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Economic Viability of Implementing Structural Health Monitoring Systems on the Support Structures of Bottom-Fixed Offshore Wind

Mario Vieira [1,2,*], Brian Snyder [3], Elsa Henriques [2], Craig White [1] and Luis Reis [2]

[1] WavEC Offshore Renewables, Edifício Diogo Cão, Doca de Alcântara Norte, 1350-352 Lisbon, Portugal; craig.white@wavec.org
[2] IDMEC, Instituto Superior Técnico, University of Lisbon, Av. Rovisco Pais nº1, 1049-001 Lisbon, Portugal; elsa.h@tecnico.ulisboa.pt (E.H.); luis.g.reis@tecnico.ulisboa.pt (L.R.)
[3] Department of Environmental Sciences, Louisiana State University, 1002-Q Energy, Coast & Environment Building, Baton Rouge, LA 70803, USA; snyderb@lsu.edu
* Correspondence: mario.vieira@wavec.org

Abstract: Offshore wind (OSW) energy is a renewable source with strong prospects of development that may decisively contribute towards energy independence. Offshore wind is, however, not yet ubiquitously cost competitive, and frequently requires support schemes to finance its extensive capital requirements. Therefore, cost reduction strategies are necessary for the future development of offshore wind technologies. Even if structural health monitoring (SHM) systems are currently applied for the inspection of critical mechanical structures, they have not been the focus of research from offshore wind stakeholders. The main goal of this study is to evaluate the viability of SHM systems on the support structures of bottom-fixed offshore wind (BFOSW), alongside the impact of implementing these systems on life-cycle. Economic models are used to estimate the impact of implementing these systems, explained using a case-study of the Kaskasi farm in the German North Sea. General results indicate that installing SHM systems on the support structures of offshore wind can shift the maintenance strategies from preventive to predictive, allowing the intervals between inspections to be increased without a reduction on equipment availability. The greatest benefit is related with the possibility of extending the operational life of the farm.

Keywords: offshore wind; structural health monitoring; cost modelling; cash flow analysis

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1. Introduction

The energetic paradigm is changing towards a low-carbon society, and Europe has been the leading force pushing this transition. The European Union (EU) has defined a 20% global quota for renewable energy sources by 2020 and 32% by 2030 [1,2]. Scenarios for 100% renewable use by 2050 have been evaluated [3] and the EU has called for countries to become carbon neutral within that timeframe [4]. OSW is an excellent energy resource due to stronger, more consistent, and less turbulent winds compared to the onshore resource. Furthermore, there are extensive areas offshore available for the installation of wind farms. For Europe, estimations are pointing towards a potential capacity of 150 GW by 2030 and 460 GW by 2050 [5,6]. Moreover, countries with large economies including the United States of America (USA) and China have been investigating OSW as a tool for reducing their carbon emissions [7,8]. In shallow waters, the monopile solution is the most affordable, accounting for 81% of the turbines installed in Europe [9]. At greater depths, the monopiles become impractical as the imposed technical challenges result in costs that exceeds the cost of other solutions, namely, floating structures and jacket foundations [10,11]. Currently, floating foundations cannot compete within the offshore wind energy market due to their lower Technology Readiness Level (TRL) [5] with the capital expenditure

(CAPEX) for OSW implementation being historically higher than those of other renewable technologies, [12–15]. Until recently, this has required the use of policy support schemes which have granted fixed prices to cover the cost of energy production for OSW farms (OSWF). In fact, tariff support is often required to boost technologies that are not yet capable of competing on a level playing field, sector or market [16].

In the first years of offshore wind implementation, the most common tariff support scheme for OSW was based on fixed compensations per unit of energy produced [17]. However, different sources have shown that fixed-tariff schemes were not contributing to the competitiveness on the sector, as costs rose considerably for the final consumer. Lately, a different scheme has been utilized, where bidding tenders are opened for certain offshore areas (also called reverse auctions) [18]. The proposal that requires the lowest cost per unit of energy usually wins the tender and the respective company or consortium becomes responsible for overseeing the installation and operation of that specific farm. Recent projects yet to be installed in the North Sea have been issued without requiring any tariff support, or subsidy-free, acting as a milestone for these technologies [19]. Nonetheless, this situation is still an exception: Cost reduction is the number one driver for the OSW stakeholders so that these technologies may compete in the non-subsidized energy market.

From the perspective of the project manager, the life-cycle of an OSWF requires a long process of surveying, licensing, production, acquisition, installation, operation, and, finally, decommissioning. These life-cycle steps may be classified according to the expenses related to each step, which are presented in Figure 1. The respective cost breakdown, by life-cycle stage, is presented in Figure 2.

Development expenditures (DEVEX) are related to the processes produced prior to the installation of the farm. They represent, typically, a small slice of the farm overall costs—Figure 1. CAPEX are the costs associated with the materials required for the construction and operation of the OSWF. They include the costs of equipment, such as electric cable connections, turbines, and foundations, but also the cost of installation, the cost of capital, and the cost of insurance. According to the sources used on Figure 2, CAPEX is responsible for approximately three quarters of the levelized cost of energy (LCoE) of an OSWF.

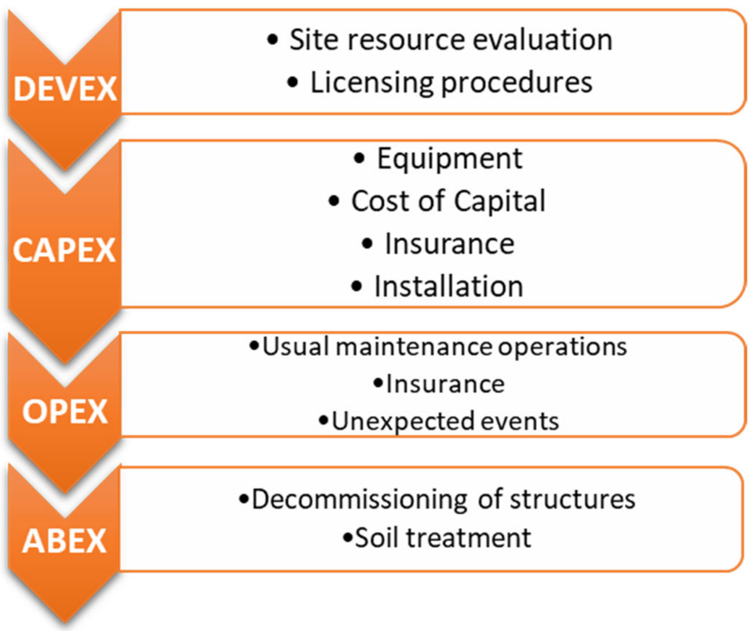

Figure 1. Life-cycle expenditures for OSW.

