innovations, improving reliability, built-in redundancy, and adapting appropriate maintenance strategies are the main drivers in the reduction of failure rates and unexpected failures (corrective maintenance). However, all these drivers incur additional costs either in CAPEX or OPEX and sometimes in both. From an O&M perspective, a preventive maintenance (PM) strategy is necessary to achieve optimal operation of a turbine including the length of its useful life. But PM tasks are associated with costs and downtime. The next section will discuss the PM scenarios.

4.4 Preventive maintenance

The time between PM tasks and PM types (e.g., scheduled maintenance, condition-based maintenance) will be usually determined from original equipment manufacturer (OEM) schedules, technical expert opinions and legal rules [9], for example, rules required by insurance companies. In the study it is assumed that a regular scheduled PM task will be carried out every two years (i.e. 50 turbines each year) and the same DP multipurpose vessel assigned to the corrective maintenance will do the PM task.

As mentioned earlier, it is expected that PM will reduce the failure rate of components. The failure rate and failure mode can determine an optimized PM interval, see for example [10]. A cost-effective PM strategy could be characterized by switching between a perfect PM, i.e. components are as good as new, or imperfect PM, i.e. components are better but not as good as new [11]. Although the tool does not have the capability to incorporate the improved lifetime of components due to PM, some of these effects can be studied through scenario analyses as explored in this section.

Depending on the assumed overall failure rate reduction per turbine due to PM, three PM scenarios are created: low failure rate reduction (PM1), medium failure rate reduction (PM2) and high failure rate reduction (PM3) as detailed in Table 4.3. In the table the optimal total number of technicians and vessels are determined through scenario creations. The number of technicians and vessels were increased until the availability of 98% (or maximum availability) was achieved for each PM1, PM2 and PM3. A higher availability, but lower total O&M costs were the deterministic criteria for selecting the PM scenarios in the table. For example, if the PM3 scenario in the table could achieve around 98% availability either by increasing the number of technicians to 20 and number of vessels to 10 or by increasing the number of technicians to 30 and number of vessels to 8. The first one was selected as the PM3 scenarios in the table because it had a lower O&M cost than the second. In the same manner, the optimal number of technicians and vessels for each PM scenario is determined as shown in Table 4.3.

Table 4.3 Preventive maintenance scenarios details.

Scenario	PM hour ¹	Cost/PM/Turbine ²	Overall turbine's failure rate reduction	No. of technicians per PM	Total no. of technicians	Total no. of vessels
PM1	50	10,000	20%	4	25	12
PM2	80	20,000	40%	5	20	12
PM3	120	30,000	60%	6	20	10

¹Accounts only for the PM operation hours onshore

²Accounts only for the consumable/spare part costs of the PM task.

The effect of adapting the three PM scenarios on the availability and OPEX (per kW and per MWh) are shown in Figure 4.4 and Figure 4.5 . As can be seen in the figures, the projects can benefit by achieving higher availability meaning higher energy revenues for all three PM scenarios. However, the change of O&M costs varies considerably between the PM scenarios. There is not a notable change in the O&M cost of PM1 compared to Base-CS because the O&M savings due to the reduced failure rates and increased availability are not offset with the PM costs.

Figure 4.4 and Figure 4.5 suggest that a thorough PM plan such as PM3 which is more expensive (longer onshore operation durations, higher number of technicians and spare-part costs) could increase the average availability of the farm by around 2% and reduce the OPEX cost by 35-38% for both locations. These scenarios are very optimistic as the assumption is that a vessel is always available and after 48 hours mobilization time, this vessel can carry out

the required maintenance task. Despite this optimistic assumption, the resulting OPEX is quite high compared to the low OPEX range (€80/kW) of a tidal commercial scale project in Table 4.2, and much higher than the OPEX of ~€60/kW for offshore wind in 2020 [12] and ~€17/MWh (assuming 40% capacity factor for offshore wind).

