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Failure Consequence Cost Analysis of Wave Energy Converters—Component Failures, Site Impacts, and Maintenance Interval Scenarios

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Abstract: In the early stages of developing wave energy converter (WEC) projects, a quantitative assessment of component failure consequence costs is essential. The WEC types, deployment site features, and accessibility should all be carefully considered. This study introduces an operation and maintenance failure consequence cost (O&M-FC) model, distinct from conventional O&M models. The model is illustrated with case studies at three energetic Atlantic sites, each of which considers two types of generic floating WECs: a 300 kW point absorber (PA) with a hydraulic power-take-off (PTO) and a 1000 kW oscillating water column (OWC) with an air-wells-turbine PTO. This study compares 39 failure modes for PA and 27 for OWC in terms of direct repair costs and indirect lost production costs, examining the impact of location accessibility, capacity factors, and the mean annual energy production. The discussion revolves around the sensitive parameters. Recommendations for failure mitigations are presented, and the impact of planned maintenance (PM) during the operational phase is examined for 20 MW PA and OWC WEC projects. For a given WEC type, the method thoroughly evaluates how the location affects performance metrics. It offers a decision-making tool for determining optimal PM intervals to meet targets such as O&M costs, operating profit, or availability.

Keywords: wave energy converter; failure mode; component criticality; O&M and FMECA metrics; maintenance mitigation; Atlantic

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1. Introduction

The potential wave energy reserve worldwide is estimated by Ocean Energy Europe to be 29,500 TWh/year [1]. Some of this energy may be captured via wave energy converter (WEC) technology [2], and the energy-decarbonisation process could benefit substantially from these potential resources. This resource is particularly important in Europe to achieve its goal of 1 GW of ocean (wave and tidal) capacity by 2030 and 40 GW by 2050 [3]. While the target for ocean energy is ambitious, its implementation is still in the early stages of development. Cumulative wave energy installation in 2021 reached 12.7 MW, but only 1.4 MW is currently in the water [4]. However, the sector is swiftly moving forward, and tests are being undertaken on scaled-down versions of commercial equipment [5].

According to the Portal and Repository for Information on Marine Renewable Energy (PRIMRE) [6], there are currently 90 active wave energy converter developers worldwide for various WEC technology types. Of these, 33 technology developers, including Carnegie Clean Energy, CorPower Ocean, Seabased AB, Eni, and others, have achieved a technological readiness level (TRL) greater than 6 (demonstration and pre-commercial stages) for their

WEC technologies tests. There are 26 wave energy test sites globally, with 16 of them having grid connectivity [6]. Figure 1 demonstrates these statistics. Point absorbers (PAs), oscillating water columns (OWCs), and oscillating water surge converters (OWSCs) are the most promising technologies for commercialisation, according to the International Renewable Energy Agency (IRENA) 2020 Outlook [7]. Currently, more than 25 wave-demonstration projects are in progress, and some of the devices are expected to be deployed in farm layouts; further information is available in [8].

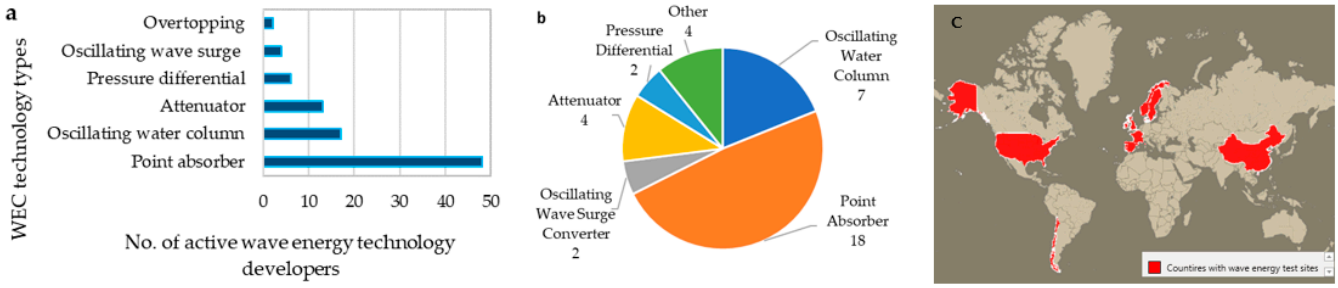

Figure 1. Active WEC technology developers. (**a**) TRL > 6 (**b**) Countries with WEC test sites. (**c**) Own elaboration using data source [6].

One of the sector's shortcomings, however, is the lack of design convergence [8], and a significant barrier to the advancement of the technology is the high levelised cost of energy (LCOE) of WECs in comparison to more well-established renewable energy sources, such as offshore wind. The Ocean Energy Systems (OES) development pathway for the first 2 MW to 75 MW of commercial WECs forecasts an LCOE ranging from 108 EUR/MWh to 424 EUR/MWh (the exchange rate of 0.9013 USD to Euro in 2015) [9]. The European Strategic Energy Technology Plan (SET Plan) forecasts an LCOE of EUR 150/MWh for 100 MW of WECs by 2030, which could be achieved through technology push, market pull, and both [10].

Because of the diversity of the WEC technologies and deployment sites, as well as insufficient experience with WEC operations at sea, obtaining the LCOE metric for WECs comes with substantial assumptions for capital expenditure (CAPEX), operation expenditures (OPEX), and annual energy production (AEP). This is why the values of these metrics vary greatly in the literature, depending on case studies and methods employed; see, for instance, [11–15]. A review of CAPEX in [11] reveals a large variation for different WEC-rated powers, ranging from 610 EUR/kW to 5687 EUR/kW. In [13], an estimated range of 600–1800 EUR/MWh of LCOE is provided for the present and near-future economic viability of the 500 MW Aqua floating WEC farm case studies in the Atlantic arc. The authors of [14] use a geographical information system tool and estimate the LCOE ranges of $\leq$110 EUR/MWh to >500 EUR/MWh for four types of WECs at a 500–2200 kW-rated capacity in the UK and Ireland. In [15], scenario analyses are employed to explore how reducing CAPEX, OPEX, altering array configurations, and improving AEP can lower the LCOE of various types of WEC technologies to less than USD 300/kWh (in 2020) in the U.S Pacific area, making them competitive with the LCOE of offshore wind energy.

Further tools and methods are required to facilitate WEC metrics calculations. In addition to the PRIMER knowledge hub [16], which functions as a central point of 20 resources and tools accessible to the marine energy sector, there are other open-access tools for modelling and assessing WECs. Among these are the LCOE calculator based on the power production of a WEC at a particular location by Aalborg University [17]; the WEC-Sim (WEC Simulator) to model the WEC devices, which was developed by the collaboration between the U.S Department of Energy's Wind and Water Power Technologies Offices, the National Renewable Energy Laboratory (NREL), and the Sandia National Laboratories (SNL) [18]; available decision-making tools such as DTOcean, a modular set of wave and tidal design tools for modelling the entire ocean energy farm throughout its lifecycle [19];

and the SELKIE Operation and Maintenance (O&M) and Logistic Models [20], which model the installation, O&M, and maintenance strategies of ocean energy devices and farms.

In the context of WECs that must operate in harsh environments, reliability, which is frequently linked to failure [21], can have a significant impact on both OPEX over the system's lifetime and revenue production. Failure analysis is an integral part of project development, starting from the initial stages. It continues throughout the design, subsystem selection, and operational phases of a project's lifetime. To facilitate this process, failure modes, effects, and criticality analysis (FMECA) [22] are commonly used. Standards like MIL-STD-162A [23] and IEC 60812:2018 provide guidelines for implementing FMECA. Some studies have taken further steps to integrate the FMECA approach in an O&M model in offshore wind turbines [24–26]. In this approach, prioritising failure modes based on their potential impact on system availability and O&M costs can be identified, and by focusing on critical subsystems, O&M efforts can be directed towards monitoring and maintenance strategies that reduce overall costs while increasing energy production or revenue. None of these studies, however, have modelled the site's time-series metocean data or randomised the time to failure.

For the WECs, few studies have examined failure analysis from an O&M perspective. The authors of [27] used a reliability-based computational tool to optimise failure rates, the maintenance schedule, component redundancy, and vessel selection. They included a case analysis of five 750 kW Pelamis P1 WECs in the North Cornwall demonstration zone of a wave hub over a ten-year lifespan, and the subsystems were divided into four categories: mooring, structure, power-take-off (PTO), and power transmission. The importance of site characteristics in the WECs O&M is highlighted in [28]. In their work, the accessibility of two offshore wave energy sites in the UK for marine operations and power generation was simulated using a Monte Carlo based O&M tool, location time-series meteorological data, and WEC component failure data. The wave farm consisted of ten 750 kW Pelamis P2 WECs, and the sensitivity of failure rates showed how the sixteen component failure modes could impact availability, OPEX, and revenues in two sites.

Failure analysis is a key aspect to consider at various stages of WEC development to comprehend why components fail and how to lower the possibility of failure. Early failures can be significantly reduced by managing design and quality aspects during the manufacturing process. Appropriate inspection and maintenance strategies could help to control, prevent, or mitigate failures later in the service life [29].

In the failure analysis of WECs, careful consideration should be given to WEC types, deployment site characteristics, and location accessibility. This study integrates the FMECA approach with an O&M model using a new method in order to objectively estimate the component failure consequence cost effects where energy production, the data of failure modes, and 20-year time-series site metocean characteristics for a WEC type are taken into consideration. Case studies are based on a 300 kW generic point absorber (PA) WEC and a 1000 kW oscillating water column (OWC) WEC in three sites in the North East Atlantic. This study aims to demonstrate the model as a useful tool for identifying the critical failure modes of each WEC component or subsystem at a specific location. It also seeks to illustrate the implication of planned maintenance (PM) scenarios as options for mitigating failure and their effects on O&M costs, availability, revenue, and the number of corrective maintenance (CM) incidents using 20 MW WEC projects in the three sites. The authors of [28] discussed how a Weibull distribution—which takes ageing factors into account—could offer a more accurate failure analysis of WECs O&M than the exponential distribution they used. This study employs a Weibull distribution to integrate an O&M model with PM as a failure-mitigation option. It also models how PM can impact a component's health, such as making them as good as new after PM. The method, input data, and assumptions are explained in Section 2. The results are presented in Section 3. Section 4 contains remarks and suggestions for future studies, and Section 5 offers the study conclusions.

2. Method

The proposed method in this study uses metrics to quantitatively compare the direct and indirect failure consequence cost rankings of WEC components in different locations. It identifies the sensitive parameters influencing the outcome and provides high-level failure-mitigation options. In addition, it employs scenario analyses of planned maintenance as strategies for mitigating failures, reducing O&M costs, and meeting an availability target for presented WEC projects.

This study first develops an O&M-based failure consequence cost (O&M-FC) model. Two types of floating WECs are considered for deployment in the West of Ireland, Wales, and Norway at average water depth of 45–60 m (intermediate and deep offshore locations based on classification in [30]): a 300 kW PA [31] and a 1000 kW OWC [32]. The selection of these WECs from the literature was influenced by the data availability, specifically the power matrix and list of component failure modes and failure rates, as well as their higher obtained TRL (see Figure 1). CorPower Ocean and Ocean Power Technologies are two companies that have produced PA devices [33] that are at a high TRL. The OceanEnergy OE35 (1 MW OWC), which is currently in the demonstration stage, will be on display for two winter seasons starting in 2024 at the European Marine Energy Centre (EMEC) (https://www.emec.org.uk/oceanenergy-sign-up-to-emec-wave-energy-test-berth/ accessed on 15 May 2024). More on the WECs and three sites will be covered later.

In the next step, a conventional O&M model for two 20 MW WEC projects at the three sites is developed, which enables the investigation of PM scenarios as a common failure-mitigation approach during the operational phase. The 20 MW projects are selected to provide a realistic size for the O&M analysis and smooth results for a Monte Carlo simulation rather than executing economies of scale, which is outside the purview of this study. Inspired by [34], the cost-effectiveness of several PM scenarios is analysed. The optimal scenario with the highest O&M cost reduction and time-based availability will be suggested. A sensitivity analysis of the port distance for the optimal scenario is carried out, and the findings are reported. The model is written in MATLAB and interfaces with Microsoft Excel for input and output files. A summary of the study's stages is shown in Figure 2, and the important features of the model calculations and data are further described in this section.

The O&M-FC model, in Figure 2, requires inputs that are similar to those used in a conventional offshore O&M model; see, for example [28,35]. But, unlike the conventional O&M model, the approach does not prioritise O&M tasks and does not take into account the interplay between component failures. Typically, hundreds of Monte Carlo cycles are used to calculate the average downtime and costs associated with a specific failure mode. Downtime is the interval of time that a component is out of service between failure and restart [11]. In each simulation, the failure times are selected randomly from a historical weather dataset at least 20 years long. For the Monte Carlo choices in O&M-FC model, a uniform discrete distribution [36] is employed, where each hour of the metocean data has an equal probability of occurring. For each component failure mode, the direct and indirect (lost production) failure consequence costs are calculated by averaging the costs of all simulations. The component failure consequence cost criticality percentage is calculated as

$$crit_i = \frac{\lambda_i(ir_i + indir_i)}{\sum_{j=1}^{T}(ir_j + indir_j)} \times 100 \quad (1)$$

where $crit_i$ is the percentage criticality number of the component failure mode i, λ_i is the annual failure rate of i; dir_i is the direct failure mode consequence of i (costs of vessel, spare-part and technician); $indir_i$ is the indirect failure mode consequence of i (kWh lost in downtime $\times$ unit price of electricity); T is the total number of failure modes. In Equation (1), the failure consequence cost of every component failure mode is denoted by the nominator, $\lambda_i(ir_i + indir_i)$.