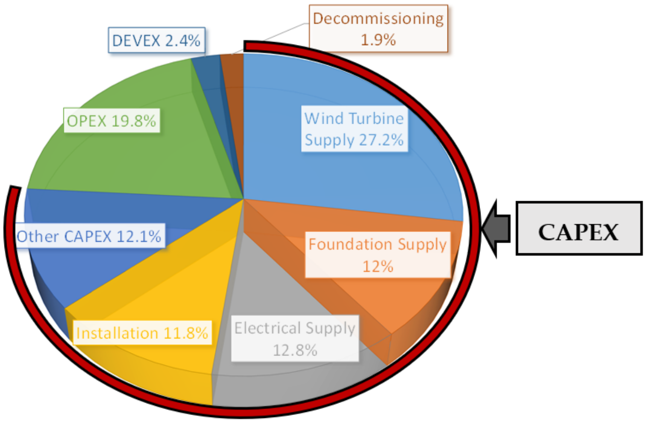

Figure 2. Cost Breakdown for Offshore Wind Levelized Cost of Energy. Data collected and adapted from NREL, The Crown Estate and TKI Wind op Zee [20–22].

Operational Expenditures (OPEX) relate to costs associated with the operation, maintenance, insurance, port activities, and licensing fees for the OSWF [23], and account for about one fifth of the LCOE of OSW. There are some opportunities regarding cost reduction for OPEX, including bigger turbines that will likely reduce OPEX as less turbines are installed for the same farm capacity [21]. Other strategies include developing inter-operator maintenance concepts [24]; introducing innovative parts which require less maintenance, such as direct-drive trains [21]; better mitigation of key risks due to accumulated operational experience [21]; and introducing complex condition monitoring to improve the maintenance of the frameworks currently used [21,25].

Finally, as the farm reaches the end of its useful lifetime, decommissioning processes are required to remove the turbine equipment and the respective foundations and cables from the seabed. International regulations define that these components must be fully removed, such as regulations stating that monopiles must be cut several meters below the mudline [26]. Nonetheless, these costs represent only a fraction of the total expenditures of a certain farm—around 2% according to Figure 2. This would be expected as the LCoE is a financially discounted measure of the cost of energy. Therefore, costs that are incurred at the end of the operation of the farm are highly discounted and have little impact on this LCoE calculation. Moreover, insurance surety bonds that will cover the decommissioning of the farm in case the project managing company cannot fulfil them, are now mandatory [27].

Several institutions have evaluated cost reduction potential for OSW, such as The Crown Estate [21], Fichtner [24], TKI Wind op Zee [22], and DNV [28], amongst many others, including academia, through internationally funded research projects. According to their conclusions, cost reductions can be achieved by efforts taken by the industry and the policy makers, both relying on their related administration actors, such as governments. Strong coherent policy frameworks should, therefore, be generated to provide the necessary stable regime to OSW utilities. On the technical side, technological innovation must be promoted, while at the same time increasing efficiency within several related processes—such as energy transmission, logistic procedures, and maintenance methods. One method to reduce costs of OSW is the implementation of structural health monitoring systems within support structures, to guarantee continuous monitoring of the condition and damage accumulation on these structures.

Structural Health Monitoring systems (SHMs) are instruments used in the inspection of the structural integrity of mechanical structures, with the main goal of acknowledging its health status, to guarantee safe operation and maximize equipment availability [29]. Compared to traditional methods of inspection, SHMs provides a more accurate and comprehensive understanding of the structural behavior and its condition. Traditional methods often rely on periodic inspections or visual assessments which may miss subtle changes or hidden defects. Furthermore, as larger farms are installed farther from shore, in deeper waters and in harsher metocean than the German portion of the North Sea (such as the Atlantic), the benefits of SHMs will become more evident [30]. Moreover, the SHMs facilitate predictive maintenance practices. By collecting and analyzing data on a continual basis, it becomes possible to identify early signs of deterioration and anomalies, allowing for proactive maintenance actions. This approach not only minimizes downtime and reduces repair costs but also extends the operational lifetime of offshore wind structures, maximizing their economic viability. These systems usually rely on the acquisition and processing of mechanical strains and vibrations, modal properties, thermal imaging, or corrosion rates [31,32]. They provide useful information to farm owners about the overall condition of the structure, allowing for more efficient operation and maintenance (O&M) planning and early acknowledgement of potential structural failures [33]. Ultimately, cost savings may be achieved from their use, but other related benefits, such as human life and reputation savings, can also be obtained. These monitoring systems are usually coupled to Supervisory Control and Data Acquisition (SCADA), which have been extensively used by the wind industry. These are specifically applied to failure-prone turbine components including the blades [31,34], generator, and drivetrain [35]. However, OSW turbine towers and their foundations have not been the extensive focus of these systems. Still, some developments have been made, which are indicated below.

Fischer and Coronado [36] from the Fraunhofer Institute for Wind Energy and Energy System Technology stated that SHMs for structural integrity of onshore and offshore wind structures are becoming more and more considered by the wind industry; in fact, they allow for a condition-based predictive maintenance. This is possible since SHMs can detect signs or indications that a functional failure may happen soon [36]. The BSH Agency (German Maritime and Hydrographic Agency) has already defined for German OSWFs mandatory SHMs on the foundations, in a cadence of 1 in every 10 turbines as defined on its standard [37]. A Standard produced by DNV-GL recommends the monitoring of the tower and foundation, although this is not yet mandatory [38]. Dai K. et al. have dedicated their research to the health monitoring of wind turbines, concluding that is fundamental to efficiently build bigger turbines [39]. The Block Island OSWF, the first in the USA, has a dedicated SHMs on the support structures specifically designed for structural performance assessment and fatigue life prediction [40].

Nonetheless, the OSW industry is not fully aware of the opportunities that arise with the implementation of SHMs on the support structures of OSW. In fact, the advantages of using these systems are not limited to operational procedures. Capital costs may decrease if the perceived risk of the project is lower, which may impact the insurance costs and the project's interest rates. Moreover, SHMs allow the determination of the remaining useful life of these structures, which is particularly relevant once the farm reaches its operational lifetime limit. If there is an opportunity to extend the lifetime of a certain farm, then thorough data regarding the condition of these structures is necessary to testify the feasibility of this life extension. Moreover, SHMs can provide useful data for designers to iterate future foundation designs: improved engineering designs are expected to result into economic savings.

This research introduces several innovative contributions that advance the current understanding of implementing SHMs on the support structures of bottom-fixed offshore wind. The key innovations and contributions of this research include:

- Development of a techno-economic analysis framework: This paper presents a comprehensive techno-economic analysis framework for evaluating the viability of SHMs on the support structure of bottom-fixed offshore wind farms. The framework takes into account various factors such as capital expenditures, operational risk reduction, maintenance optimization, life extension potential, and an overall economic feasibility;
- Incorporation of Monte Carlo simulations: The study employs Monte Carlo simulation methods to model and evaluate the performance of SHMs in offshore wind operations. The simulated random failure events and failure detection efficiencies provide a quantitative assessment of the impact of SHMs on the overall energy production and lifetime of wind farms;

- Integration of financial considerations: In addition to technical aspects, this research integrates financial considerations by assessing the cost-benefit analysis of implementing SHMs. By quantifying the trade-off between initial capital costs and long-term operational benefits, the study offers insights into the economic viability and potential revenue gains associated with SHM implementation.