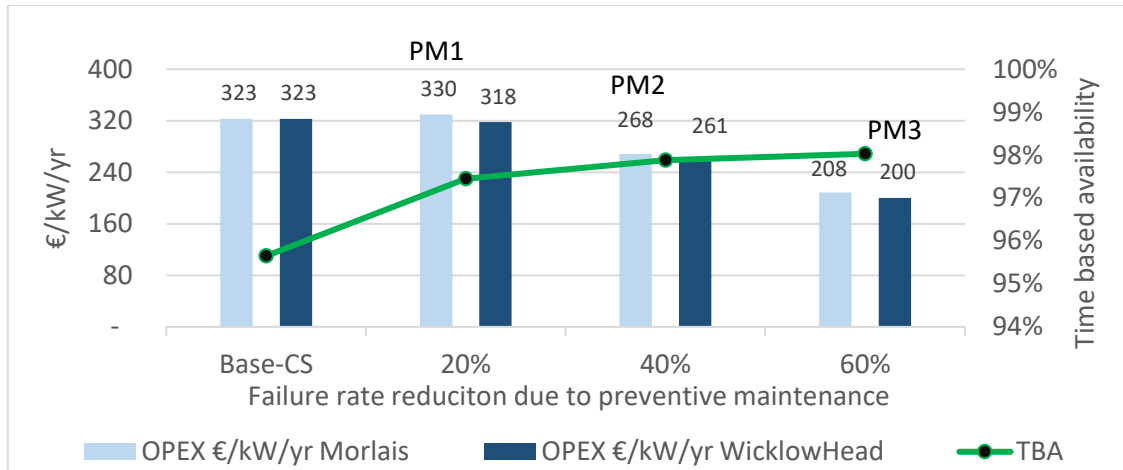


Figure 4.4 Preventive maintenance scenarios and impacts on availability and annual OPEX/kW compared to Base-SC.

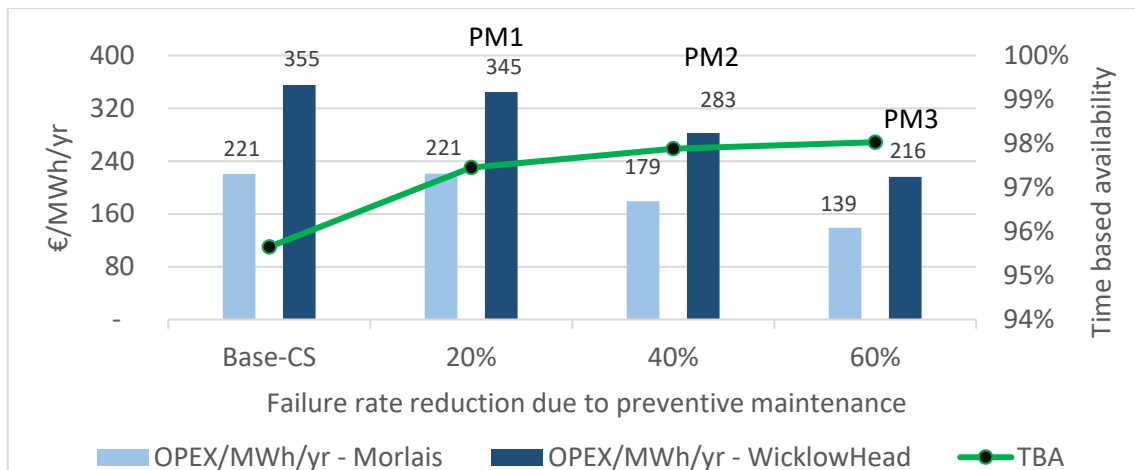


Figure 4.5 Preventive maintenance scenarios and impacts on availability and annual OPEX/MWh compared to Base-SC.

Looking at the OPEX breakdown in Figure 4.6 shows that the vessel rental costs and spare-part costs are the big contributors to OPEX.