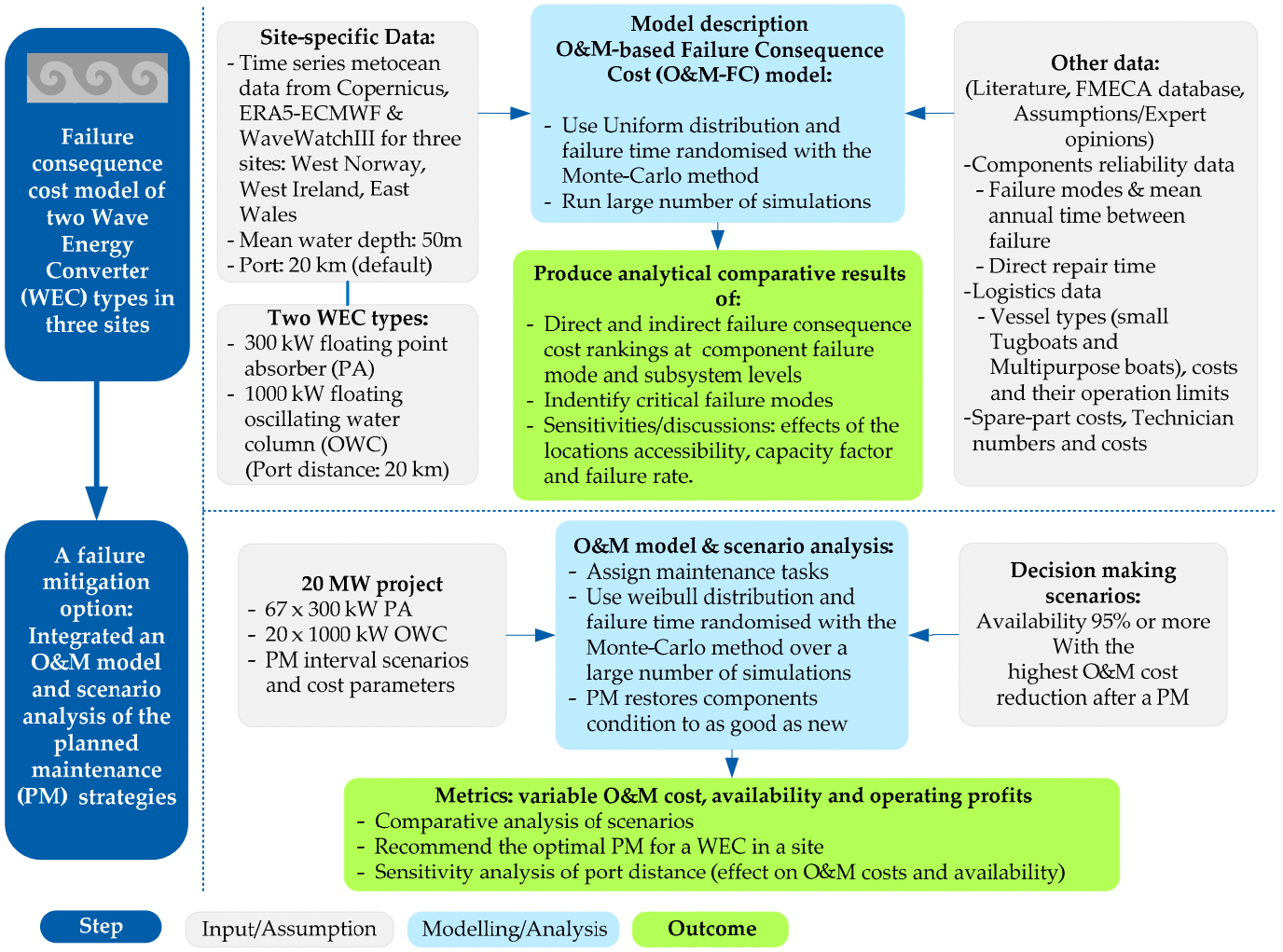

Figure 2. An overview of the study.

The *dir* in Equation (1) is given by

$$dir = V + F + T + S \tag{2}$$

$$Von = \left\lceil \frac{4Dp}{24Sp} + \frac{Rt}{24} \right\rceil \cdot Vr + M \text{ or } Voff = \left\lceil \frac{2Dp}{24Sp} + \frac{Rt}{24} \right\rceil \cdot Vr + M \tag{3}$$

$$Fon = C.Fc \cdot \frac{4Dp + Rt}{Sp} \text{ or } Foff = C.Fc \cdot \frac{2Dp}{Sp} \;\&\; T = Tc.Th \tag{4}$$

where V is vessel hire cost for an onshore repair (Von) or offshore repair ($Voff$); F is vessel fuel cost; T is technician cost; S is spare part cost; Dp is distance from WEC to port in km; Sp is speed of the vessel in km/h; Vr is vessel daily rate for hire in EUR; Rt is the direct mean time to repair (MTTR) in hours; M is the vessel mobilisation fee in EUR; symbol ⌈ ⌉ denotes a value rounded up to the next whole number; F is the fuel cost, for onshore (Fon) or for offshore ($Foff$); C is vessel fuel consumption in litres/hour; Fc is fuel cost in EUR/litre; Tc is cost of one technician per hour; Th is total number of technician hours to carry out repairs.

The *indir* in Equation (1) is determined using Equation (5), while the downtime is calculated based on Equation (6):

$$indir = L.E \tag{5}$$

$$Don = \frac{4Dp}{24Sp} + Rt + Mt + W \text{ or } Doff = \frac{2Dp}{24Sp} + Rt + Mt + W \tag{6}$$

where L is the MWh of lost production; E is the EUR/MWh of electricity price (EUR 200/MWh, as suggested by [28]). D is downtime in hours for either onshore repair (*Don*) or offshore repair (*Doff*); Mt is mobilisation time, i.e., time waiting for vessel to arrive to the port from its previous location; and W is waiting time for a period of $\frac{4Dp}{24Sp} + Rt$ (for onshore repair) or $\frac{2Dp}{24Sp} + Rt$ (for offshore repair), during which the weather is acceptable for the vessel to be used for the repair and the journey. In Equation (6), *Doff* and *Don* determine the true MTTR, taking journey times into consideration.

The logic and maintenance task sequences of the O&M model are comparable to those of the model explained in [28,34,37,38]. The O&M model employs a Weibull distribution, which takes component ageing into account [34,39]. Moreover, the model incorporates the influence of PM strategies on component health conditions. The following describes these two attributes.

The two parameters of the Weibull distribution, shape (β) and scale ($\mathcal{E}$), are derived using Equations (7) and (8) [34]:

$$MTBF = \mathcal{E}\Gamma\ (1\ +\ \frac{1}{\beta}) \tag{7}$$

$$CDF = 1 -\ e^{-(\frac{x}{\varepsilon})\beta} \tag{8}$$

where *MTBF* is mean time between failure, which is the inverse of a component's annual failure rate; Γ is the gamma function; *CDF* is the cumulative distribution function; and x is time.

The two equations above can be empirically solved by assuming a 10% risk of component failure by half of its MTBF, resulting in a shape factor of 2.780, which is consistent with other studies such as [40]. The scaling factor for each component is derived using

$$\beta = \frac{\ln(-\ln(1 - CDF))}{\ln(\frac{x}{\varepsilon})} \tag{9}$$

The specific feature of the O&M model used to assess the influence of PM strategies on component health conditions is based on the notion that PM, as an alternative to failure mitigation, can extend component life. The PM outcome for each component can be defined by assigning a number between 0 (no effect) and 1 (perfect effect, suggesting that the component is as good as new). This value will have an impact on the component's MTBF when the PM is completed. The PM duties can be scheduled throughout the summer to take advantage of the weather. For each scenario, the costs of PM tasks and PM time will be assessed, as will the influence of the PM strategy on the reduction in unexpected failures, which require corrective maintenance (CM), for each component.

2.1. Time Series Metocean Data

The three study sites in the Atlantic region are West Ireland (lat 52.7° N, long 9.7° W), West Wales (lat 51.5° N, long 5.1° W), and West Norway (lat 62.0° N, long 4.5° E). Time-series metocean data for the sites in Norway, including wind speed at 10 m above mean sea level, significant wave height (Hs), and wave period (Tp), were obtained from WaveWatch III [41,42] in the IMPACT project (https://www.impact-h2020.eu/ accessed on 10 June 2024), while those in Wales and Ireland were obtained from the Copernicus Marine Service (CMC) [43] in the SELKIE project (https://www.selkie-project.eu/ accessed on 10 June 2024) [14,44]. Table 1 provides a brief overview of the data sources, followed by a summary of the sites' statistic specifications in Table 2.

Table 1. Description of metocean data sources.

Site	Parameter	Spatial Resolution	Temporal Resolution and Period	Data and Model	Reference
West Ireland and Wales	Wave data (Hs and Tp)	0.017° × 0.017°	Three-hourly * 2000–2019	Copernicus Atlantic—European North-West Shelf-Wave Phsics Reanlayis; underlying model: Wave watchIII	[44]
	Wind	0.25° × 0.25°	Hourly 1940–2022	Copernicus ERA5 hourly data on single levels; underlying model: the European centre for Medium-Range Weather Forecasts (ECMWF)	
Norway	Wave and Wind data	0.25° × 0.25°	Three-hourly * 1979–2009	WaveWatch III third-generation wave model, developed at the US National Centers for Environmental Prediction (NOAA/NCEP) in line with the WAM model	[41,42]

* The three-hour data of significant wave height (Hs) and peak period (Tp) are transformed into hourly data using linear interpolation.

Table 2. Site statistic specifications.

Parameter	Ireland	Wales	Norway
Wind speed (m/s)			
Mean	6.7	7.8	8.3
25 percentile	4.4	5.1	4.8
75 percentile	8.6	10.3	11.1
Tp (s)			
Mean	10.9	9.6	9.5
25 percentile	9.1	7.5	7.4
75 percentile	12.4	11.6	11.1
Hs (m)			
Mean	2.3	1.8	2.5
25 percentile	1.2	0.9	1.4
75 percentile	3.0	2.3	3.2
Wave energy intensity (kW/m) *			
Mean	40.2	19.3	39.0
25 percentile	6.6	3.0	6.7
75 percentile	45.2	21.4	45.7

* Wave energy flux per unit of wave-crest length in deep water [45]. If the wave resource classification system offered by [46] is applied, the three sites are categorised as having moderate (for Wales) to high (for Ireland and Norway) power sites, which can support utility-scale projects.

2.2. WECs

The generic floating 300 kW PA WEC and 1000 kW OWC WECs considered in this study are similar to reference model 3 in [31] and Ocean Energy OE35 [32], respectively. The explanation of the PA and OWC principles, as well as the chain of energy conversion, can be found, for instance, in [31,47]. The PA WEC, weighing 687 t, is a two-body point absorber that converts wave energy into electricity primarily through the device's heave oscillation caused by incident waves; the piston, accumulator, and motor constitute the hydraulic PTO subsystem of the PA WEC, which is combined with an electric generator [31]. The OWC WEC, weighing 826 t [48], is a watertight hollow structure operating on the basis of an oscillating water column compressing/decompressing air to move a turbine connected to an electrical generator [47,49]. The air chamber, air turbine (rotary blades, hub), and energy storage (flywheel) connected to the electric generator constitute the air turbine PTO of the OWC WEC. A typical three-line catenary mooring system with drag-embedded anchors connects the PA and the OWC to the seabed.

All the WEC subsystems and components should operate as a single unit to accomplish the primary function of the WEC, which is to generate electricity. The WEC subsystems are grouped into five categories as recommended by the DNV GL [50,51]: (i) The hydrodynamic subsystem, which consists of the heaving buoy in the PA WEC and the oscillating body in the OWC WEC, is responsible for absorbing the force of the waves. (ii) The PTO subsystem (to harvest power from the waves), which has interfaces with the hydrodynamic subsystem and station-keeping subsystem. (iii) The electrical and transmission subsystem used to transmit compliant electrical power into the electric grid. (iv) Control subsystems to regulate the WEC and its metrics. (v) The stationing-keeping subsystem that keeps the position of the WEC through mooring and anchoring systems. It also offers a PTO subsystem reaction point and supports the hydrodynamic subsystem. The WEC devices may share features like mooring, transmission and control subsystems, but they differ, particularly in their hydrodynamic and PTO subsystems.

2.3. Power Matrix and Potential Power Production

A power matrix characterises the WEC power for a range of sea states that assume a parametric spectral form for the incident waves, such as the JONSWAP or Bretschneider spectrum, and using only two parameters, generally the significant wave height (Hs) and the peak wave period (Tp) [52]. The device's electric power is approximated for a set of Hs and Tp pairs, with each pair representing a power matrix cell [52]. The power matrix of a 300 kW PA WEC and a 1000 kW OSW WEC is generated using the power matrices reported by [31] and OE35 [53] in Figure 3. These power matrices are then used to estimate the power output in a given sea state by matching the hourly Hs and Tp parameters of the sites' metocean data with the corresponding power matrices cell for each WEC device, employing linear interpolation between adjacent power matrix cells [54]. The hourly power estimates are then summed annually to obtain the theoretical AEP (assuming no losses), and the average of 20 years will be the mean AEP. For informational purposes, the percentage joint probabilities of Hs and Tp for each of the three sites are shown in Figure A1 (Appendix A), which serves as an illustration of their co-occurrence possibility.

PA WEC

HS(m) \ Tp [s]	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5
0.25	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
0.75	4	7	9	11	12	12	11	9	8	6	5	4	3	3	2	2
1.25	11	18	26	31	34	32	29	25	21	17	14	12	9	8	6	5
1.75	22	36	50	60	64	62	56	48	40	33	27	22	18	15	13	10
2.25	36	59	82	99	105	101	90	78	65	54	44	36	30	25	20	17
2.75	54	88	121	145	154	148	133	114	96	79	65	53	44	36	30	25
3.25	75	123	168	201	212	203	182	157	131	109	89	73	60	50	42	35
3.75	100	163	222	264	277	265	238	205	172	142	117	96	79	66	55	46
4.25	128	208	283	300	300	300	300	259	218	180	148	122	100	83	69	58
4.75	159	259	300	300	300	300	300	300	268	222	183	150	124	103	86	72
5.25	194	300	300	300	300	300	300	300	300	268	220	181	150	124	104	87
5.75	232	300	300	300	300	300	300	300	300	300	261	215	178	148	123	104
6.25	274	300	300	300	300	300	300	300	300	300	300	252	208	173	144	121
6.75	300	300	300	300	300	300	300	300	300	300	300	291	240	200	167	140
7.25	300	300	300	300	300	300	300	300	300	300	300	300	275	228	191	161
7.75	300	300	300	300	300	300	300	300	300	300	300	300	300	259	217	182
8.25	300	300	300	300	300	300	300	300	300	300	300	300	300	291	244	205
8.75	300	300	300	300	300	300	300	300	300	300	300	300	300	300	273	230
9.25	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	255
9.75	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	282

Figure 3. *Cont.*

OWC WEC

HS(m) \ Tp [s]	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5
0.25	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.75	7	8	16	29	45	64	75	72	62	54	51	51	50	44	44	44
1.25	7	8	16	29	45	64	75	72	62	54	51	51	50	44	44	44
1.75	13	15	31	55	87	123	143	138	120	105	98	98	97	84	84	84
2.25	21	25	51	91	143	202	235	227	197	172	161	160	159	138	138	138
2.75	33	38	78	138	212	301	350	338	293	256	239	239	236	205	205	205
3.25	48	56	115	198	296	419	488	531	469	357	333	332	329	286	286	286
3.75	41	48	98	208	393	557	649	687	604	535	502	502	498	381	381	381
4.25	62	73	148	289	504	713	832	803	697	669	627	627	621	488	488	488
4.75	111	130	265	441	629	860	964	948	861	761	708	707	701	610	610	610
5.25	121	139	283	544	761	962	1000	1000	972	911	865	865	855	744	744	744
5.75	129	147	299	658	859	1000	1000	1000	1000	990	974	974	968	869	869	869
6.25	157	176	359	782	923	1000	1000	1000	1000	1000	1000	1000	1000	962	962	962
6.75	188	207	423	901	978	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
7.25	205	223	456	956	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
7.75	208	233	479	960	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
8.25	211	236	488	964	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
8.75	213	239	492	971	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
9.25	216	243	497	974	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
9.75	219	255	502	980	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000

Figure 3. Power matrices of the 300 kW PA WEC and 1000 kW OWC WEC, based on [31,53].