These contributions collectively contribute to the existing body of knowledge by providing a comprehensive evaluation of the benefits and feasibility of SHMs in offshore wind energy. The findings of this research have significant implications for the design, operation, and maintenance strategies of offshore wind farms, ultimately fostering the growth and sustainability of this renewable energy sector.

This paper is structured into four main sections; Introduction; Methods; Results; and Discussion and Conclusions. The Introduction section provides an overview of the research topic and highlights the significance of implementing SHMs in bottom-fixed offshore wind energy. It presents the key objectives addressed in the study, as well as the innovations and contributions of the research. The Methods section outlines the approach and methodology employed, including the techno-economic analysis framework and the utilization of Monte Carlo simulation methods. The Results section presents the findings of the analysis, including the impacts of SHMs on capital expenditure, operational risk reduction, maintenance optimization, and overall economic feasibility for the case-study of the Kaskasi OSWF. Finally, the Discussion and Conclusions section interprets the results, discusses their implications, and highlights the contributions of the study to the existing body of knowledge. It also offers insights into the future directions of research and practical implications for the implementation of SHMs in offshore wind projects.

2. Methods

SHMs may impact different stages of the life-cycle and the respective operational cash-flow of a certain OSWF. Firstly, the implementation of SHMs increases the capital expenditures, due to acquisition and installation. Here, the CAPEX of a new farm is estimated using a model developed within this research. Indicative values for the cost of SHMs are provided, according to complexity of the considered system (more complexity can detect more failure modes, but with an additional cost). Then, a simulation model of failure events and their detection prior to the function loss is used to evaluate the impact of including these systems during operation. The detection efficiency of the SHMs is compared with the interval between physical inspections employed on a certain farm, amongst several other operational parameters. Moreover, a discussion on the influence of SHMs on the operational insurance costs is provided. In the end, a cash-flow model is used to discuss the viability of SHMs on OSW towers and foundations. Life-extension of the farm evaluated on the case-study is considered, and the respective economic benefits from this extension are discussed.

2.1. Capital Expenditures of Offshore Wind

Capital expenditures for OSW are currently declining, but this was not always the case in the past, where OSW CAPEX rose unexpectedly up to values higher than EUR 4 million per MW of new capacity back in 2016 [15]. Furthermore, impacts of the pandemic and the Ukrainian war still need to be considered in future models. In this research, the OSWF database [15] and an estimation model for future OSW CAPEX [41] are used. The number of farms and installed capacity per country considered on the said database is presented in Figure 3.

The CAPEX estimating model is based on multiple linear regressions built from the mentioned database, using as the explanatory variables three technical parameters of farms (Turbine Capacity, Average Depth, and Distance to Shore) together with two dummy variables (Rest of Europe, and Tripod and Jacket) that reflect the effect of different countries with different support policies and the effect of different foundations. The first takes the value 0 if the farm is installed in the UK, and 1 if elsewhere in Europe. The second takes the value 1 if a tripod or jacket foundation is used, and 0 if not (Table 1).

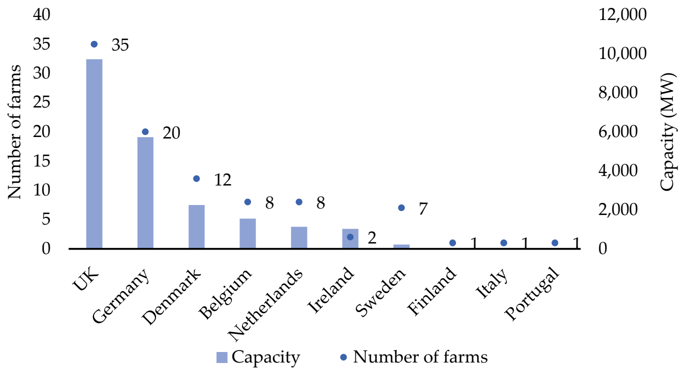

Figure 3. Capacity and number of farms considered for each European country by the Vieira M. et al. database [15].

Table 1. Explanatory variables for the multiple linear regression model presented in Equation (2).

Explanatory Variables	Units
Turbine Capacity (TC)	MW
Average Depth (AD)	m
Distance to Shore (DTS)	km
Rest of Europe (RE)	Non-dimensional (0 or 1)
Tripod & Jacket (TJ)	Non-dimensional (0 or 1)

Then, the non-technical influences affecting the CAPEX per MW of OSW, which can be caused by demand peaks, variations on price indexes, and changes within policy schemes, amongst other socioeconomic factors, are considered using an exponential trendline that connects the CAPEX/MW peak of OSW in 2016 (at 4.23 million EUR/MW) [15] to the value expected for OSW by WindEurope by 2030, at 2 million EUR/MW [42]—as shown in Figure 4. It is important to highlight that these three trends shown in Figure 4 reflect non-technical influences on CAPEX. Real Trend 79 was built by averaging the CAPEX of each farm for each commissioning year.

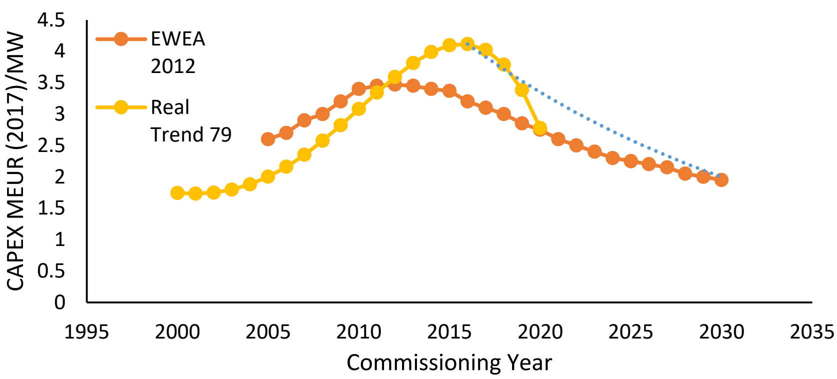

Figure 4. CAPEX/MW predictions from EWEA, actual behavior and the proposed scenario up to 2030 of the non-technical cost trend through an exponential curve (blue line) [15].