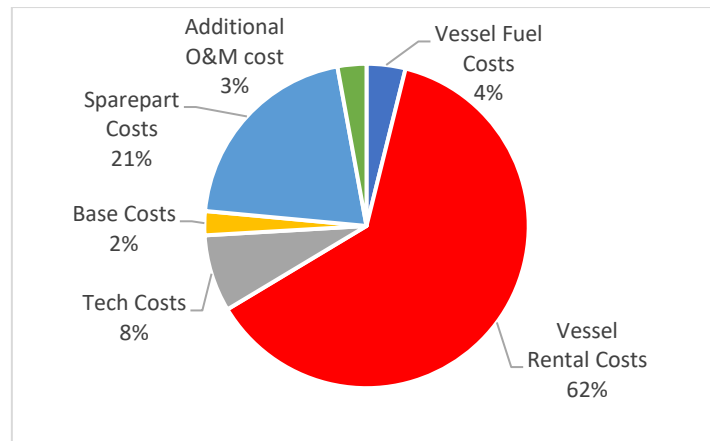


Figure 4.6 Breakdown of the annual OPEX (with PM3 strategy in Morlais as an example).

For the spare part cost, inventory management of spare parts and development of supply chain strategies are essential aspects of maintenance to ensure their cost-effectiveness and timely availability, for example see the recommendations in [13] for offshore wind energy.

For the vessel costs, it is possible to achieve a reduction by, for example:

- Hiring a cheaper vessel. For the Sabella device with almost all maintenance activities to be carried out onshore, it seems that the DP multipurpose vessel is a suitable vessel. The model has considered a very moderate assumed daily cost (€20,000) and mobilization cost (€50,000) for this vessel.
- Hiring a vessel that can carry two or more devices at the same time. This requires a bigger vessel which may be more expensive, with a longer mobilization time, and higher cost. Furthermore, to optimize the vessel's ability to carry multiple devices, it should be hired when 2 or 3 failures have occurred. This may result in a delay to the first few repairs and therefore result in a loss of revenue. The advantage to such a large vessel would be clear when several failures are likely to happen in quick succession, or when several tasks such as scheduled maintenance are due in a short period of time.
- Purchasing a vessel.

A DP vessel could cost hundreds of million Euro. It will increase the project CAPEX and its cost needs to be investigated by taking into account the service lifetime of the vessel, the vessel's end-of-life values as well as the possibility of reducing the vessel cost by providing services to the neighbouring offshore industry, e.g., wind and wave energy farms. These aspects need to be studied in the future to understand how the vessel purchased scenario would affect the CAPEX.

Nevertheless, for a commercial scale project and a 25-year lifetime, it is reasonable to consider that at least one vessel will be purchased for maintaining the farm. In the case study, 87% of the failure modes are minor meaning that the failures happen more frequently although they can be repaired in a relatively short time and with low spare part costs. But since the device will be retrieved, more frequent use of the vessel for minor repairs would be

very costly resulting in losing revenues due to the downtime. Vessel purchased scenarios will be investigated Section 4.5.

4.5 Vessel purchased scenario

In the vessel purchased scenarios, it is assumed that the vessel has a fixed annual operation and maintenance cost of €50,000 with an average fuel consumption of 400 litres/hr; it is capable of 24-hour operations and can carry 2 tidal turbines if required. The average results of 10 simulations for each scenario are presented in Figure 4.7 and Figure 4.8.