2.4. Failure and Repair Data

The failure modes of WEC components and their associated mean annual failure rates and repair data are key inputs to the model. The failure definition in this study is similar to [55] in that only failure modes that cause unplanned interruptions in WEC electricity production necessitating CM are considered. Tables 3–5 contain these data, and their sources are listed below with additional information that follows:

- The biggest information source for these data is gathered from the generic WEC FMECA database [56] for the IMPACT project (https://www.impact-h2020.eu/, accessed on 10 May 2024). The database in [56] is primarily obtained from the Offshore & Onshore Reliability Data (OREDA@Cloud) (https://store.veracity.com/oreda-cloud-offshore-onshore-reliability-data, accessed on 10 May 2024) database and includes other literature, such as the Structural Design of Wave Energy Devices (SDWED) report by DNV GL [57]. The OREDA database offers data on maintenance and reliability, including the annual failure rates for each relevant component, failure mechanisms (the primary causes of failures), failure modes (the manner in which a failure occurs), and the direct time required to fix a failure mode.
- Marine and Hydrokinetic Data Repository (MHKDR) [58] for moorings and anchors, and failure rates of minor material damage of float and hull from [59].
- Based on expert opinions, depending on the component failure mode, the direct time to repair can range from 6 to 20 h and involve 1–4 technicians. For instance, one technician spends 4 h fixing a leaky valve, whereas two technicians work 20 h fixing the accumulator breakdown or generator breakage. For the substructure components of the cable and mooring system, two technicians will work for 10 h.
- Spare-part costs are based on [31,60] and expert judgements.

Based on the input data shown in Tables 3–5, the overall mean annual failure rates per PA and OWC are 4.2 and 2.3, respectively. The average yearly spare part cost for a PA device (structural and substructural) will be around EUR 30,000, and EUR 27,000 for an OWC device. This is computed by multiplying the mean annual failure rate of each component by the cost of the spare part for that component in Tables 3–5.

Table 3. Components and repair data—floater and PTO.

Subsystem	Component	Most Common Failure Types	Annual Failure Rate	Most Common Failure Causes	Material Cost (EUR)
Structure	Float [a] Hull [b]	Minor material damage	0.300 0.180 [b]	Marine growth, weather impact, other	10,000 15,000 [b]
		Major structural damage	0.010	Severe storm, lightning, corrosion, fatigue, collision	800,000 1,000,000 [b]
		Hole/Crack	0.032		80,000
PTO	Actuators [a]	Leakage	0.196	Seal failure, rod corrosion, high pressure	1500
		Mechanical failure	0.110		30,000
		Bearing failure	0.080		30,000
	Accumulator [a]	Piston external leakage	0.084	Contamination, corrosion, jammed piston	1500
		Pressure loss	0.117		15,000
		Gas and oil mixture	0.101		2000
		Breakdown	0.035		15,000
	Pump (motor) [a]	Parameter deviation	0.188	Clearance/alignment, mechanical failure, overheating, wear	1500
		Leakage	0.273		1500
		Breakdown	0.117		6500
		Vibration and other	0.275		6500
	Valve (general) [a]	Leakage	0.143	Clearance/alignment, contamination, deformation, looseness	2500
		Fail to close/open	0.139		2500
		Other failure	0.060		2500
	Filter (general) [a]	Leakage	0.143	Plug, material failure, looseness	2500
		Fail to open/close	0.143		2500
	Heat exchanger (generic)	Leakage	0.099	Blockage, corrosion, wear, mechanical failure	1500
		Insufficient heat transfer	0.205		5000
	Air wells turbine [b]	Hub deformation/fracture	0.015	Wear, vibration, corrosion, contamination ingress, lubrication fail	50,000
		Hub surface damage	0.035		8000
		Blades deformation/fracture	0.069		15,000
		Bearing	0.050		10,000
		Surface damage	0.035		5000
		Shaft deformation/fracture	0.012		25,000
		Flywheel bearing damage	0.123		10,000

[a] Only for PA, [b] Only for OWC; otherwise shared by both WECs.

Table 4. Components and repair data—electric generator and transmissions.

Subsystem	Component	Most Common Failure Mode	Annual Failure Rate	Most Common Failure Cause	Spare-Part Cost (EUR) *
Electric generator	Electric generator	Leakage	0.202	Blockage, cavitation, corrosion, mechanical failure, short circuit, software failure, vibration	2000
		Breakage	0.043		15,000
		Overheating	0.078		15,000
		Low/faulty output voltage	0.324		5000
		Vibration and other	0.081		5000
Transmission and Control	Transformer converter	Fail to function on demand	0.182	Mechanical failure, leakage, open circuit, short circuit, general electrical failure, software failure	10,000
		Low output	0.034		15,000
		Parameter deviation and other	0.114		5000
	Switch gear	Fail to function on demand	0.010	Breakage, general electrical failure, software	2000
	Cable	Mechanical failure	0.010	Damage to tension members of the cable, corrosion, wear, and damage to insultation	90,000
		Electrical failure	0.030		10,000
	Sensor	Signal failure	0.030	Blockage and control failure clearance, faulty alarm, general instrument failure, and software	1000
	Programmable Logic Controller (PLC)	Fail to function on demand	0.037		4000
		Minor in-service problem	0.099		1000

* For the electric generator components, transformer converter, and switch gear, a 50% higher spare-part cost is assumed for OWC.

Table 5. Components and repair data—station-keeping.

Subsystem	Component	Most Common Failure Mode	Annual Failure Rate	Most Common Failure Cause	Spare-Part Cost (EUR)
Station-keeping	Mooring lines	Single bridle line failing Single line break	0.030 0.010	Material degradation, Environmental issues, corrosion	10,000 60,000 *
	Joint/connection	Material failure	0.110	Fatigue, corrosion, and marine growth	15,000
	Anchor	Material failure	0.030		65,000 *

* A 20% higher cost for OWC is assumed.

2.5. Vessel

For the purpose of performing onshore repairs on the WEC's structural components, small tugboats are typically needed to tow the device to the port. With a mobilisation period of less than a day or, in certain situations, up to several days, tugboat expenses and times range from EUR 1000 to EUR 8000 per day [61]. Offshore vessels are usually utilised for substructural component repairs, including those pertaining to mooring, cables, anchors, and other related issues. A small, multipurpose workboat with a winch, ample deck space, and dynamic positioning is an example of a vessel, as in [31], that could be used. Based on [31,61,62] and expert opinions, a summary of the vessel input data is provided in Table 6. This study conducts a sensitivity analysis of the vessel operation's wave height and wind speed limitations, which have an impact on the actual MTTR components.

Table 6. Vessel input data.

	Vessel Types	
Parameter	**Tug-Boat Pair**	**Multipurpose Workboat**
Max Wave, m	1.2	1.75
Max Wind, m/s	15	20
Daily hire, EUR	6000 (10,000) *	20,000
Mobilisation fee, EUR	8000 (12,000) *	25,000
Mobilisation time, hr	72	168
Mean speed, knot **	12	17
Mean fuel L/h	150 (250) *	300

* Bigger tugboats for the OWC WEC. ** 1 knot equals 1.854 km/h.

2.6. PM Scenarios

The implementation of a failure-mitigation strategy could lead to increases in the costs of CAPEX, OPEX, or both; PM involves expenses that are linked to the variable O&M costs of OPEX. In this study, three on-shore PM scenarios, annual (PM1), every two years (PM2), and every three years (PM3), are investigated to determine the structural components. PM activities include all repair and maintenance types, if needed, such as cleaning and painting (e.g., the structural float and hull components), repairing or replacing damaged components, and upgrading various systems and equipment. Five technicians are required for each device for 24 h to complete the PM. A conservative estimate of spare-part costs per device for PM1, PM2, and PM3 is assumed to be EUR 20,000, EUR 25,000, and EUR 30,000, based on the overall spare-part costs shown in Tables 3–5. Every three-year PM is also taken into account for the substructural components. Ten hours of labour are required from four technicians, and a spare part cost of EUR 15,000 is assumed. The PM tasks will be completed by the vessel types that match those listed in Table 6.

3. Results and Discussion

3.1. Failure Consequence Costs

The result of the O&M-FC method is presented as the failure consequence costs in this section, whereas the results of the O&M model based on integrated corrective and/or

planned maintenance strategies in Section PM Scenario Analysis. are referred to as O&M costs. This hinges on the methodological distinctions outlined in Section 2 between the O&M-FC approach and the typical O&M model.

The O&M-FC results presented here are derived from Equation (1) and the input data described in Section 2. The average of 600 simulations is used to represent the costs and criticalities of failure severities for subsystems and components. A large number of Monte Carlo simulations can help to improve the accuracy of the findings. Based on a pre-analysis (see Figure A2 in Appendix A), 600 simulations were chosen for this study, with confidence intervals (CI) ranging from ±0.5% to ±5.0% of the mean consequence cost across all components. Figure 4 depicts the mean annual failure consequence costs (direct and indirect), as well as the percentage share of indirect costs at the subsystem level for each case study (PA on the left and OWC on the right).

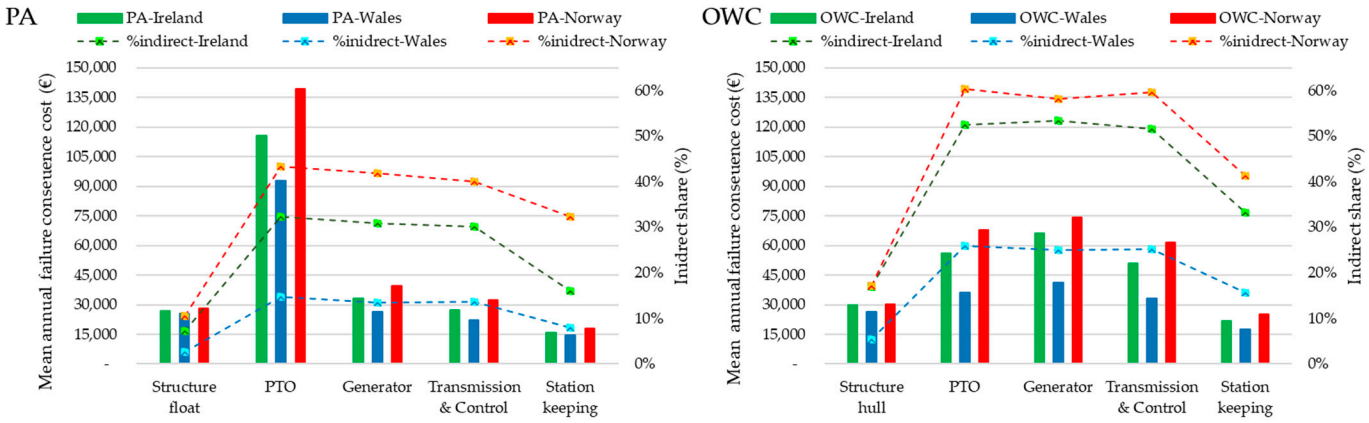

Figure 4. Total failure consequence costs at subsystem levels of PA (**left**) and OWC (**right**) in 3 sites (the secondary axis displays the share of indirect failure costs relative to the total cost for each subsystem at a location).

Figure 4 provides a useful visual representation of the most critical subsystems to be aware of. The figure shows that in all three locations, the failure consequence costs of the PTO and electric generator are the two highest costs for both WEC types. The other subsystems in decreasing order of failure consequence cost are the Transmission and Control, Structural Floater/Hull, and Station-Keeping subsystems. This suggests that the improved reliability of the PTO and Electric Generator needs to be prioritised to lower the long-term financial risks associated with operating these WECs. Section 3.2 provides an overview of the criticality percentage score for each failure mode within each subsystem, as well as some mitigation recommendations.

There are significant differences in the failure consequence costs between PA and OWC among the subsystems in the three sites (see Appendix A for more details). The sites in Norway and Ireland exhibit more pronounced variations. Of the total failure consequence costs, the indirect failure costs (production loss costs due to downtime) for PA in Ireland, Wales, and Norway make up 27%, 12%, and 38%, respectively. These numbers are 46%, 21%, and 53% for the OWC. The three primary determinants of these variations that the proposed model has taken into account are as follows:

(1) The AEP of each device, which is related to the device capacity factor (CF), is the ratio of the average power generated, e.g., over the course of a year, by a fully functional WEC to the maximum rated power that can be generated [63]. Figure 5 compares the AEP and CF of the two WECs. The AEP and CF of PA in Norway are higher by 22% and 76% compared to PA in Ireland and PA in Wales, respectively. For OWC, these metrics in Wales are 43% lower than those in Norway, but they are nearly identical in Norway and Ireland.

(2) The mean weather window waiting time of sites (an important element affecting the downtime and actual MTTR). Figure 6 compares the weather window waiting times of the three sites.

(3) The probability of annual failure in Tables 3–5 affects the costs of failure consequences in two ways: directly (via the frequency of using vessels, spare parts, and technicians) and indirectly (through production loss during failure).

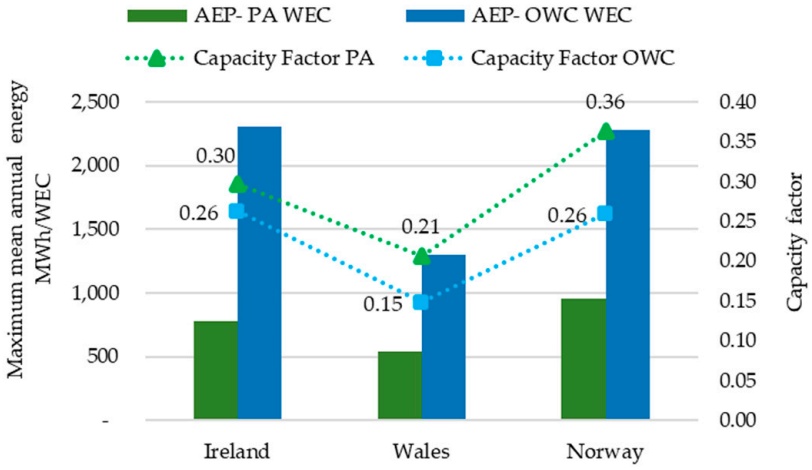

Figure 5. Mean annual energy production (AEP) and capacity factors of the two WECs.