The CAPEX/MW estimation for a certain generic farm i can then be obtained using Equation (1):

$$\hat{R}_i = \frac{\widehat{\text{CAPEX/MW}}_i - T(y)}{\widehat{\text{CAPEX/MW}}_i} \tag{1}$$

where $\widehat{\text{CAPEX}/\text{MW}}_i$ is the estimated CAPEX per MW, $\hat{R}_i$ is a residual that reflects the difference between the non-technical cost trend assumed and the CAPEX of a specific farm, which reflects its technical influences (turbine capacity, distance to shore, etc.). This residual is calculated from Equation (2) by calculating the residual between each farm and the Real Trend plotted in Figure 4:

$$\hat{R}_i = -0.43 - 0.03355 \cdot TC + 0.0186 \cdot AD + 0.2078 \cdot DTS^{\frac{1}{3}} - 0.142 \cdot RE + 0.147 \cdot TJ - 0.00538 \cdot (DTS * AD)^{\frac{1}{3}} \quad (2)$$

T(y) is obtained from the exponential curve shown in Figure 4 and described in Equation (3):

$$T(y) = 1.397 \times 10^{46} \cdot e^{-0.052y} \quad (3)$$

This CAPEX estimating model has an explanatory power of 0.78 for existing farms, measured by the Pearson correlation coefficient as shown in Figure 5, which compares the real CAPEX of the farms included in the database, and the CAPEX estimated through the residual method.

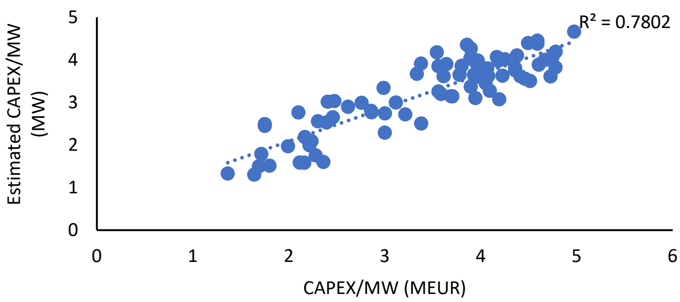

Figure 5. Correlation between real and estimated CAPEX/MW values.

Cost of Implementing Structural Health Monitoring Systems

To estimate the impact of SHMs on the capital expenditures, the intrinsic cost of acquiring and installing these systems needs to be estimated. Firstly, the failure modes associated with the support structures of OSW must be assessed and categorized. These failure modes were detailed based on the results from structural computational models and from operational failures occurring at real OSWFs for the monopile foundation [41]. When monitoring systems are not implemented, in-site inspections are used to evaluate evidence on the initiation or propagation of these failure modes. With SHMs, different dedicated systems can be deployed to detect them instead. During this research, several companies specialized in the manufacturing and installation of SHMs were approached. These contacts provided technical information regarding the market existing systems, as well as the associated qualitative costs for their implementation. These companies included DNV-GL (Høvik, Norway), FiberSensing—HBM (Porto, Portugal), Nortek (Providence, RI, USA), SamCon (Lohra-Altenvers, Germany), SPECMAN (Portuguese Brüel & Kjær representative) (Lisbon, Portugal), StrainLab (Stockholm, Sweden), SmartBolts (Frederick, MD, USA) and Zensor (Etterbeek, Belgium). Only the monopile foundation is analyzed in this research, as it accounts for 81% of the foundations used in Europe [9]. Other foundations will have different failure modes, which need to be independently evaluated.

Table 2 presents the failure modes considered for the monopile foundation support structures, and the respective estimated cost for a SHMs implemented to detect each mode. For the cash-flow model, this value is added to the CAPEX estimated from the model of Section 2.1, if a SHMs is implemented at the support structures of the tested farm. The proposed monitoring systems are technically detailed below:

Table 2. Failure modes considered for the monopile foundation support structures of OSW and the respective monitoring system.

Failure Mode	Description	Monitoring System	Approximate Cost (EUR)
1	**Monopile Buckling**	Stress Measurement	3000
2	**Scouring**	Acoustic Emissioners, Acceleration Measurement	38,800
3	**Grout Failure**	Stress Measurement	31,500
4	**Coating Failure Transition Piece**	Corrosion Rate Measurement	15,000
5	**Coating Failure Tower**	Visual Inspection, Corrosion Rate Measurement	22,250
6	**Crack at hotspot in Tower Door**	Stress Measurement	7500
7	**Failure at bolted connection TP—Tower**	Acceleration Measurement, Monitoring bolts	20,700
8	**Crack at hotspot in connection TP—Tower**	Acceleration and Stress Measurement	5300
9	**Failure at bolted connection Tower—Nacelle**	Acceleration Measurement, Monitoring bolts	20,700
10	**Crack at hotspot in connection Tower —Nacelle**	Stress Measurement	0 (Same system as Mode 6)
11	**Tower Buckling**	Stress Measurement	0 (Same system as Mode 6)
		Total System Cost (EUR)	**164,750**

Figure 6 presents the generic locations for the installation of the sensors dedicated to monitor scouring, the grout connection, and the dynamics of the tower. On the top of the tower, usually inside the nacelle and near the connection between the nacelle and the tower, an acceleration sensor is installed that allows the characterization of the dynamic behavior of the tower, such as its vibration shapes and modal frequencies. Below, next to the sea line, monitoring of the grout condition can be conducted using strain gauges which are installed at the top of the cementitious material, allowing measurement of the stress level subjected into it. Displacement probes may be included in the SHMs that measure the relative displacement between the TP and the monopile. This is a clear indicator of failure of the grout material, in the case relevant displacements are registered. In total, four strain gauges are considered here, as well as four displacement probes. Finally, three scouring monitors based on acoustic emissions are considered on the bottom of the transition piece, with the goal of measuring in real time the scouring depths around the monopile. These monitors have already been tested in conditions and are currently being used for several situations where scouring may represent an issue to structural integrity.

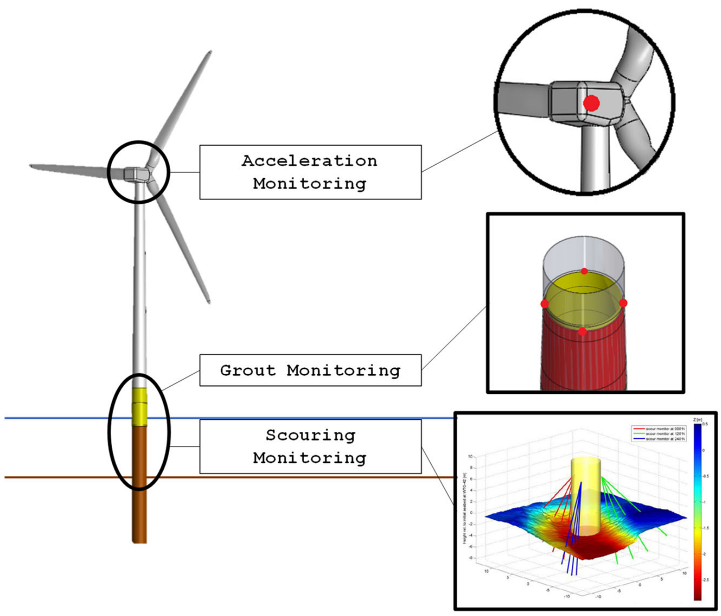

Figure 6. Scheme of the generic locations of monitoring system implementation for grout, scouring, and tower dynamics.