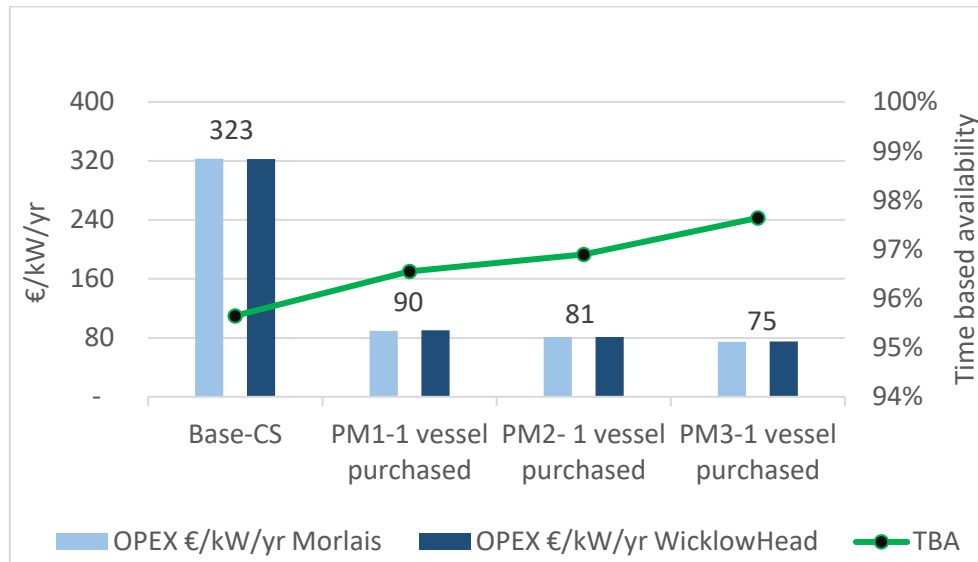


Figure 4.7 One vessel purchased with PM scenarios, OPEX/kW.

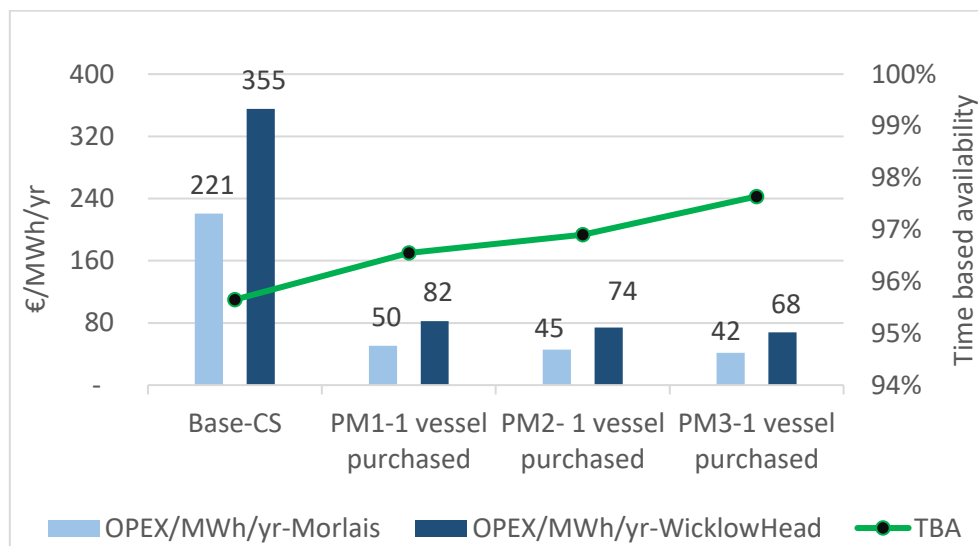


Figure 4.8 One vessel purchased with PM scenarios, OPEX/MWh.

The scenario results in Figure 4.7 and Figure 4.8 show that by adapting preventive maintenance strategies (in PM1-3) and purchasing one vessel, a high reduction of OPEX by around 77-81% compared to Base-CS could be expected. The OPEX of €75/kW for PM3 scenario (the best case), is below the OPEX value of a generic tidal project in the literature,

although it is still high compared to the €60/kW OPEX of offshore wind energy in 2020 as explained earlier.

In terms of availability, there is an improvement in all the preventive maintenance scenarios. The best scenario, PM3, shows an availability of around 98%, i.e., 2% improvement compared to the Base-CS. With a vessel purchased, the availability improvement for PM2 and PM3 compared to the Base-CS is around 0.3% and 0.7% respectively. A sensitivity analysis of availability to the offshore operation hours is discussed in the next section.