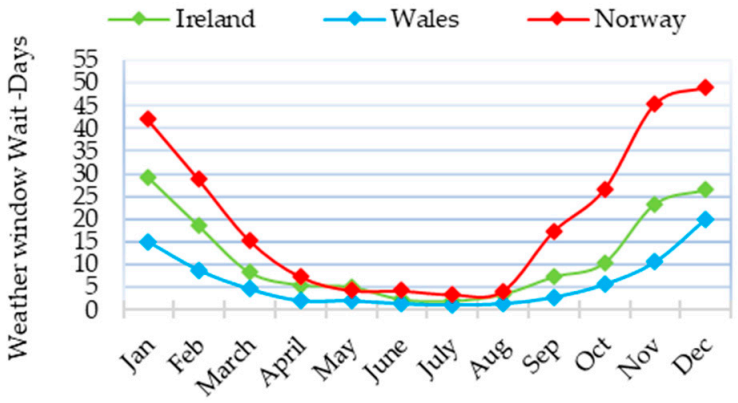

Figure 6. Monthly average waiting time for weather window (10 h GAP, 1.2 m Hs, 15 m/s wind). The figure is produced using 20 years of metocean data for each location, and the average is taken over the waiting times calculated for each hour of each month.

In Figure 4, the AEP and location accessibility for vessel operations are the only variables that differ between the same device (PA or OWC) in different locations. These two factors are interconnected, which means that a device with a higher AEP and a lower location accessibility will incur higher production loss costs depending on when and how frequently failure occurs.

The model for each individual failure mode accounts for the impact of the weather window waiting time for each location; for the purpose of demonstration, Figure 6 uses an example of a 10 h window of favourable weather for the tugboat, which is the vessel used to tow the device to port for structural component repairs. Not surprisingly, the analysis shows a large mean weather window waiting time in Norway and Ireland in the winter season. For example, if a failure occurs in November or December in Norway, on average, it may have to wait until January or February of the following year to have a suitable weather window.

For the WEC with a higher AEP in a harsher environment, like the PA or OWC in Norway, the indirect cost of energy loss due to downtime when failure occurs is significant,

as shown in Figure 4. This effect is more noticeable for components or subsystems with a higher probability of failure (e.g., the PTO subsystem, especially for the PA).

AEP and CF are among the common performance indicators for WECs. Studies have looked into ways to improve these metrics, including optimising PTOs by using appropriate control methods [64] and downscaling or upscaling WECs according to local wave climate conditions [53]. The design of a WEC device for a specific environment or the assessment of potential deployment sites are still areas that warrant investigation [65]. Optimising or enhancing AEP/CF is not the aim of this study; however, the relatively low capacity factor of PA or OWC in Wales compared to other locations (see Figure 5) may imply that a different type or scale of a WEC would be more appropriate for this site, even though the Wales site is a sheltered location that offers a calmer sea (and so a shorter mean weather window time, as shown in Figure 6).

The results of the analyses indicate that improving the device's reliability first in Norway, followed by Ireland and then Wales, should take precedence because of two reasons: the locations are more energetic (conceivably higher AEP) but less seasonally accessible (which could result in greater production loss). A sensitivity analysis of two significant variables (failure rates and vessel operations weather limits) is presented in the following sub-section.

Sensitivity Analysis

The pie chart distribution of failure consequence costs for the two WECs at three sites is shown in Figure A5 of Appendix A. As might be expected, vessel costs account for the majority of direct costs, 60% in the PA and 54% in the OWC. The cost of vessels also makes up a significant portion of the costs associated with subsystem failure consequences, with the exception of the structural components (float or hull), where the replacement part cost is the highest. The vessel costs are determined by its frequency of use (correlated with component failure rates or MTBF) and associated costs (fuel, mobilisation, and daily rates, as shown in Table 6). In terms of indirect costs, downtime and associated costs are affected by both failure rates and weather restrictions on vessel operations.

Sensitivity analyses were conducted for two key variables: the component failure rates in Equation (1) and the vessel weather limits involved in the calculation of MTTR (Equation (6)). Figure 7 (top) shows the results of applying a range of $\pm$20% deviations from the initial failure rates and weather limits (bottom) for vessel operation.

The change in the failure rate has obviously a proportional linear impact on failure consequence costs for the PA and OWC. For instance, a 20% reduction in the failure rate would result in a 20% reduction in failure consequence costs (direct and indirect). The effect of failure rate changes on availability (availability is obtained as [1-(Downtime/8760)]) in Figure 7 (top) shows that the PA is more sensitive than the OWC, and the effect is more noticeable in Norway. The greater availability increase in the event of a failure rate reduction can be attributed to PA's nearly 87% higher mean annual failure rate compared to OWC's, primarily due to differences in their PTO subsystems in Table 3 (the more downtime is reduced, the more availability is increased).

Weather limitations that impact vessel operations influence downtime or availability, which in turn affects indirect failure consequence costs. Figure 7 (bottom) illustrates the sensitivity of the vessel weather limits and demonstrates that, in terms of changes in availability, the PA is again more sensitive to the change than the OWC. The impact is more pronounced in the Norwegian site; for instance, if the Hs and wind speed limits were reduced by 20% (1 m for Hs and 12 m/s for wind speed), the availability for the PA in Norway and the OWC in Norway would be reduced by about 13% and 7%, respectively. However, Ireland exhibits greater improvement than Norway in the event of a 20% increase in the limits. A further analysis of the location weather data in Figure 8 can explain this behaviour.

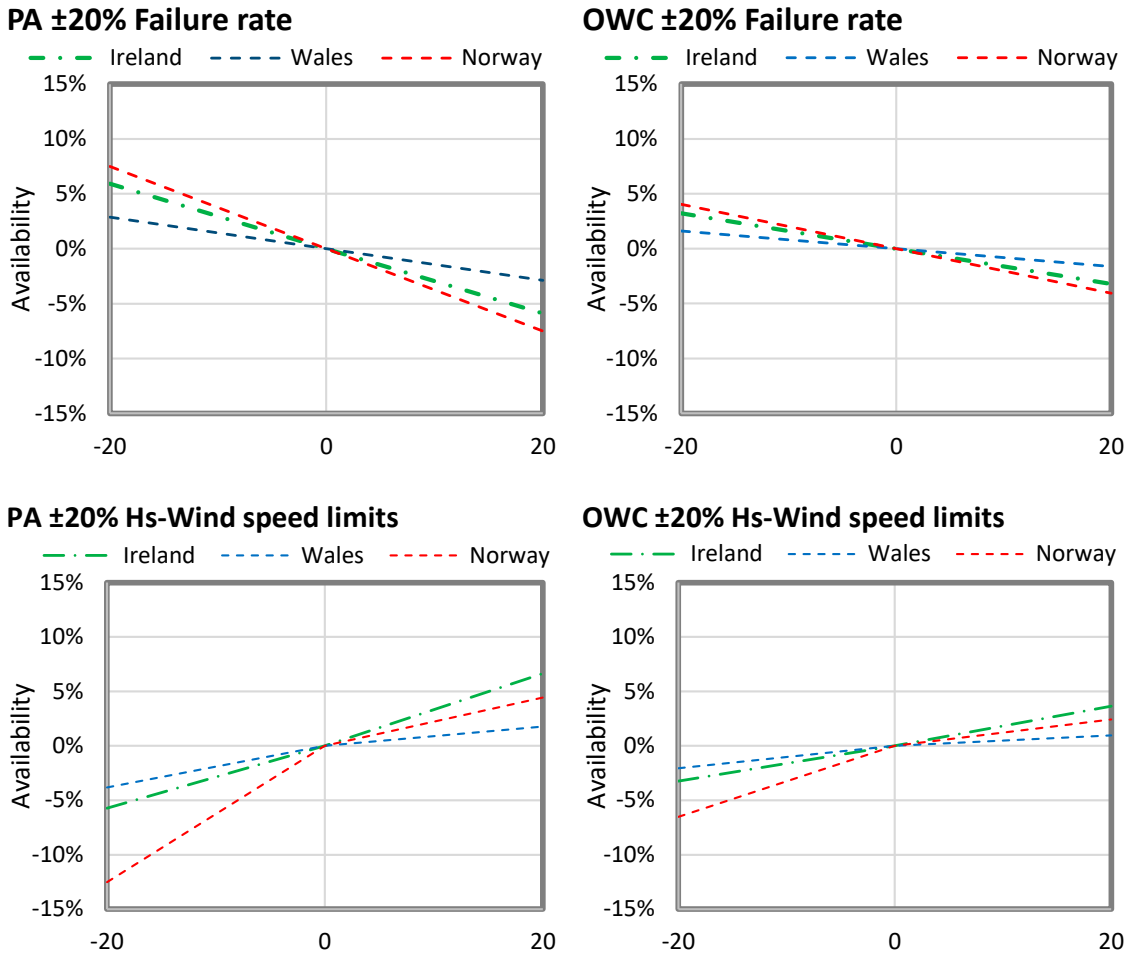

Figure 7. Sensitivity analyses of failure rate (**top**) and weather limits for vessel operations (**bottom**).

Norway- Wind speed limits (m/s)							
Hs limits (m)	0-10	10-12	12-15	15-17	17-20	20-25	>25
0.0-1.0	14	14	14	14	14	14	14
1.0-1.2	22	23	23	23	23	23	23
1.2-1.5	35	35	35	35	35	35	35
1.5-1.7	42	43	43	43	43	43	43
1.7-2.5	61	65	66	66	66	66	66
2.5-3.0	68	73	76	77	77	77	77
3.0-4.0	74	83	88	89	89	89	89
4.0-5.0	76	86	93	95	96	96	96
>5.0	77	87	96	98	100	100	100

Ireland-Wind speed limits (m/s)							
Hs limits (m)	0-10	10-12	12-15	15-17	17-20	20-25	>25
0.0-1.0	17	17	17	17	17	17	17
1.0-1.2	26	26	26	26	26	26	26
1.2-1.5	38	39	39	39	39	39	39
1.5-1.7	46	46	46	46	46	46	46
1.7-2.5	69	70	70	70	70	70	70
2.5-3.0	78	80	80	80	80	80	80
3.0-4.0	87	90	91	91	91	91	91
4.0-5.0	90	95	96	96	96	96	96
>5.0	91	97	100	100	100	100	100

Wales-Wind speed limits (m/s)							
Hs limits (m)	0-10	10-12	12-15	15-17	17-20	20-25	>25
0.0-1.0	30	32	33	33	33	33	33
1.0-1.2	39	42	44	44	44	44	44
1.2-1.5	50	55	57	57	57	57	57
1.5-1.7	56	62	65	65	65	65	65
1.7-2.5	71	79	84	84	84	84	84
2.5-3.0	75	84	90	90	91	91	91
3.0-4.0	78	89	96	97	97	97	97
4.0-5.0	79	91	98	99	99	99	99
>5.0	80	91	99	100	100	100	100

Figure 8. An illustration of the percentage mean accessibility of the three sites for joint Hs and wind speed limits for vessel operations—with a 10 h gap as an example.

In Figure 8, a matrix of the joint percentage probabilities of Hs height and wind speed pairs that are appropriate for vessel operation is generated. For instance, the figure shows that the average accessibility for the vessel to perform the repair is 35% in Norway for the Hs range of 1.2–1.5 m and wind speed of 15–17 m/s, compared to 39% in Ireland and 57% in Wales for the same ranges. This explains why Ireland will benefit more from increased Hs and wind speed limits for vessel operation than Norway, and Wales will benefit the least as it already has a large amount of accessibility, so there is less room to improve. This suggests that the weather limits of the vessels should be improved significantly if less downtime in Norway and Ireland is desired.

The site's features and accessibility need to be carefully considered when performing a WEC failure analysis. The recommended approach here and its use in case studies tackle

this need. The failure consequence cost criticality of component failure modes for every subsystem is discussed in the following section.

3.2. Failure Mode Consequence Cost Ranking

The distribution of total system failure consequence cost criticality for all 39 and 30 failure modes of PA and OWC WECs, respectively, is arranged in descending order, as shown in Figure 9, for Norway as an example. Similar trends are observed in Ireland and Wales, though with a smaller portion of indirect effect (light green and blue portions in the figure). A PA's indirect shares are 38% and 77% lower in Ireland and Wales, respectively. This is 24% lower in Ireland and 76% lower in Wales for the OWC.

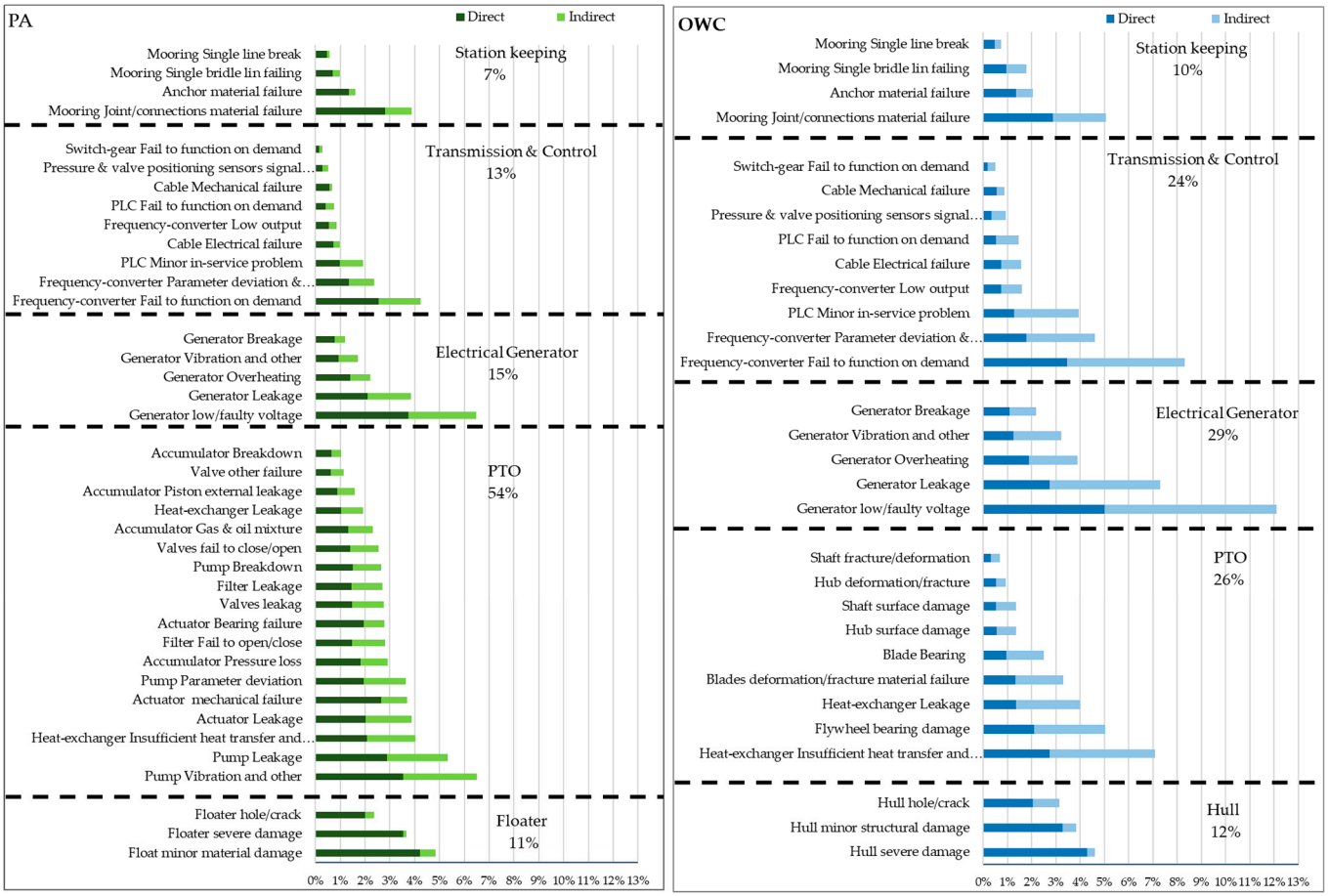

Figure 9. Failure consequence cost distributions for component failure modes for two WEC types in Norway. The outputs in the figures are obtained from the O&M-FC model simulation, following methods explained in Section 2.