Figure 7 presents the generic locations for the installation of the sensors dedicated to monitor the bolted connections, the tower stress measurements, and the transition piece.

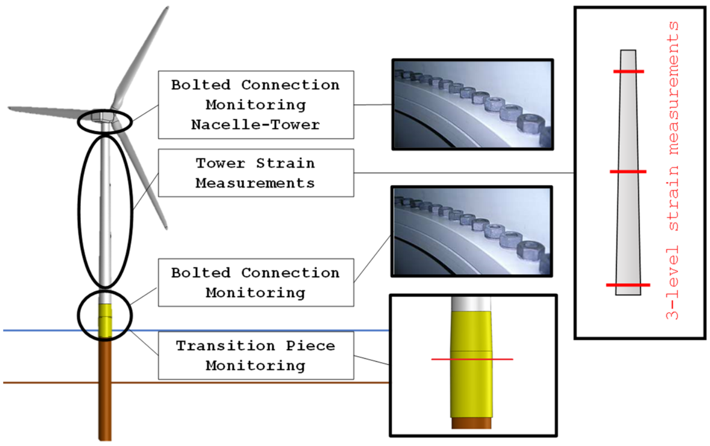

Figure 7. Scheme of the generic locations of monitoring system implementation for stress damage accumulation, bolted connection and grout monitoring.

Cracks and structural failures such as those caused by buckling may be detected using strain and acceleration measurements. Furthermore, strain measurements allow the characterization of the loadings subjected to the structures throughout time. Acceleration and strain data patterns may change when the rigidity of the structure is modified due to damage, which can be used to identify potential failures on the structure [43–45]. Here, the installation of strain gauges at a minimum of three different levels is proposed, with a cadency of 4 rosette-type strain gauges per level. Still, more levels could be added to raise the detail of loads measured. Rosette-type strain gauges are better suited than uniaxial strain gauges as these allow the determination of principal stresses and respective directions and of equivalent stresses [46]. As such, these can identify shear stresses applied to the tower, contrary to uniaxial gauges which are vertically aligned.

Both bolted connections: one between the nacelle and the tower; and the other one between the tower and the TP, are monitored using state-of-art monitoring bolts that provide information on the preload throughout the lifetime of the turbine. These solutions are currently commercially available from the companies Strain-Labs and Transmission Dynamics [47,48]; the general idea behind these systems is to monitor a certain number of bolts from a specific bolted connection. In this research, it is considered that half the bolts of a certain connection may be monitored, according to the experience provided by Strain-labs [47]. Furthermore, these bolted connections can be monitored from the analysis of acceleration patterns [49,50]. Thus, four accelerometers are installed per bolted connection. It is important to mention that in this document, it is assumed that the tower is a unique component. This is not always the case; many times, turbine towers are divided into different segments which are connected between each other using flanged bolted connections. These additional connections should also be monitored according to the described setup.

Finally, the monitoring of the transition piece is also proposed, including four rosette-type strain gauges at a predefined level. Moreover, an accelerometer may be included here to evaluate the vibrational level at the transition piece.

Figure 8 presents the generic locations for the installation of the sensors dedicated to monitoring corrosion rates on the turbine tower and transition piece. This can be measured using corrosion rate data loggers, using electrical resistance sensors to evaluate the corrosion speeds registered between two different points of the structure. These corrosion rate measurers are commercially available from some suppliers with offshore expertise, such as Zensor and Cosasco. For the suggested setup, two of these systems are installed, one for each support structure (transition piece and tower). Then, visual monitoring is suggested based on CCTV recording from three different cameras, to cover for the 360 degrees around the monopile. Finally, strain measurements on the monopile itself are also recommended to eventually detect signs of structural buckling.

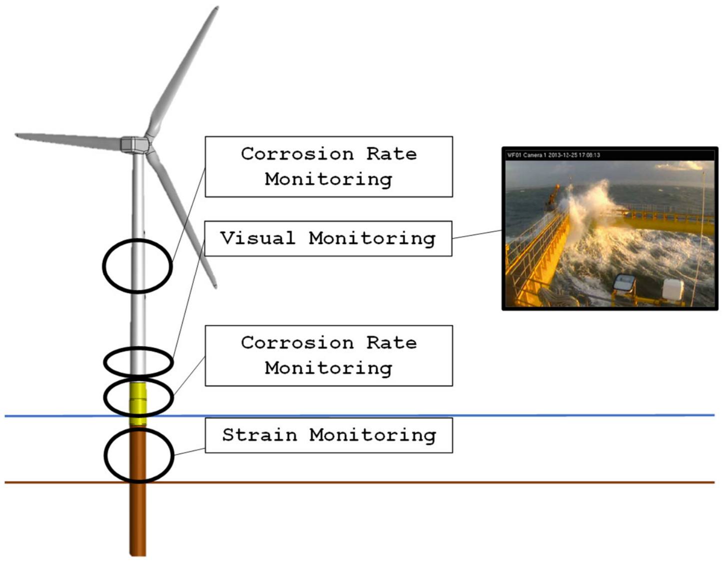

Figure 8. Scheme of the generic locations of monitoring system implementation for surveillance, corrosion monitoring and stress damage accumulation for the monopile.

2.2. Operational Expenditures

Structural Health Monitoring systems may decisively impact the costs associated with operation and maintenance, since they open the possibility of using more advanced maintenance strategies [51]. Failures occurring at the support structures of OSW may result in the catastrophic failure of the turbine, with obvious negative economic and reputational impacts. By continuously monitoring the structure, its condition can be acknowledged in real-time and its accumulated damage can be computed and potential failures can be detected early on, especially with the use of machine learning algorithms that process extensive operational data [52,53]. On the other hand, SHMs may also positively impact other processes; as it decreases the risk of a certain project, it can reduce expenses associated with operational insurance and; as it can be used as tool to estimate the accumulated damage on the support structures, it can help during life extension decisions.

2.2.1. Insurance Costs

There are few data available on the literature regarding the operational insurance costs of OSW. Therefore, six specialists from the insurance sector working with OSW were contacted and interviewed under small, structured interview conditions. These specialists highlighted how difficult it is to estimate the costs of operational risk insurance prices down to one number, due to the intricate influence of a multitude of factors. Furthermore, these costs appear to be decreasing year after year, as the technological maturity increases. Still, a range of costs were obtained, from 0.01 to 0.015 million EUR per MW of installed capacity per year of operation. Moreover, whilst some specialists admitted that any system which may help reduce the number of losses or minimize the impact of those losses will have a direct impact on the insurance cost, others stated that SHMs will have a limited effect on insurance costs since insurance providers are more worried about catastrophic events, such as storms and collisions. Nonetheless, SHMs were viewed by the experts as an advantage at the long run, especially because they allow for more effective maintenance strategies, but with little short-term impact. A decrease on the insurance costs caused by the implementation of SHMs was deemed very unlikely by some of the interviewees, while others admitted that such systems could reduce insurance costs at about a few percent.