4.6 Offshore operation durations

The PM scenario analysed in the previous section showed that a high availability of nearly 98% could be achieved in the best case scenario (PM3). For the tidal energy case studies, the offshore operation time of 9 hours for retrieving the device and another 9 hours for reinstalling it after the onshore repair, are initially obtained from industry consultation. But there is an inherent uncertainty in the offshore duration time. Taking the results of the third scenario, PM3, in Figure 4.7, a sensitivity analysis of the offshore operation hours is carried out and results are presented in Figure 4.9. This sensitivity analysis indicates that for every 10% decrease (or increase) in offshore operation hours required for retrieving and reinstalling the turbine, there could be on average 0.5% increase of availability (up to -20% change in availability hours). But for every 10% increase, there would be a more pronounced 1.6% average decrease in the availability factor as the operations hours increase up to 60%.

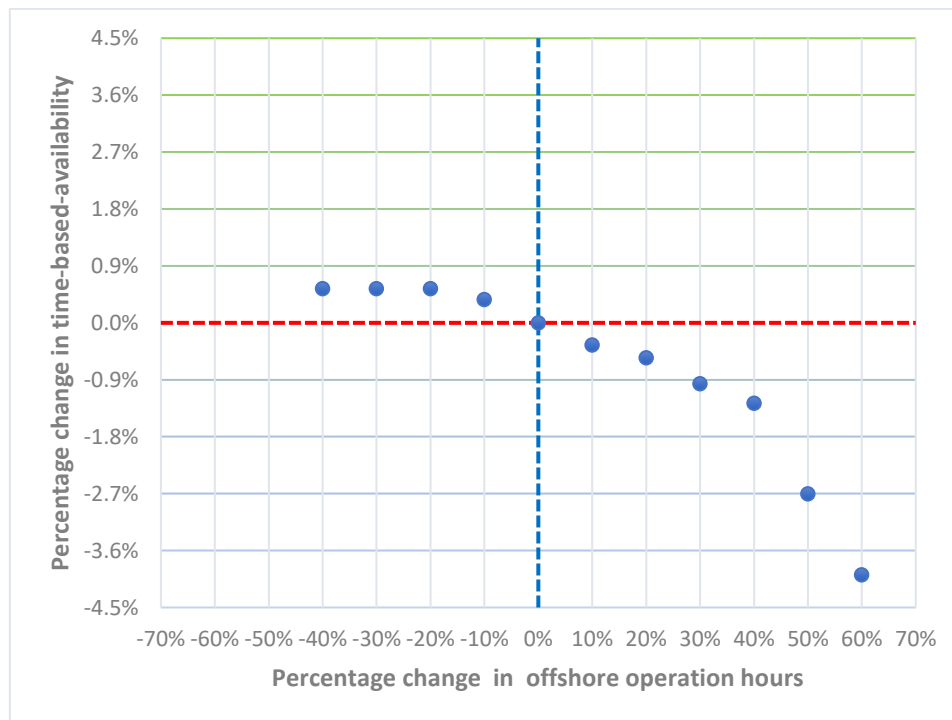


Figure 4.9 Sensitivity analysis of offshore operaiton hours- PM3 scearrio with a vessel purchased.

The experience obtained during the operation (learning-by-doing) and through the knowledge shared among stakeholders involved (learning-by-interacting) [14] could reduce the offshore operation time required for retrieving and reinstalling tidal turbines. However, as can be seen in Figure 4.9, the improvement of availability will reach to its limit at about a

20% reduction in the offshore operation time indicating that the minimum weather window waiting time has been effectively achieved for the given choice of vessel and port distance for these case studies. This minimum is the mean waiting time for any (short) period of required weather conditions to come about.

The availability is very sensitive to increased offshore operation time. Clearly there is a direct effect due to the increased time spent at sea, but also an indirect effect of having an increased waiting time for the longer weather window required. For example, if the retrieval/reinstallation time increases by 60% (i.e. 14.4 hours instead of 9 hours), the availability can decrease by around 4% (i.e., an average availability of 94% for the farm) which would considerably reduce the project's revenue.

4.7 Optimised scenario - tidal

Based on the scenario results in Sections 4.4 and 4.5, 30 simulations are run for an optimised scenario of a 50 MW commercial tidal project in Wicklow and in Morlais with:

- A thorough (every two-year) preventive maintenance (PM3) with €30,000 spare-part cost per turbine and an assumed 60% reduction of a turbine's failure rate.
- One purchased vessel for the O&M activities that is capable of 24-hour operations which can carry up to 2 turbines if required. An annual maintenance cost of €50,000 and a 33% increase in the fuel consumption is considered for this vessel.
- An average of 18 hours offshore operation for retrieving and/or reinstalling the device after each maintenance activity.