The analysis in Figure 9 provides an overview of the components in which failures may result in higher costs and downtime than other components. The PTO subsystem and electric generator, for instance, account for 64% and 54% of the system's overall criticality in the PA and OWC, respectively. Material damage to the float or hull in the structural hydrodynamic subsystem, joints and connections in the mooring system, and so forth are also critical. Since indirect costs result from downtime, the figure also gives a visual understanding of which component failures may be the primary cause of decreased availability; this is represented by the blue and light green sections. For example, in the PA, the first five failure modes with the greatest impact on availability reduction are "pump vibration and leakage", "generator faulty voltage and leakage", "heat-exchanger failure", "actuator leakage", and "converter failure". For the OWC, these include "generator faulty voltage and leakage", "converter failure", "flywheel bearing damage", "blade deformation

and bearing", and "PLC failure". This analysis, combined with the information on common failure mechanisms found in Tables 3–5 and the literature, offers the following findings and recommendations.

Wave actuator structural failure modes (Float in PA and Hull in OWC): In both the PA and OWC, the structural component of float and hull have the second-lowest criticality share of all the WEC systems (Figure 9). However, these structural components, which are primarily composed of steel and fibre-reinforced polymer, are among the priciest parts of the WEC device [12,22]. Thus, even if the likelihood of major structural damage is as low as 0.01 (i.e., 100-year MTBF in Table 3), it is prudent to carefully consider each failure mode of this component because of its high failure consequence costs (project loss in the worst case).

Among the suggested measures to reduce failure during operation are visual inspections, routine maintenance, and the creation of safety/exclusion zones. During the early stages of modelling and design, it is also recommended to lower the level of uncertainty in loading estimates by performing hydrodynamic modelling, site characterisation measurements, and design fatigue factors; see DNVGL-RP-C203, 2021 [66]. For cases with a high likelihood of wear, additional thickness should be considered.

PTO failure modes: The PTO ranks as the most critical subsystem in the PA (45%) and the second in the OWC (23%). In the PA, the pump (33%), actuator (22%), and accumulators (15%) are the components that contribute to nearly 70% of the PTO's total estimated failure consequence cost. The top five most critical failure modes, accounting for almost 67% of the failure consequence cost of the PA's PTO, are: 'leakage' in most parts and components, such as seals and subunits (e.g., lubrication); 'pressure loss' in accumulators (with leakage as the dominant failure mechanism); actuators 'mechanical failure'; motors 'vibration'; and actuators 'bearing failure'.

The primary failure modes in the OWC are 'flywheel bearing' (19%), 'blade deformation and bearing' (22%), and 'heat exchanger inadequate heat transfer and leakage' (42%), which together account for 84% of the OWC PTO failure consequence cost.

For the hydraulic PTO in the PA, a number of general mitigating strategies in the design, manufacturing, and operation phases include using a fluid with an acceptable viscosity index and good lubricating properties [57]; verifying the total loading during deployment and using site assessment data to determine loads that are prudent for the location [58]; enacting condition-based-monitoring, such as using a pressure sensor or pressure transducer to detect the leaks of oil or water [67]; implementing risk-reduction design measures, such as redundant valves and filters; and regular maintenance.

For the PTO in the OWC, most failure mechanisms in Table 3, such as fatigue, wear, corrosion, vibration, and so on, are ascribed to errors in manufacturing or design. For example, cyclic pressures applied to the contact surface that exceed the material's fatigue resistance typically result in surface degradation [68]. However, by making sure there is enough lubrication, possibly by adding an additional lubrication system or performing routine maintenance that includes both lubrication and cleaning, these failure modes may be lessened.

Electric Generator (generic): This component, which is actually part of the PTO subsystem, is shown separately to highlight the differences between the PA and OWC because, as Table 4 states, OWC's larger generator has higher spare part costs. Towing an OWC also costs more when using larger tugboats (Table 6). The three most common failure modes, which account for 73% of all component failure modes, are 'low/faulty output voltage', 'leakage' (e.g., insulation loss), and 'overheating'. These and other failure mechanisms in Table 4 indicate that design and manufacturing errors (e.g., underestimating the operational temperature and insulation degradation) are the primary root causes [24]. However, a monitoring system that evaluates the generator's internal temperature, vibration, and moisture content [24], as well as the proper intervals for preventive maintenance, can mitigate the risk associated with the electric generator component, which has a high percentage criticality score in both the PA and OWC, but more so in the OWC.

Transmission and Control subsystem: For this subsystem, in both the PA and OWC, the failure modes in the frequency converter, PLC, and cable account for approximately 94% of the overall subsystem failure consequence costs. As the figure shows, the frequency converter is dominant (54% in the PA and 61% in the OWC). The failure mechanisms listed in Table 4 imply multiple root causes of manufacturing, material, and design errors, as well as incorrect installation (for cables) and operation, which should be taken into consideration.

Station-keeping: In both the PA and OWC, this subsystem has the lowest criticality scores, ranking below structural components. However, as with the floater and hull, a major failure in the station-keeping components could result in enormous economic costs (e.g., loss of the device). Some recommended actions from [58] include ensuring that a corrosion allowance is defined as per DNV-OS-E301 (https://www.academia.edu/32788430/OFFSHORE_STANDARD_DNV_GL_AS_Position_mooring accessed on 10 June 2024) (e.g., for chain and bridle shackles, including wear and tear) while taking annual inspection into account, proving that the anchor capacity at the deployed site satisfies design requirements (full-scale testing following installation), offering a third-party certification of the properties of used mooring components, and using a load-calculation method to account for loading errors resulting from hydrodynamic models and site characterisation observations. Although the station-keeping subsystem has a low criticality cost, the failure consequence cost criticality of joint and connection material failure modes ranks fifth and fourth in the PA and OWC whole systems, respectively, necessitating regular maintenance.

The suggested O&M-FC approach provides an objective estimation of both direct and indirect failure consequence costs for a given WEC at a location. These metrics are comparable to the subjectively determined severity factors in an FMECA approach, which is based on expert judgements and typically overlooks location accessibility. This study contributes to the need to move towards an objective quantitative evaluation assessment of ocean energy technology, as stressed by the Technology Collaboration Programme of the OES [22]. Furthermore, it can be converted to an O&M model to explore one of the most common failure-mitigation recommendations in the operational phase, which is planned maintenance. This option is investigated through some scenarios for the study cases in the following section.

PM Scenario Analysis

A cost–benefit analysis approach can suggest which of the PM scenarios (in Section 2) is most cost-effective in terms of lowering failure and variable O&M costs (EUR/kWh), increasing income, as well as improving availability) for the 20 MW WEC projects in each site. Figure 10 illustrates these results. Availability is the ratio of the total time less the downtime (due to CM and PM) to the total time.

The PM scenarios shown in Figure 10 indicate that the highest O&M cost reduction and better availability of 0.95 or more could occur in all three locations at intervals of every two years (PM2) for the PA project and every three years (PM3) for the OWC project. The improvements are due to a reduction in annual CM incidents to around 0.4 per WEC for both the PA and OWC (80% or greater CM reductions from base cases), even with PM costs.

The high initial failure rate of the PA WEC (also discussed in sensitivity analysis; Figure 7) accounts for the significant difference in O&M costs between PA-Base and OWC-Base. This unquestionably emphasises how crucial it is to increase component reliability before the operation phase (i.e., improving design, using a control system, redundancy, etc., but probably at the expense of CAPEX). Nonetheless, the findings demonstrate that using suitable PM intervals as a failure-mitigation strategy can lower O&M expenses and boost availability during the operational stage.

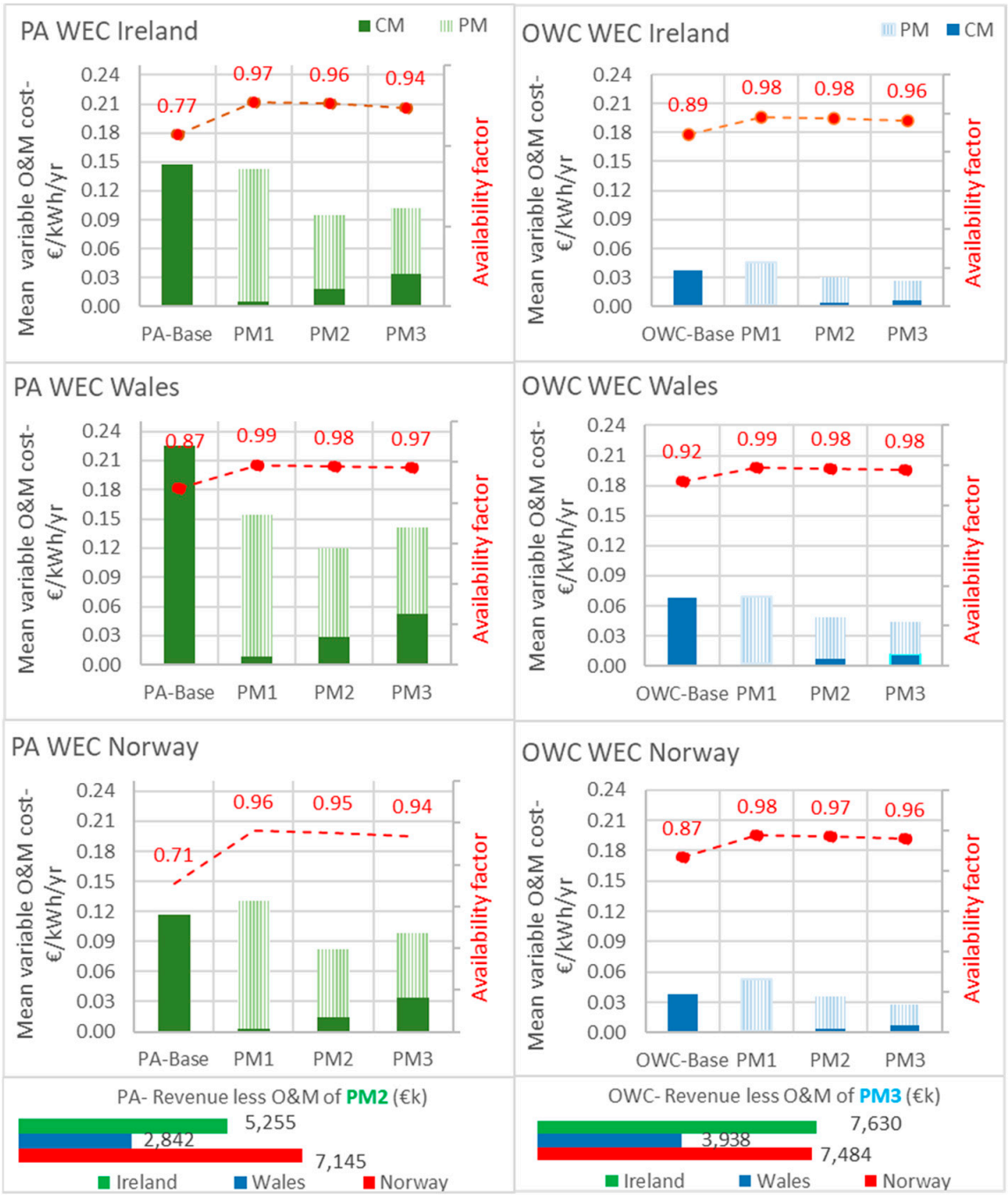

Figure 10. Effect of PM scenarios on the variable O&M costs and other metrics for PA WECs (**left**) and OWC WECs (**right**) in three sites. The bottom bars represent the revenue for each case's optimal PM.

A useful comparison metric for the optimal PM2 and PM3 scenarios in Figure 10 is the revenue less O&M costs or operating profit [51]. For example, the high CF factor of 0.36 for the PA compared to 0.26 for the OWC (Figure 5) indicates that even with 203% higher O&M cost for PA-PM2 than OWC-PM3 in Norway, the operating profit difference is only 5% (at a 200 EUR/MWh electricity tariff) in favour of Norway. Therefore, the PA could gain more from a 1% increase in availability than OWC in Norway, resulting in 641 MWh versus 456 MWh more AEP and a 4% increase in revenue less O&M costs. Under the assumptions in the case studies, an OWC in Ireland could gain more, even if the availability of the PA would increase to 98%. For Wales, despite a high availability factor of 0.98 for both PA-PM2 and OWC-PM3 in Figure 10, due to the relatively low CF for the PA, the OWC WEC type

could gain substantially higher operating profit (39%) than a PA WEC. Nevertheless, the CF of 0.21 of an OWC WEC in Wales is not attractive.

Using the proposed model as a tool, PM scenarios can be run, for example, to achieve specific O&M costs or an availability target. Offshore wind energy often cites availability as a prerequisite for commercialisation. An availability of 0.98 is established for floating offshore wind projects, for instance, in [69]. The OES predicts an availability factor of 0.95 to 0.98 for the first commercial WEC of 2 MW to 75 MW in 2030 [9]. The availability in both the PA and OWC WECs can be greatly enhanced by the PM scenarios, but most notably in the PA (for example, the availability of the PA-WEC in Norway can go from 0.71 to 0.95 in the PM2 scenario, while the O&M cost is reduced by 30%). For the OWC, the PM3 application still has benefits due to lower O&M costs and increased availability from 0.87 to 0.96 or more.

For all the simulations, the model has assumed a default port distance of 20 km. The port distance is highly uncertain; it is a parameter that affects the vessel transition time and therefore the vessel cost in Equation (2) and MTTR in Equation (6). At the study's sites, the potential ports for the provision of facilities for the maintenance activities are Bergen port in Norway at 55 km (estimated using coordinators specifications), Shannon–Foynes port in Ireland at 45 km in Ireland, and Pembrokeshire port in Wales at 27 km [14]. For each of the optimal PM scenarios, a sensitivity analysis of various port distances at intervals of 10 km is carried out, and O&M costs and availability are computed. Using the Norway case study as an example, the sensitivity analysis for the optimal PM scenarios port distance and O&M costs is shown in Figure 11.