Overall, the common opinion was that these systems can provide bigger advantages to farm owners on other processes rather than in insurance, and their use is highly recommended.

2.2.2. Simulation Model

Monte Carlo simulation methods involve the generation of random numbers to study interesting phenomena by considering the probability of specific events [54]. In this study, a Monte Carlo-based model is employed to assess the value of SHMs during the operation of offshore wind farms. The objective of this model is to estimate the total energy production of a wind farm over its lifetime. Failures in the support structures are assumed to occur randomly, with an annual failure rate of 0.18, consistent with the value estimated by James Carroll et al. [55]. The detection of failures depends on the monitoring efficiency of SHMs (SHME), whereby failures may or may not be detected randomly. In the absence of monitoring, failures may be detected during periodic on-site inspections conducted at a specific interval (interval between inspections—IbI). Regardless, the wind farm undergoes inspections at a designated IbI. Further details on this model can be found in Vieira M. et al. [56].

In Figure 9, the sequence of events for a turbine without Structural Health Monitoring (SHMs) is illustrated. During operation, a potentially critical failure arises under Mode 6. Despite the absence of SHMs, a subsequent inspection successfully resolves the issue. However, another potentially critical failure emerges under Mode 9. In the subsequent time step, the turbine experiences an irreversible failure.

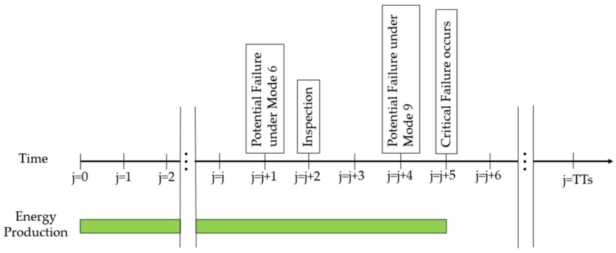

Figure 9. Flow of events over time for a turbine without SHMs. Adapted with permission from Ref. [56]. 2022, Elsevier.

In contrast, Figure 10 depicts the sequence of events for a turbine equipped with Structural Health Monitoring (SHMs). While in operation, a potentially critical failure arises under Mode 6, which is promptly detected by the SHMs. Consequently, the turbine is promptly shut down, and maintenance operations are conducted to address the situation. Subsequently, another potentially critical failure emerges under Mode 9, which goes undetected by the SHMs. Nonetheless, the issue is successfully resolved during the subsequent inspection, ensuring the turbine returns to a fully operational state.

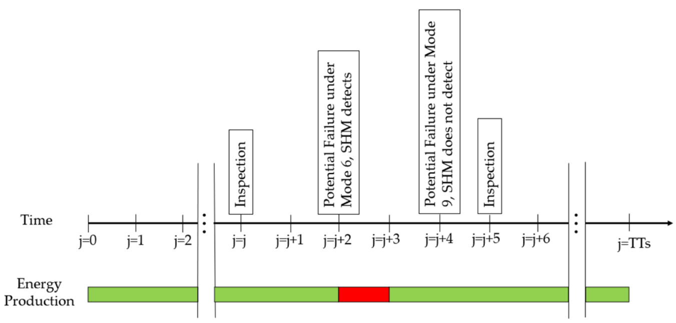

Figure 10. Flow of events over time for a turbine with SHMs. Adapted with permission from Ref. [56]. 2022, Elsevier.

Figure 11 illustrates the average outcomes derived from ten model runs for a representative wind farm comprising one hundred 5-MW turbines, with a typical capacity factor of 40%, operating for 25 years. These results demonstrate the fluctuation in the overall energy production of the wind farm based on the interval between inspections (IbI) and the detection efficiency of the SHMs (SHME). They indicate that a higher SHME and a lower IbI contribute to increased energy production for the farm. Additionally, the findings reveal that implementing SHMs with a significant SHME (above 0.6) enables the extension of IbI without diminishing the overall energy production.

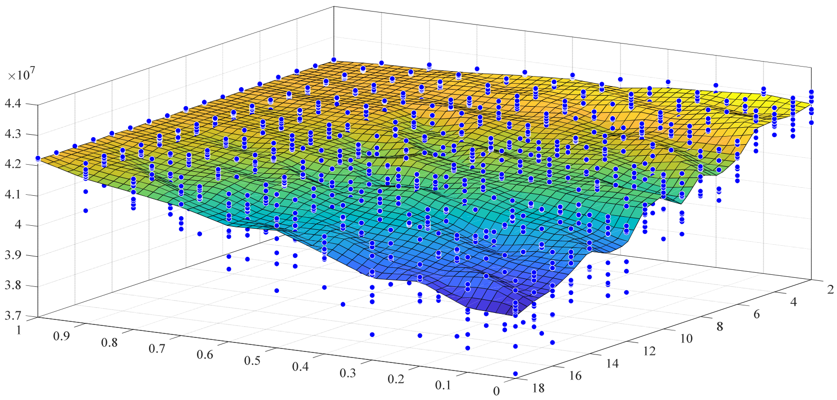

Figure 11. Total Farm Production variation with SHME and IbI obtained from the Monte Carlo model for a generic farm [56]. Blue dots represent the result obtained for each of the 10 runs produced. Reprinted with permission from Ref. [56]. 2022, Elsevier.

Results from Figure 11 do not consider electricity prices, nor the costs of inspecting and maintaining the farm. Inspecting a farm is an expensive operation that is also dependent on weather conditions. Figure 9 presents the earnings obtained from the same generic farm installed in 2020, considering the electricity prices estimated by BrainPool up to the year 2050 [57], and the inspection and maintenance costs estimated by Iain Dinwoodie [58].

Results from Figure 12 are considerably different from those of Figure 11, now that revenues, inspection, and maintenance costs are included. As shown, an IbI of 2 months strongly affects the farm earnings, mainly due to the costs associated with inspection. In fact, an SHME above 0.6 allows the use of longer IbIs, with higher earnings than those with no SHMs implemented for any IbI.

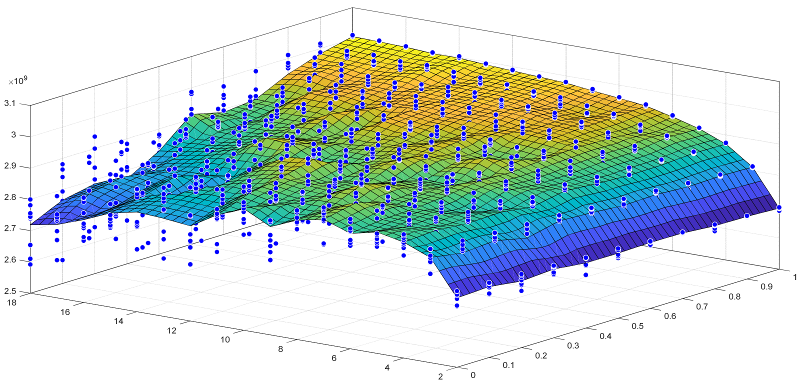

Figure 12. Total Farm Earnings variation with SHME and IbI obtained from the Monte Carlo model for a generic farm. Blue dots represent the result obtained for each of the 10 runs produced.