The average results are presented in Table 4.4 and are further discussed in this section.

Table 4.4 Summary of O&M simulation results.

50 MW tidal case-study	OPEX cost (€/kW/yr)	OPEX cost (€/MWh)	Annual energy production (MWh)	Time based availability
Base-CS Morlais	323	221	73,203	96%
Optimized- CS Morlais	75	42	89,724	98%
Base-CS Wicklow Head	323	355	45,406	96%
Optimized-CS Wicklow Head	75	68	55,291	98%

In terms of the annual energy production (AEP), and thus the revenue, the optimized case studies can achieve around a 23% increase of AEP in both locations compared to 'Base-CS'. However, in the optimized tidal project, Morlais has the potential to produce approximately twice as much energy than Wicklow Head using the same tidal project. The results support the economic attractiveness of a tidal project in Wales compared to the same project in Ireland.

In terms of annual OPEX, for the optimal case-study, with a purchased vessel and every 2-year preventive maintenance task which reduces the turbine's failure by 60%, there would be a considerable reduction of around 77% in €/kW and 81% in €/MWh OPEX in both locations. This is due to the reduced vessel costs as shown in Figure 4.10. In the optimal scenario, the vessel cost (fixed plus fuel costs) accounts for around 8% of the total OPEX in both locations. In the case-study, the fixed annual cost of a purchased vessel (excluding fuel) is around 1€/kW (0.5 €/MWh in Morlais- 0.9 €/MWh in Wicklow Head), and with fuel, it is 6€/kW (3.3 €/MWh in Morlais- 5.4 €/MWh in Wicklow Head). In a pessimistic assumption, with an annual vessel cost as high as 500,000 €/yr (i.e. 10 times higher than the model input), the annual OPEX in Table 4.4 goes up to €85/kW (48 €/MWh in Morlais- 77€/MWh/yr).

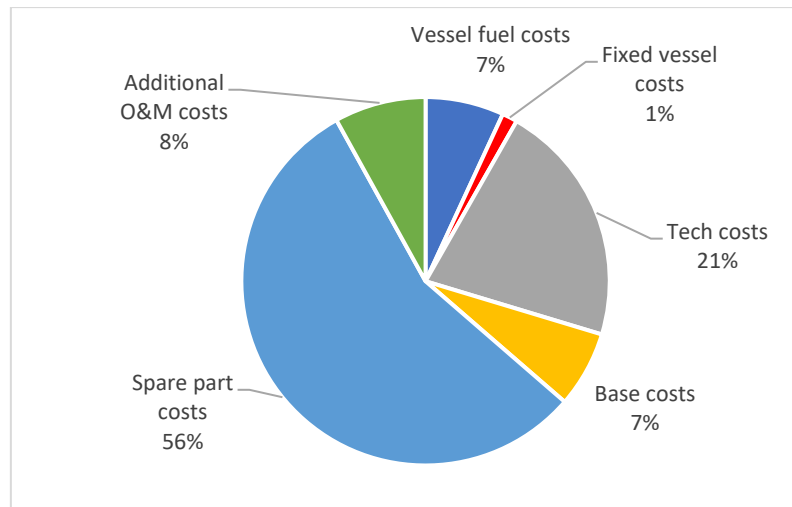


Figure 4.10 Breakdown of OPEX/kW for optimal case studies in Morlais and Wicklow Head.

In the Optimized-CS, the dominant contributor to OPEX in Figure 4.10, is spare-part costs, which accounts for 24.0 €/MWh in Morlais and 38.0 €/MWh in Wicklow Head. This could be an area for decreasing the O&M costs. In the case study it is assumed that the spare parts are available when required, and over the 25-year-project lifetime, their prices are constant. Although, this assumption is a common practice in the O&M modelling, considering a dynamic spare part analysis which is linked to a supply-chain model would improve the results reliability. This needs to be investigated in a future study.