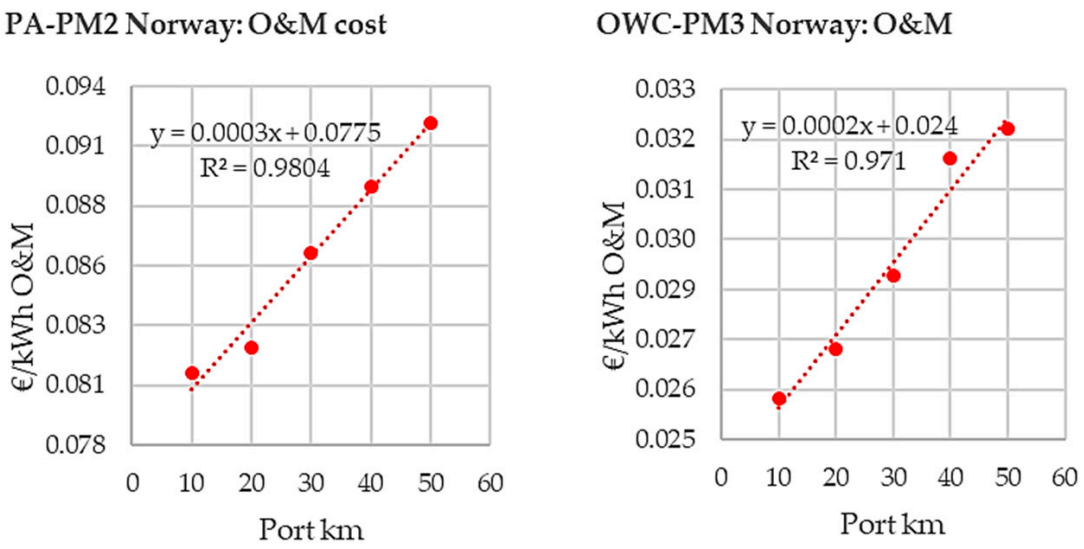

Figure 11. Sensitivity of O&M costs as a function of km port distance—examples of Norway's optimal PM scenarios.

The results of the sensitivity analyses of the optimal PM scenarios involving the port distance indicate that the O&M cost of the PA is more susceptible to the port distance compared to the OWC. For the PA in all three sites, every 10 km increase in port distance is linked to an increase of 0.003 EUR/kWh O&M costs. Likewise, for the OWC, an increase in port distance of 10 km would correspond to an increase in O&M costs of 0.002 EUR/kWh O&M.

The availability is less affected by an increase in port distance in optimal PM scenarios due to a low CM intervention of approximately 0.4 across all cases. This translates to an additional 26 h of downtime annually, or 1.1-day production loss for PA and 18 h of downtime annually (or 0.7-day production loss) for the OWC in Ireland and Norway. There is a negligible impact on Wales for every 10 km increase in port distance.

Given the maturity of the offshore or marine energy O&M models, the application of the proposed method is practical. The method, evaluation metrics, and sensitivity analyses can be used, as discussed in the Results section, to compare the operating performance of different types of WECs in various locations; it can offer answers or conditions for reaching answers to the following questions:

- Which subsystem and which failure mode within a subsystem/component has a bigger effect on the failure consequence costs for a specific location or type of WEC, both in terms of direct repair costs and indirect costs? (See Sections 3.1 and 3.2). These quantitative measures can be used, much in line with an FMECA approach, to help guide decisions about enhancing product reliabilities at various stages of development.
- How does the case study location impact the assessed metrics for a particular WEC type? Or which type of WEC is preferred in a particular location given the inputs and their sensitivity in the case study? (See Section 3.1).
- If PM is used as a potential failure-mitigation option, which PM interval is ideal in terms of reducing O&M costs, gaining an acceptable availability, and increasing operating profits? What percentage of projected WEC farms' O&M expenses are related to CM and PM? (See Section PM Scenario Analysis).

4. Remarks and Future Studies

The focus of this study was to develop and implement a method for integrating FMECA and O&M. Comparative quantitative analyses of failure consequence costs of WEC types deployed in different locations were obtained by using a suitable failure distribution model for time-to-failure and hundreds of simulations. This approach allows for unbiased estimates of the direct failure costs and indirect costs associated with downtime for any failure mode. In a future study, the model can be used to perform an OPEX analysis on a specific case study, similar to [28], and integrated into an LCOE analysis if data are available.

The tool offers the opportunity to perform sensitivity analyses of key parameters in relation to WECs in different locations. The sensitivity of a few of the parameters that were included in the generic case studies were MTBF, MTTR (Section Sensitivity Analysis), and port distance (Section PM Scenario Analysis). However, more sensitivity analyses are required in future research to include cost inputs such as vessel hiring costs, the first dominant cost component in repair/replacement activities, or spare part costs, the second dominant contributor, as indicated in Figure A5.

The study data were compiled using publicly available databases and expert opinions, as explained in Section 2. Obviously, accurate data for a specific case study would be useful in improving estimates of metrics such as availability, O&M costs, and operating revenues in Section 3.1. Commercial WECs are expected to have CF values that are higher than those found in the models (Figure 5). In the OES report, a CF range of 35–40% is anticipated for the first commercial WEC [9], and in this study, only the PA in Norway falls within this range. The CF is described as the relationship between the power matrix and actual power captured by a WEC in an area [70]. A WEC in a specific location should have its CF determined. Therefore, it is possible that the power matrices of the generic WECs used in the model vary in different locations. As previously stated, novel methods and more tools that facilitate scenario and sensitivity analyses for all the uncertainties associated with the WEC input data could assist in the estimation of relevant metrics for WECs.

5. Conclusions

For WECs with a wide range of technology types and deployment sites, a quantitative assessment of failure risks prior to market introduction is important. This study proposed a new method for integrating O&M and FMECA, allowing the severity of failure consequences of failure modes, which are typically estimated subjectively by experts in an FMECA, to be objectively quantified. The Monte Carlo method is used to run hundreds of simulations with a uniform and unbiased failure distribution. The model was used in case studies with a generic floating 300 kW PA and a 1000 kW OWC at three energetic

North-East Atlantic sites in Wales, Ireland, and Norway, each with a mean energy density of 19.3 kW/m, 39.0 kW/m, and 40.2 kW/m. The model incorporates the location's time series meteorological data, including significant wave height, wave period, and wind speed. The WEC types with relatively high TRLs and locations were selected based on their data availability and abundance of wave resources.

This study demonstrated how important it is to consider location characteristics when conducting a quantitative failure-risk analysis on WECs. Location, which affected the energy production and accessibility for vessel operations, was particularly important in Ireland and Norway. This study discussed how these two factors and the component failure rates were responsible for the differences in the failure consequence costs of the two WECs in the three sites. It provided a detailed explanation of the relative contributions of the direct and indirect (downtime-related) failure consequence costs at 4 subsystem and 15 component levels, as well as at the levels of the 39 and 30 failure modes of the PA and OWC WECs, in each of the three sites. The O&M-FC outputs showed that despite the PA WEC having an annual failure rate input nearly twice that of the OWC WEC, there were no substantial differences in the total failure consequence costs between them in both Ireland and Norway. This was primarily attributed to the higher indirect failure costs associated with OWC. However, in a sheltered area such as Wales, the difference was approximately 15% higher for PA compared to OWC. The PTO subsystem's most common failure modes, which accounted for a significant portion of the overall failure consequence costs at all sites, were actuator bearing failures in the hydraulic PTO, motor vibration, and component leakage. The PTO component failure of the OWC was primarily affected by bearing-related failures, fatigue, wear, and corrosion.

This study recommended several failure-mitigation strategies, such as design improvements, the implementation of a control system, and redundancy, which may incur CAPEX costs. It investigated the impact of failure mitigation through planned maintenance by simulating the O&M of 20 MW PA and OWC projects at three sites. This analysis considered both the ageing factor affecting component failures and the influence of planned maintenance on component health. This paper demonstrated how to create a decision-making tool that can help achieve goals such as increasing availability while minimising O&M costs or maximising operating profit (revenue minus O&M costs).

The proposed method enables a quantitative risk analysis of component failure modes, as well as scenario and sensitivity analyses of different WEC types at various locations. Researchers and developers can use it to help prioritise cost-effective failure mitigation strategies so that WECs can reach their full potential when used in a commercial setting.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Ireland

Hs (m) \ Tp (s)	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
0.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.75	0.19	0.15	0.33	1.06	1.62	1.11	0.83	0.51	0.30	0.17	0.07	0.03	0.02	0.03	0.02
1.25	0.18	0.37	0.83	1.75	3.78	3.59	2.96	1.98	1.19	0.65	0.35	0.17	0.16	0.08	0.06
1.75	0.00	0.08	0.51	1.09	2.73	3.85	3.71	2.57	1.80	1.04	0.57	0.24	0.17	0.09	0.06
2.25	-	0.01	0.07	0.50	1.41	2.85	3.46	3.16	1.98	1.13	0.44	0.22	0.12	0.07	0.03
2.75	-	-	0.01	0.09	0.54	1.55	2.37	2.96	2.09	1.25	0.63	0.29	0.14	0.05	0.04
3.25	-	-	-	0.01	0.13	0.60	1.32	1.98	1.92	1.26	0.65	0.32	0.15	0.06	0.03
3.75	-	-	-	0.00	0.02	0.14	0.65	1.47	1.70	1.05	0.55	0.32	0.15	0.06	0.02
4.25	-	-	-	-	-	0.03	0.34	0.78	1.26	1.06	0.58	0.30	0.18	0.06	0.02
4.75	-	-	-	-	-	0.00	0.08	0.35	0.80	0.91	0.52	0.30	0.15	0.07	0.02
5.25	-	-	-	-	-	-	0.01	0.17	0.46	0.72	0.47	0.25	0.17	0.07	0.04
5.75	-	-	-	-	-	-	-	0.03	0.23	0.48	0.46	0.24	0.12	0.05	0.03
6.25	-	-	-	-	-	-	0.00	0.01	0.10	0.28	0.30	0.28	0.11	0.05	0.02
6.75	-	-	-	-	-	-	-	0.00	0.02	0.15	0.19	0.19	0.13	0.04	0.03
7.25	-	-	-	-	-	-	-	-	0.00	0.05	0.13	0.15	0.11	0.05	0.02
7.75	-	-	-	-	-	-	-	-	-	0.02	0.07	0.07	0.07	0.04	0.02
8.25	-	-	-	-	-	-	-	-	-	0.00	0.02	0.05	0.07	0.05	0.03
8.75	-	-	-	-	-	-	-	-	-	-	0.01	0.03	0.05	0.04	0.01
9.25	-	-	-	-	-	-	-	-	-	-	0.00	0.01	0.03	0.02	0.00

Wales

Hs (m) \ Tp (s)	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
0.25	0.00	0.00	0.00	0.05	0.05	0.06	0.04	0.02	0.04	0.03	0.04	0.03	0.01	0.02	0.02
0.75	1.85	0.44	0.51	1.53	2.25	2.91	2.39	1.53	0.96	0.59	0.36	0.21	0.23	0.14	0.08
1.25	2.38	2.89	1.41	1.42	2.51	3.47	3.35	2.74	2.15	1.23	0.57	0.35	0.30	0.11	0.09
1.75	0.05	2.27	2.86	1.88	1.77	2.00	2.46	2.38	1.87	1.18	0.58	0.29	0.19	0.09	0.04
2.25	-	0.16	1.51	2.24	1.72	1.48	1.69	1.68	1.32	0.85	0.48	0.27	0.17	0.07	0.04
2.75	-	0.00	0.23	1.23	1.66	1.08	0.94	1.15	1.05	0.72	0.39	0.22	0.15	0.05	0.02
3.25	-	-	0.01	0.28	1.07	1.09	0.83	0.69	0.80	0.51	0.27	0.15	0.10	0.05	0.02
3.75	-	-	0.00	0.03	0.34	0.85	0.61	0.54	0.62	0.45	0.18	0.11	0.08	0.03	0.02
4.25	-	-	-	0.00	0.04	0.41	0.58	0.45	0.41	0.30	0.17	0.09	0.06	0.03	0.02
4.75	-	-	-	-	0.00	0.09	0.39	0.36	0.31	0.24	0.13	0.07	0.05	0.03	0.01
5.25	-	-	-	-	-	0.01	0.13	0.32	0.24	0.15	0.08	0.07	0.05	0.03	0.01
5.75	-	-	-	-	-	0.00	0.02	0.16	0.15	0.11	0.06	0.03	0.02	0.02	0.01
6.25	-	-	-	-	-	-	0.00	0.05	0.09	0.06	0.04	0.02	0.01	0.01	0.00
6.75	-	-	-	-	-	-	-	0.00	0.04	0.05	0.02	0.01	0.01	0.01	-
7.25	-	-	-	-	-	-	-	0.00	0.01	0.03	0.02	0.01	0.01	0.00	0.00
7.75	-	-	-	-	-	-	-	-	-	0.01	0.02	0.01	0.00	0.00	0.00
8.25	-	-	-	-	-	-	-	-	-	0.00	0.01	0.00	-	-	0.00
8.75	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	-	0.00
9.25	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	-

Norway

Hs (m) \ Tp (s)	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
0.25	0.01	0.00	0.00	0.00	0.00	0.01	-	-	-	-	-	-	-	-	-
0.75	0.19	0.51	0.54	0.31	0.59	0.69	0.53	0.25	0.14	0.08	0.03	0.02	0.01	0.01	0.00
1.25	0.45	1.32	2.97	2.26	1.62	2.10	2.29	1.45	0.89	0.44	0.26	0.11	0.07	0.04	0.02
1.75	0.06	1.26	2.43	3.41	2.54	2.00	2.23	1.85	1.39	0.87	0.44	0.22	0.09	0.04	0.02
2.25	0.00	0.19	1.84	2.60	2.65	2.01	1.56	1.18	1.29	0.87	0.61	0.24	0.08	0.03	0.02
2.75	-	0.01	0.48	1.95	2.43	1.92	1.32	1.04	1.04	0.93	0.60	0.25	0.08	0.02	0.01
3.25	-	-	0.05	0.99	1.81	1.69	1.28	0.87	0.81	0.74	0.55	0.26	0.10	0.01	0.01
3.75	-	-	0.01	0.23	1.28	1.57	1.10	0.68	0.52	0.60	0.46	0.29	0.11	0.03	0.00
4.25	-	-	0.00	0.03	0.57	1.29	1.20	0.66	0.46	0.44	0.33	0.26	0.07	0.02	0.00
4.75	-	-	-	0.00	0.17	0.87	1.04	0.60	0.36	0.32	0.26	0.14	0.06	0.02	0.00
5.25	-	-	-	-	0.02	0.43	0.86	0.53	0.31	0.24	0.20	0.11	0.06	0.02	-
5.75	-	-	-	-	0.00	0.10	0.63	0.52	0.26	0.15	0.13	0.10	0.04	0.00	0.00
6.25	-	-	-	-	-	0.03	0.26	0.44	0.27	0.13	0.12	0.07	0.04	0.00	-
6.75	-	-	-	-	-	0.00	0.10	0.31	0.24	0.11	0.10	0.06	0.02	0.01	-
7.25	-	-	-	-	-	-	0.01	0.17	0.17	0.12	0.07	0.04	0.02	0.00	-
7.75	-	-	-	-	-	-	0.00	0.03	0.11	0.11	0.04	0.02	0.01	0.00	-
8.25	-	-	-	-	-	-	0.00	0.01	0.09	0.09	0.04	0.02	0.00	0.00	-
8.75	-	-	-	-	-	-	-	0.01	0.03	0.08	0.05	0.02	0.01	0.00	-
9.25	-	-	-	-	-	-	-	0.00	0.01	0.05	0.04	0.01	0.00	0.00	-

Figure A1. Percentage joint probabilities of Hs and Tp in the three sites.