2.3. *The Cash-Flow Model*

Cash flow analyses are calculations that evaluate the in-and-out flows of money for a specific company or project. Moreover, they usually take into consideration taxes and the cost of money: more on this topic can be read in the literature [59,60]. In this section, the discounted cash flow model which analyzes the life-cycle stages that have are susceptible to the implementation of SHMs—construction, operation, and potential life extension—is presented. These stages are those where SHMs could more relevantly impact the OSW global costs.

Figure 13 presents the general framework of the developed model. Initially, the construction of the farm takes place and for that the farm owner must guarantee the necessary liquidity to fulfil payments to suppliers of equipment and providers of relevant services, such as farm installation. This CAPEX is estimated using the model presented in Section 2.1. Then, throughout operation, which is assumed to start two years after the beginning of the farm's construction, the operational revenue, expenditures, and insurance costs are considered, as well as debt payments and equity compensations.

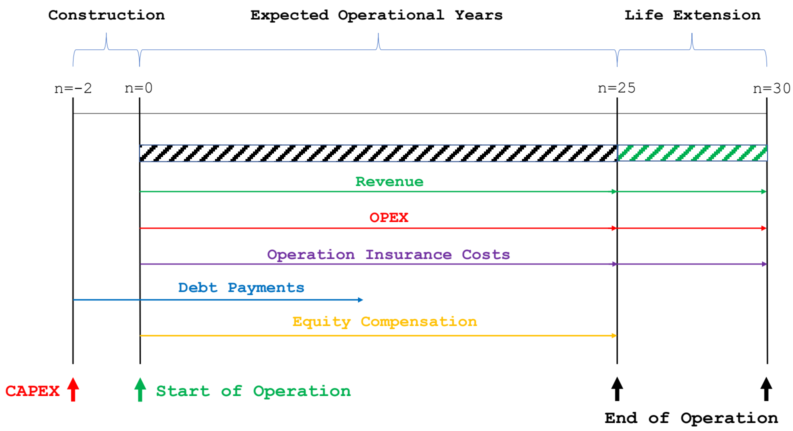

Figure 13. Framework of the cash-flow model developed, which considers three main life-cycle stages: construction, operation, and life extension.

Finally, the model assumes that monitored farms may have their lifetime extended for 5 years after the initially expected lifetime is reached. In fact, according to the respective standard from DNV-GL [61], extending the lifetime of a turbine requires the provision of documentation proving that the turbine still possesses the necessary structural integrity to endure additional operational years. SHMs should provide information on the accumulated damage throughout the expected operational years, plus be able to continuously monitor the structures during the additional extended period. Without them, life extension can result in additional uncertainties and risks, which will result in increased insurance and operational costs. Moreover, it is not clear that the certifying bodies would approve life extension periods on farms that do not provide strong evidence that the support structures will structurally sustain these additional years.

Discounted cash flows consider that money on hand today has a higher intrinsic value than money to be received in the future [60]. Grant Thornton, an independent accounting and consulting organization, has evaluated discount rates for OSW projects in different countries [62]. For the two OSW European leaders, it estimated levered discount rates of 8.25% for Germany and 8.75% for the UK. The industry is maturing through learning and scaling effects; therefore, a lower value of 6% will be considered for the discount rate on this research.

The non-discounted cashflow of a certain project for a certain expected operational life (OY) can be described through the following Equation:

$$nDCF_n = Debt + Eq - \mathrm{CAPEX} + \sum_{n=-CY}^{n=OY} (Rev_n - Ins_n - DebtPay_n - EquitPay_n - \mathrm{OPEX}_n) \quad (4)$$

where $Debt$ is the total debt contracted at the beginning of the project, Eq is the total equity used at the beginning of the project, and CAPEX is the total capital expenditures required to guarantee the commissioning of the farm. These three quantities are related with the start of the installation, which happens *CY* years prior to commissioning. *Rev* is the revenue obtained for each *n*-period, *Ins* is related to the operational insurance expenses taken at period *n*, *DebtPay* is the debt payment produced at the specific *n*-period, and *OPEX* are the operational expenses undertaken at period *n*. Likewise, *EquitPay* are associated with the compensations provided to the shareholders.

If the time value of money is considered in this analysis, then the discounted cash flow of the project follows:

$$DCF_n = Debt + Eq - \text{CAPEX} + \sum_{n=-CY}^{n=OY} \frac{Rev_n - Ins_n - DebtPay_n - EquitPay_n - \text{OPEX}_n}{(1+r)^n} \quad (5)$$

where *r* is the discount rate assumed for the project.

The model presented here estimates both non-discounted and discounted cash flows of a certain OSWF by calculating, year by year, the respective flows of money. The model assumes that debt payments start in the same year debt was contracted, and the duration of the loan is one of the model's variables. Compensations to the project's stakeholders are assumed throughout the expected operational period of the farm. These will have to be retrieved from the operational margin and decided by the company's management. The main input variables considered by the model are presented in Table 3:

Table 3. Generic Input variables used on the cash flow simulations.

Number of Turbines	NT
Turbine Capacity	TC
Construction Years	CY
Operational Years	OY
Debt to Equity Ratio	DB
Years to Pay Debt	YtD
Discount Rate	r
Cost of Insurance	CoI
Cadency of monitored turbines	SHMCad
Complexity of monitoring system	SHMC
Efficiency of SHMs Detection	SHME

Two different situations are analyzed in this research:

- OSWF monitored at its support structures;
- OSWF not monitored at its support structures.

Debt and Equity are considered to cover for the CAPEX of the farm. CAPEX is estimated according to the model presented in Section 2.1. Operational insurance costs are estimated according to the conclusions presented on Section 2.2.1, and the Farm Revenue and OPEX are estimated according to the Monte Carlo model outlined on Section 2.2.2 [56].

The model considers that the expected operational life of any farm is set at 25 years. The extension of the operational life of the farm is only considered for the cases where SHMs were installed at the support structures for an additional operation of 5 years.

3. Results

The results of this research are presented as a case-study that intends to estimate the impact of installing SHMs on the support structures of one installed OSWF. The selected farm was the Deutsche Kaskasi in Germany. All Euro currency values are updated to 2017, according to the Producer Price Index by OECD.

Kaskasi Offshore Wind Farm

Kaskasi was installed at the North Sea and was consented back in 2013. It was installed in 2021 and commissioning was completed in 2022. The main figures of this farm are presented in Table 4.