In terms of availability, the tidal projects in both locations show a high availability of around 98% for the optimal case-studies. As mentioned earlier, the failure rate, port distance, vessel types and the locations' weather conditions all affect the downtime and therefore availability. For the tidal case study, a DP vessel is used which has a high accessibility (e.g., Hs ≥2m). Also the distance of Holyhead port at 8km in the Morlias site and Dublin port at 12 km in the Wicklow Head site are relatively short, for example compared to the wave case study in this report. The 30% shorter port distance of the Morlias site compared to the Wicklow Head site can offset the harsher environment of the Morlais site. Therefore, the results do not show a noticeable difference between the availability of the two projects and thus, the weather window effect is not substantial for the tidal case studies in this report.

4.8 Concluding remarks- tidal case study

For tidal projects where almost all the maintenance tasks will be carried out onshore, reducing the failure rate (e.g. by improving the reliability and adapting an appropriate preventive maintenance strategy) can substantially influence the project O&M cost.

This study used the developed open-access O&M tool in the SELKIE project and examined some of these opportunities through the following key sensitivity and scenarios analyses:

- Including a range of Hs limits between 1m to 3m for the vessel operations.
- Reducing components' failure rates at 10% intervals.
- Adapting three preventive maintenance strategies (PM1, PM2 and PM3) with different costs and assumed failure rate reductions.
- Considering one purchased vessel with a fixed annual cost.
- Sensitivity analysis of offshore operation duration.

In an optimal 50 MW tidal project scenario, purchasing a vessel which can carry up to 2 turbines as well as carrying out preventive maintenance (PM3) every 2 years, could lessen the OPEX cost by 77-81%. This will reduce the OPEX costs from:

- €323/kW (for Base-CS) to 75€/kW (in both locations),
- €221/MWh for Base-CS in Morlais to €42/MWh and €355/MWh in Base-CS in Wicklow Head to €68/MWh.

The reduced OPEX of the optimal tidal project in the study is lower than the minimum range of OPEX of around €80/kW for a generic tidal project in the literature [8]. But it is still high compared to the generic offshore wind energy, which is less than €66/kW in the BVG-Catapult database⁵ in 2019 and €60/kW in 2021 (€17/MWh assuming 40% capacity factor) in the Offshore Wind Market Report [12]. This emphasizes the need for further improvements, for example, reduction of the failure rates, optimization of the preventive maintenance intervals, building redundancy and improving the capacity factor of the tidal turbine.

In the optimal tidal case study in the report, spare part costs can account for around 56% of the annual OPEX. A future study could seek for opportunities to reduce the O&M cost and its uncertainty by including, for example, an optimized spare part management process and the associated supply chain.

5 Conclusion

This report is the last deliverable of WP8 from the SELKIE project and links to the previous deliverables D8.2, D8.3 and D8.4 in WP8. In D8.2, an open-access O&M and logistics tool for tidal and wave energy is developed. In D8.3 and D8.4, the developed tool is used to examine the OPEX, installation costs and availability of pilot projects as well as upscaled projects of wave and tidal case studies in Wales and Ireland. The wave case study is based on 1.4 MW

⁵ <https://guidetoanoffshorewindfarm.com/wind-farm-costs>

oscillating water column WEC device similar to OE35, and the 50 MW tidal case study is based on a 500 kW tidal stream turbine similar to the Sabella D15.

This report focuses on the 72 MW commercial wave case study in D8.3 and the 50 MW tidal case study in D8.4. It demonstrates how the tool can be used to seek potential solutions to achieve the highest availability and lowest OPEX for optimal commercial wave and tidal energy projects in Ireland and Wales. The indicative case studies in the report can help to provide an understanding of the tool capability in developing scenarios. It provides insights on the key uncertain parameters that affect the availability factors and the O&M costs. Potential users of the tool can develop their decision making capabilities examining O&M strategies for tidal stream and wave energy projects based on their own data.

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