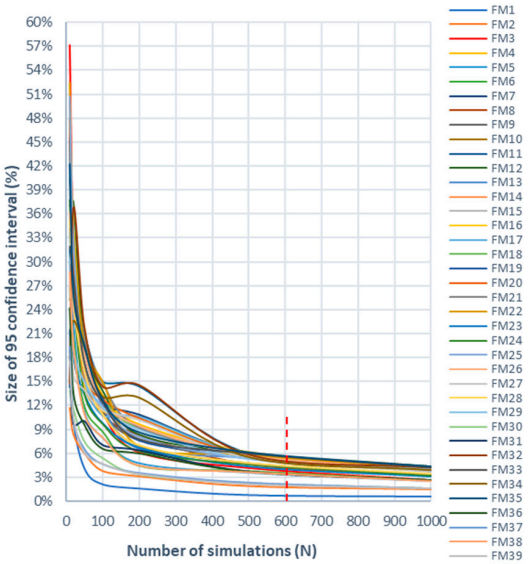

Figure A2. Size of confidence interval (CI) as a percentage of each measure for component-failure modes. An example of PA in Norway. The CI size shows a steady decline after 600 simulations. N = 600 is suitable for this study. All 39 component failure modes have maximum CIs of less than +/−5%. Increasing N does not significantly decrease the CI size while increasing computing time. FM represents all 39 failure modes of PA.

PA-Ireland	PTO	Electric Generator	Frequency Conv. Trans. & Control	Float	Station keeping
Direct Effect	36%	11%	9%	11%	6%
Indirect Effects	17%	5%	4%	1%	1%
Total-€/yr	115,652	33,210	27,349	26,726	15,847

OWC-Ireland	Electric Generator	PTO	Frequency Conv. Trans. & Control	Station keeping	Structural Hull
Direct Effect	14%	12%	11%	11%	7%
Indirect Effects	16%	13%	12%	2%	3%
Total-€/yr	65,965	56,096	50,845	29,874	21,954

PA-Wales	PTO	Electric Generator	Frequency Conv. Trans. & Control	Float	Station keeping
Direct Effect	43%	13%	14%	11%	8%
Indirect Effects	8%	2%	0%	2%	1%
Total-€/yr	92,685	26,589	22,339	25,631	14,758

OWC- Wales	Electric Generator	PTO	Frequency Conv. Trans. & Control	Station keeping	Structural Hull
Direct Effect	20%	17%	16%	16%	9%
Indirect Effects	7%	6%	5%	1%	2%
Total-€/yr	41,219	36,204	33,255	26,326	17,400

PA-Norway	PTO	Electric Generator	Frequency Conv. Trans. & Control	Float	Station keeping
Direct Effect	31%	9%	8%	10%	5%
Indirect Effects	23%	6%	5%	1%	2%
Total-€/yr	139,387	39,662	32,285	28,018	18,078

OWC- Norway	Electric Generator	PTO	Frequency Conv. Trans. & Control	Station keeping	Structural Hull
Direct Effect	12%	10%	10%	10%	6%
Indirect Effects	17%	16%	14%	2%	4%
Total-€/yr	74,349	68,016	61,674	30,038	24,973

Figure A3. Failure consequence cost distributions at subsystem levels.

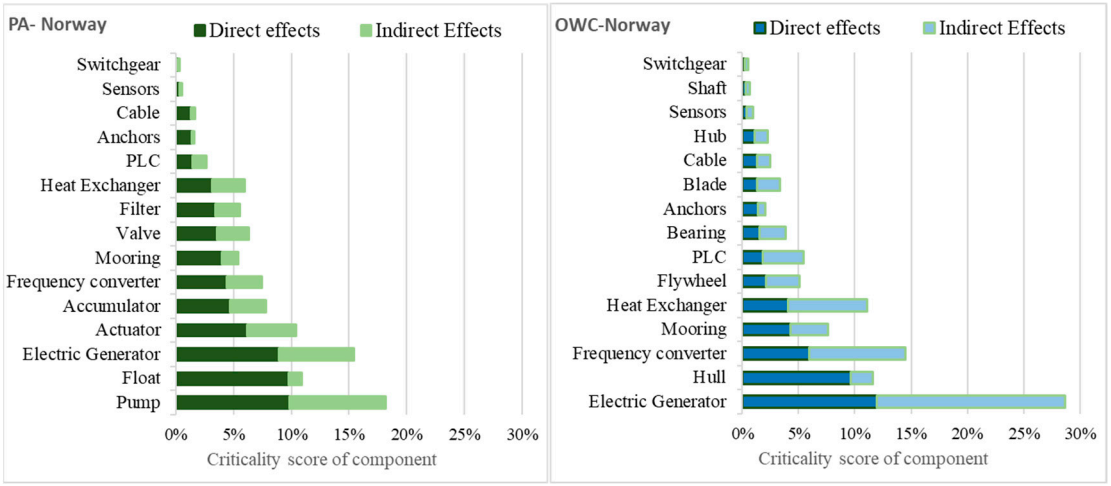

Figure A4. Comparative component percentage criticality rankings for the Norway site PA (**left**) and OWC (**right**).

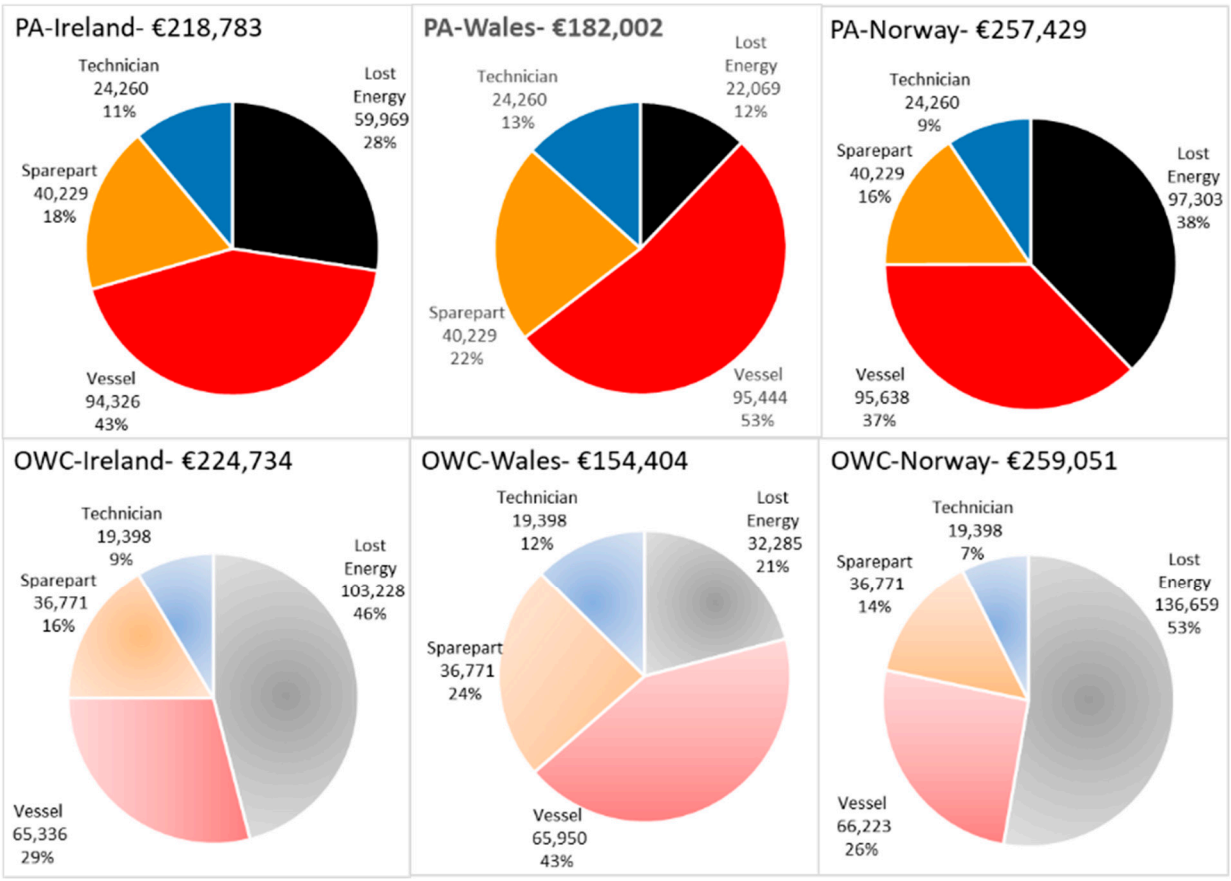

Figure A5. Pie chart distribution of mean annual failure consequence costs of a PA WEC (**top**) and an OWC WEC (**bottom**).

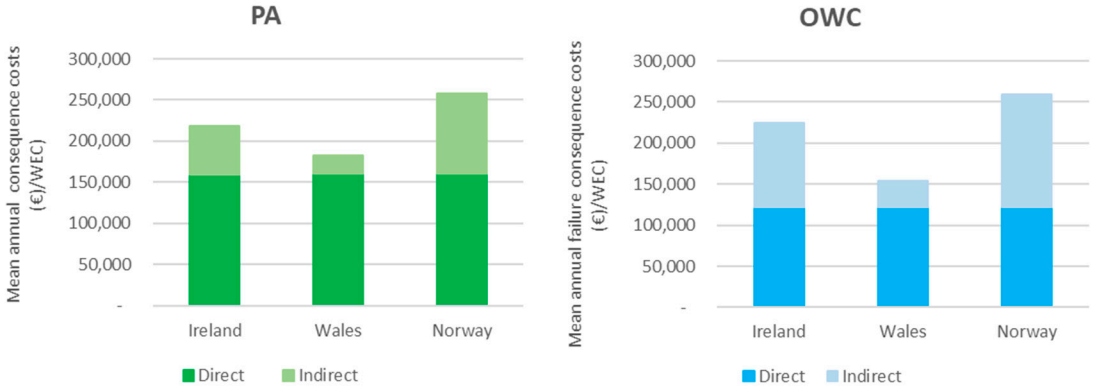

Figure A6. Total failure consequence cost (direct and indirect) comparisons of PA (**left**) and OWC (**right**) across three sites.

References

1. Heikkilä, E.; Välisalo, T.; Tiusanen, R.; Sarsama, J.; Räikkönen, M. Reliability Modelling and Analysis of the Power Take-Off System of an Oscillating Wave Surge Converter. *J. Mar. Sci. Eng.* **2021**, *9*, 552. [CrossRef]
2. Galparsoro, I.; Liria, P.; Legorburu, I.; Bald, J.; Chust, G.; Ruiz-Minguela, P.; Pérez, G.; Marqués, J.; Torre-Enciso, Y.; González, M.; et al. A Marine Spatial Planning Approach to Select Suitable Areas for Installing Wave Energy Converters (WECs), on the Basque Continental Shelf (Bay of Biscay). *Coast. Manag.* **2012**, *40*, 1–19. [CrossRef]
3. European Union. *An EU Strategy to Harness the Potential of Offshore Renewable Energy for a Climate Neutral Future*; EU: Brussels, Belgium, 2020; p. 27.
4. OEE. *Ocean Energy Europe. Key Trands and Statistics 2021. Ocean Energy*. 2022. Available online: https://www.oceanenergy-europe.eu/wp-content/uploads/2022/03/OEE_Stats_and_Trends_2021_web.pdf (accessed on 10 February 2024).

5. Jones, C.; Chang, G.; Dallman, A.; Roberts, J.; Raghukumar, K.; McWilliams, S. Assessment of wave energy resources and factors affecting conversion. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 6–9 May 2019. [CrossRef]
6. PRIMRE. Portal and Repository for Information on Marine Renewable Energy—PRIMRE Databases. 2023. Available online: https://openei.org/wiki/PRIMRE/Databases/Projects_Database (accessed on 10 December 2023).
7. IRENA. *Innovation Outlook: Ocean Energy Technologies*; IRENA: Masdar City, United Arab Emirates, 2020.
8. Magagna, D.; Uihlein, A. Ocean energy development in Europe: Current status and future perspectives. *Int. J. Mar. Energy* **2015**, *11*, 84–104. [CrossRef]
9. OES—IEA. International Levelised Cost of Energy for Ocean Energy Technologies. 2015. Available online: https://www.ocean-energy-systems.org/oes-projects/levelised-cost-of-energy-assessment-for-wave-tidal-and-otec-at-an-international-level/ (accessed on 10 December 2023).
10. October, R.; Working, I.; Ocean, G. SET-Plan Ocean Energy—Implementation Plan. vol. 2021, no. March 2018, 2021. Available online: https://setis.ec.europa.eu/document/download/8d2ad133-13ee-441f-9776-46c7aef98714_en?filename=SET%20Plan%20OCEAN%20ENERGY%20Implementation%20plan.pdf (accessed on 19 July 2024).
11. Göteman, M.; Shahroozi, Z.; Stavropoulou, C.; Katsidoniotaki, E.; Engström, J. Resilience of wave energy farms using metocean dependent failure rates and repair operations. *Ocean Eng.* **2023**, *280*, 114678. [CrossRef]
12. Guo, C.; Sheng, W.; De Silva, D.G.; Aggidis, G. A Review of the Levelized Cost of Wave Energy Based on a Techno-Economic Model. *Energies* **2023**, *16*, 2144. [CrossRef]
13. Castro-Santos, L.; Filgueira-Vizoso, A.; Costoya, X.; Arguilé-Pérez, B.; Ribeiro, A.S. Economic viability of floating wave power farms considering the energy generated in the near future. *Renew. Energy* **2024**, *222*, 119947. [CrossRef]
14. O'Connell, R.; Kamidelivand, M.; Furlong, R.; Guerrini, M.; Cullinane, M.; Murphy, J. An advanced geospatial assessment of the Levelised cost of energy (LCOE) for wave farms in Irish and western UK waters. *Renew. Energy* **2024**, *221*, 119864. [CrossRef]
15. Chang, G.; Jones, C.A.; Roberts, J.D.; Neary, V.S. A comprehensive evaluation of factors affecting the levelized cost of wave energy conversion projects. *Renew. Energy* **2018**, *127*, 344–354. [CrossRef]
16. OpenEI. Open Energy Information, Data and Resources Primre/Tools. Available online: https://openei.org/wiki/PRIMRE/Tools (accessed on 15 April 2024).
17. Aalborg University. An Open-Access COE Calculation Tool for Wave Energy Converters: The Danish Approach. Available online: https://vbn.aau.dk/en/publications/an-open-access-coe-calculation-tool-for-wave-energy-converters-th (accessed on 15 March 2024).
18. NREL. WEC-Sim Wave Energy Converter Simulator. Available online: https://data.nrel.gov/submissions/39 (accessed on 15 February 2024).
19. Sandia National Laboratories. Optimal Design Tools for Ocean Energy Arrays (DTOcean). Available online: https://energy.sandia.gov/programs/renewable-energy/water-power/projects/dtocean/ (accessed on 20 May 2024).
20. SELKIE Tools. Logistics and Operation and Maintenance (O&M) Decision-Support Tool. Available online: https://www.selkie-project.eu/logistics-and-operation-and-maintenance-om-decision-support-tool/ (accessed on 10 June 2024).
21. Rodrigues, J.M.; Langhele, N.K.; Rølvåg, T.; Cruz, J.; Cruz, M.A.; Martini, M.; Garcia-Rosa, P.B.; Kamidelivand, M.; Alessandri, G.; Gallorini, F. Compilation of Development Metrics Applicable to Wave Energy Converters (WECs): Current Status and Proposed Next Steps. In Proceedings of the 33rd International Ocean and Polar Engineering Conference, Ottawa, SO, Canada, 19–23 June 2023. [CrossRef]
22. Hodges, J.; Henderson, J.; Ruedy, L.; Soede, M.; Weber, J.; Ruiz-Minguela, P.; Jeffrey, H.; Bannon, E.; Holland, M.; Maciver, R.; et al. An International Evaluation and Guidance Framework for Ocean Energy Technology 2O21 2-Task 12. 2021. Available online: www.formasdopossivel.com (accessed on 10 May 2024).
23. MIL-STD-1629. Failure Mode Effects and Criticality Analysis. 1993. Available online: https://www.sciencedirect.com/science/article/abs/pii/0026271472903927?via=ihub (accessed on 8 December 2023).
24. Scheu, M.N.; Tremps, L.; Smolka, U.; Kolios, A.; Brennan, F. A systematic Failure Mode Effects and Criticality Analysis for offshore wind turbine systems towards integrated condition based maintenance strategies. *Ocean Eng.* **2019**, *176*, 118–133. [CrossRef]
25. Cevasco, D.; Collu, M.; Lin, Z. O&M Cost-Based FMECA: Identification and Ranking of the Most Critical Components for 2–4 MW Geared Offshore Wind Turbines. In Proceedings of the WindEurope Conference 2018 within the Global Wind, Hamburg, Germany, 25–28 September 2018; Volume 1102. [CrossRef]
26. Tazi, N.; Châtelet, E.; Bouzidi, Y. Using a hybrid cost-FMEA analysis for wind turbine reliability analysis. *Energies* **2017**, *10*, 276. [CrossRef]
27. Rinaldi, G.; Thies, P.R.; Walker, R.; Johanning, L. On the Analysis of a Wave Energy Farm with Focus on Maintenance Operations. *J. Mar. Sci. Eng.* **2016**, *4*, 51. [CrossRef]
28. Gray, A.; Dickens, B.; Bruce, T.; Ashton, I.; Johanning, L. Reliability and O&M sensitivity analysis as a consequence of site specific characteristics for wave energy converters. *Ocean Eng.* **2017**, *141*, 493–511. [CrossRef]
29. CarbonTrust. *Guidelines on Design and Operation of Wave Energy Converters: A Guide to Assessment and Application of Engineering Standards and Recommended Practices for Wave Energy Conversion Devices*; CarbonTrust: London, UK, 2005.
30. Bertram, D.V.; Tarighaleslami, A.H.; Walmsley, M.R.W.; Atkins, M.J.; Glasgow, G.D.E. A systematic approach for selecting suitable wave energy converters for potential wave energy farm sites. *Renew. Sustain. Energy Rev.* **2020**, *132*, 110011. [CrossRef]

31. Neary, V.S.; Lawson, M.; Previsic, M.; Copping, A.; Hallett, K.C.; Labonte, A.; Rieks, J.; Murray, D. *Methodology for Design and Economic Analysis of Marine Energy Conversion (MEC) Technologies*; Sandia National Laboratories: Livermore, CA, USA, 2014; p. 261.
32. Bull, D.L.; Smith, C.; Jenne, D.S.; Jacob, P.; Copping, A.; Willits, S.; Fontaine, A.; Brefort, D.; Gordon, M.E.; Copeland, R.; et al. *Reference Model 6 (RM6): Oscillating Wave Energy Converter*; Sandia National Laboratories: Livermore, CA, USA, 2014; Volume 6.
33. Raj, N.; Bharathi, K. Electrical Networks of CorPower Wave Farms: Economic Assessment and Grid Integration Analysis. 2017. Available online: https://www.semanticscholar.org/paper/Electrical-Networks-of-CorPower-Wave-Farms-%3A-and-of-Bharathi/69f2210536eafcd242384b6d5c40d8a0f08c2e05 (accessed on 8 April 2024).
34. Kamidelivand, M.; Deeney, P.; McAuliffe, F.D.; O'Connell, R.; Mulcahy, I.; Murphy, J. Adapting Optimal Preventive Maintenance Strategies for Floating Offshore Wind in Atlantic Areas by Integrating O&M Modelling and FMECA. In Proceedings of the OCEANS 2023—Limerick, Limerick, Ireland, 5–8 June 2023; pp. 1–8. [CrossRef]
35. Judge, F.; McAuliffe, F.D.; Sperstad, I.B.; Chester, R.; Flannery, B.; Lynch, K.; Murphy, J. A lifecycle financial analysis model for offshore wind farms. *Renew. Sustain. Energy Rev.* **2019**, *103*, 370–383. [CrossRef]
36. Chen, J. Uniform Distribution: Definition, How It Works and Example. Investopedia, 2023. Distributions Are Probability Distributions, the Mean Occur More Frequently. Available online: https://www.investopedia.com/terms/u/uniform-distribution.asp#:~:text=Uniform (accessed on 8 May 2024).
37. Kamidelivand, M.; Deeney, P.; McAuliffe, F.D.; Leyne, K.; Togneri, M.; Murphy, J. Scenario Analysis of Cost-Effectiveness of Maintenance Strategies for Fixed Tidal Stream Turbines in the Atlantic Ocean. *J. Mar. Sci. Eng.* **2023**, *11*, 1046. [CrossRef]
38. McAuliffe, F.D.; Judge, F.; Kamidelivand, M. Modified Installation, Operations, Maintenance and Logistics Model for Irish and Welsh Wave and Tidal Technologies and Locations. 2022. Available online: https://www.selkie-project.eu/tools/wp8/ (accessed on 10 May 2024).
39. Lotovskyi, E.; Teixeira, A.P.; Soares, C.G. Availability analysis of an offshore oil and gas production system subjected to age-based preventive maintenance by petri nets. *Eksploat. Niezawodn.* **2020**, *22*, 627–637. [CrossRef]
40. Nguyen, T.A.T.; Chou, S.Y. Improved maintenance optimization of offshore wind systems considering effects of government subsidies, lost production and discounted cost model. *Energy* **2019**, *187*, 115909. [CrossRef]
41. The WAVEWATCH Development Group. *WW3DG. User Manual and System Documentation of WAVEWATCH III Version 6.07; NOAA/NWS/NCEP/MMAB Technical Note 2019; p. 311*. Available online: https://polar.ncep.noaa.gov/waves/wavewatch/manual.v5.16.pdf (accessed on 19 July 2024).
42. Chawla, A.; Spindler, D.M.; Tolman, H.L. Validation of a thirty year wave hindcast using the Climate Forecast System Reanalysis winds. *Ocean Model.* **2013**, *70*, 189–206. [CrossRef]
43. Copernicus. ERA5 Hourly Data on Single Levels from 1959 to Present (2022). Available online: https://cds.climate.copernicus.eu/%0Acdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview (accessed on 1 December 2022).
44. O'Connell, R.; Furlong, R.; Guerrini, M.; Cullinane, M.; Murphy, J. Development and Application of a GIS for Identifying Areas for Ocean Energy Deployment in Irish and Western UK Waters. *J. Mar. Sci. Eng.* **2023**, *11*, 826. [CrossRef]
45. Rusu, L.; Rusu, E. Evaluation of the worldwide wave energy distribution based on ERA5 data and altimeter measurements. *Energies* **2021**, *14*, 394. [CrossRef]
46. Neary, V.S.; Coe, R.G.; Cruz, J.; Haas, K.; Bacelli, G.; Debruyne, Y.; Ahn, S.; Nevarez, V. Classification systems for wave energy resources and WEC technologies. *Int. Mar. Energy J.* **2018**, *1*, 71–79. [CrossRef]
47. Rosati, M.; Henriques, J.C.C.; Ringwood, J.V. Oscillating-water-column wave energy converters: A critical review of numerical modelling and control. *Energy Convers. Manag. X* **2022**, *16*, 100322. [CrossRef]
48. Blain, L. Giant, Megawatt-Scale Wave Energy Generator to be Tested in Scotland. NEW ATLAS, 2022. Available online: https://newatlas.com/energy/oceanenergy-oe35-wave-power/ (accessed on 7 May 2024).
49. Nambiar, A.J.; Collin, A.J.; Karatzounis, S.; Rea, J.; Whitby, B.; Jeffrey, H.; Kiprakis, A.E. Optimising power transmission options for marine energy converter farms. *Int. J. Mar. Energy* **2016**, *15*, 127–139. [CrossRef]
50. Hamedni, B.; Cocho, M.; Ferreira, C.B. *Generic WEC System Breakdown*; Deliverable 5.1. The Structural Design of Wave Energy Devices (SDWED) Project; DNV.GL: Bærum, Norway, 2014; pp. 1–41.
51. Pecher, A.; Kofoed, J.P. *Handbook of Ocean Wave Energy. Ocean Engineering & Oceanography Volume 7*; Springer International Publishing: Berlin/Heidelberg, Germany, 2017.
52. Mérigaud, A.; Ringwood, J.V. Power production assessment for wave energy converters: Overcoming the perils of the power matrix. *J. Eng. Marit. Environ.* **2018**, *232*, 50–70. [CrossRef]
53. Bozzi, S.; Besio, G.; Passoni, G. Wave power technologies for the Mediterranean offshore: Scaling and performance analysis. *Coast. Eng.* **2018**, *136*, 130–146. [CrossRef]
54. Xu, X.; Robertson, B.; Buckham, B. A techno-economic approach to wave energy resource assessment and development site identification. *Appl. Energy* **2020**, *260*, 114317. [CrossRef]
55. Anderson, F.; Dawid, R.; Cava, D.G.; McMillan, D. Operational Metrics for an Offshore Wind Farm & Their Relation to Turbine Access Restrictions and Position in the Array. In Proceedings of the EERA DeepWind'2021, Trondheim, Norway, 13–15 January 2021. [CrossRef]
56. Kamidelivand, M.; Murphy, J. FMECA DataBase H2020 IMPACT D4.1. 2022. Available online: https://zenodo.org/records/7839861 (accessed on 10 May 2024).

57. Hamedni, B.; Ferreia, C.B. *Generic WEC Risk Ranking and Failure Mode Analysis*; The Structural Design of Wave Energy Device (SDWED) project. Deliverable D5.2; DNV GL: Bærum, Norway, 2014.
58. Rhinefrank, K. StingRAY Failure Mode, Effects and Criticality Analysis: WEC Risk Registers [Data Set]. 2016. Available online: https://www.osti.gov/biblio/1415597 (accessed on 5 January 2024).
59. Mueller, M.; Lopez, R.; McDonald, A.; Jimmy, G. Reliability analysis of wave energy converters. In Proceedings of the 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA), Birmingham, UK, 20–23 November 2016; Volume 5, pp. 667–672. [CrossRef]
60. Gueguen, S.; Fourmigué, J.-M. *Risk Assessment of Marine Energy Projects*; KTH School of Industrial Engineering and Management: Stockholm, Sweden, 2016.
61. Lopez-Mendia, J.; Ruiz-Minguela, P.; Rodríguez, R.; De Miguel Etxaniz, P.; Flannery, B.; Goodwin, P. Deliverable D6.2, OPERA—Operational Model for Offshore Operation of Wave Energy Converters—Open Sea Operating Experience to Reduce Wave Energy Costs. Available online: https://proactive-h2020.eu/wp-content/uploads/2021/04/PROACTIVE_20210312_D6.2_V5_PHE_Scenario-Development-and-Evaluation-Methodology_revised.pdf (accessed on 14 June 2024).
62. Ahn, D.; Shin, S.C.; Kim, S.Y.; Kharoufi, H.; Kim, H.C. Comparative evaluation of different offshore wind turbine installation vessels for Korean west–south wind farm. *Int. J. Nav. Archit. Ocean Eng.* **2017**, *9*, 45–54. [CrossRef]
63. Starling, M. *Guidelines for Reliability, Maintainability and Survivability of Marine Energy Conversion Systems. Marine Renewable Energy Guides*; European Marine Energy Centre: Stromness, Scotland, 2009.
64. Jusoh, M.A.; Ibrahim, M.Z.; Daud, M.Z.; Albani, A.; Yusop, Z.M. Hydraulic power take-off concepts for wave energy conversion system: A review. *Energies* **2019**, *12*, 4510. [CrossRef]
65. Coe, R.G.; Ahn, S.; Neary, V.S.; Kobos, P.H.; Bacelli, G. Maybe less is more: Considering capacity factor, saturation, variability, and filtering effects of wave energy devices. *Appl. Energy* **2021**, *291*, 116763. [CrossRef]
66. DNVGL-RP-203. Fatigue Design of Offshore Steel Structures- Recommended Practice. 2021. Available online: https://www.dnv.com/oilgas/download/dnv-rp-c203-fatigue-design-of-offshore-steel-structures.html (accessed on 5 April 2024).
67. Mortazavizadeh, S.A.; Yazdanpanah, R.; Gaona, D.C.; Anaya-Lara, O. Fault Diagnosis and Condition Monitoring in Wave Energy Converters: A Review. *Energies* **2023**, *16*, 6777. [CrossRef]
68. ROMEO-D2.1. Failure Mode Diagnosis/Prognosis Orientations. No. 745625, 2020. Available online: https://www.romeoproject.eu/wp-content/uploads/2019/06/D2.1_ROMEO_Failure_mode_diagnosis_prognosis_orientations.pdf (accessed on 8 February 2024).
69. Marie-Antoinette, S.; Borisade, F.; Espelage, J.; Johnson, E.; Vicente, R.D.; Munoz, S.; Hylland, P.; He, W.; Urbano, J.; Comas, F.J.; et al. COREWIND D4.2 Floating Wind O&M Strategies Assessment. no. August, 2021. Available online: http://corewind.eu/wp-content/uploads/files/publications/COREWIND-D4.2-Floating-Wind-O-and-M-Strategies-Assessment.pdf (accessed on 19 July 2024).
70. Aderinto, T.; Li, H. Review on Power Performance and Efficiency of Wave Energy Converters. *Energies* **2019**, *12*, 4329. [CrossRef]

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