Table 4. Input variables used on the cash flow simulations for the Kaskasi OSWF—Part 1.

Kaskasi Offshore Wind Farm	
Country	Germany
Owner	Innogy SE
Capacity	325 MW
Turbine	Siemens Gamesa 8.0-167 DD
Number of Turbines	38
Foundation	Monopile
Commissioning Year	2022
Average Depth	21.5 m
Distance to Shore	48 km
Total Estimated CAPEX without SHMs	872 million EUR

Table 5 presents the values used on the variables of the cashflow model, whilst Table 6 presents the test cases evaluated for the Kaskasi OSWF.

Table 5. Input variables considered in the Cash Flow model for the Kaskasi OSWF—Part 2.

Operational Expenditures	20 EUR/MWh
Rest of Europe	1
Construction Years	2
Operational Years	25 (+5)
Debt to Equity Ratio	75/25
Years to Pay Debt	15
Discount Rate	0.06
Cost of Insurance	0.015 million EUR/MW/year
Efficiency of SHMs Detection	0.8
Total cost of the SHMs	6.4 million EUR

Table 6. Input variables considered in the Cash Flow model for the Kaskasi OSWF—Part 3.

	SHMs?	**Interval between Inspections (Months)**	**Operational Lifetime (Years)**
Test 1	**No**	**4**	**25**
Test 2	**No**	**8**	**25**
Test 3	**Yes**	**4**	**25**
Test 4	**Yes**	**4**	**30**
Test 5	**Yes**	**8**	**25**
Test 6	**Yes**	**8**	**30**

The main results from these tests are presented on Table 7:

Table 7. Main results for the six tested cases for the Kaskasi OSWF, in Million Euros.

	Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**
Revenues (million EUR)	1919	1915	1923	2404	1959	2440
Maintenance Costs (million EUR)	554.7	540.6	552	663.6	546.4	659.8
Insurance Costs (million EUR)	122.6	122.6	121.3	145.6	121.3	145.6
Equity Payments (million EUR)	233.4	233.4	233.4	233.4	233.4	233.4
Debt Payments (million EUR)	697.1	697.1	700.2	700.2	700.2	700.2
Total Expenses (million EUR)	1607	1593	1607	1743	1601	1739
Non-Discounted Cash Flows (million EUR)	312.2	322.7	316.2	661.4	357.2	700.9
Discounted Cash Flows (million EUR)	−87.4	−80.6	−87.8	−12.9	−68.9	5.1

The first interesting result to retrieve from these simulations is that, if 25 operational years are assumed and the farm possesses SHMs, the non-discounted savings with insurance costs may reach more than 1 million Euros, if a decrease of 1% in these costs is assumed. A decrease of around 6% on the operational insurance costs would be necessary to completely pay for the SHMs.

Figure 14 compares the non-discounted and discounted cash flows of the six tested scenarios.

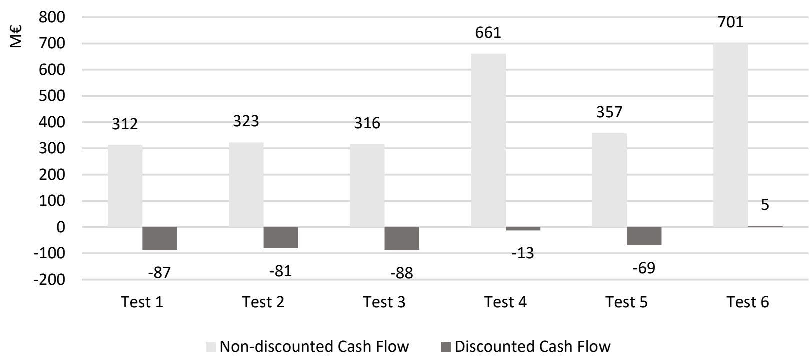

Figure 14. Non-discounted and discounted Cash Flows for the six test cases evaluated for Kaskasi OSWF.

The non-discounted cash flow considerably grows when the operational life of the farm is extended. Still, small rises are registered when SHMs are included, and no life extension is considered. Moreover, when SHMs are included, greater intervals between inspections also result in lower OPEX. For example, when comparing the non-discounted cash flow of Tests 3 and 5, a difference of around EUR 41 million is registered. This is a consequence of the costs associated with inspecting OSW, as discussed in Section 2.2. This benefit is not registered when the SHMs are not included (when comparing Tests 1 and 2), because the rise in the interval between inspections results in higher turbine losses, decisively affecting the energy output of the farm. The EUR 41 million already largely compensate for the installation of the SHMs on the support structures of OSW.

Finally, Table 8 presents the LCoE for the six evaluated Tests, plus the respective non-discounted costs of energy.

Table 8. Levelized costs of energy and non-discounted costs of energy for the tested cases of the Kaskasi OSWF.

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Levelized Cost of Energy (EUR/MWh)	128.65	129.24	129.62	121.38	128.52	120.34
Non-discounted Cost of Energy (EUR/MWh)	92.36	92.29	92.60	81.60	91.18	80.40

The advantages of using the SHMs are not immediately perceived from the analysis of the LCOE values. For example, the LCOE of Test 1 (no SHMs, IbI of 4 months) is only slightly higher than the one of Test 5 (SHMs installed and IbI of 8 months). However, if the non-discounted cost of energy is analyzed, then the economic benefits of implementing SHMs are more palpable. The same pattern is found for the rest of the Tests, with the costs of energy being lower than the levelized ones.

These results may be surprising but can be explained due to two issues: First of all, the LCOE is blinded to growing revenues over time, which are a consequence of the expected rise in electricity prices in Europe in the next years. In fact, the LCOE equation only considers the undertaken expenses and the overall energy produced by the farm. Furthermore, the LCOE is based on economic rules that overvalue soon-to-be revenues (which are proportional to the produced energy), and undervalue revenues/energy output which are to be obtained during an extended time span. In fact, SHMs may provide advantages, but these will most certainly be better perceived as the expected operational lifetime of a certain farm is reached. In the beginning of operation, the advantages of their implementation may not be immediately perceived.

Although these results do not intend to evaluate the attractiveness of the Kaskasi project, since the model makes a series of assumptions due to lack of operational data, some conclusions may be drawn from them. Life extension of the OSWF is decisively impacting both the discounted and non-discounted cash flows of the farm. The difference in the non-discounted cash flow between Tests 5 and 6 is greater than EUR 300 million (an increase of almost 100%). When these values are discounted, the differences are shrunk because the revenues from the extended operational period are highly discounted. Still, Test 6 is the only tested scenario which registered a positive discounted cash flow.

These results seem to indicate that:

- The impact of using SHMs on operational insurance costs can only cover for a small slice of the costs associated with the implementation of SHMs, around EUR 1 million (assuming a reduction of 1% on the insurance cost);
- Using SHMs allows the use of longer intervals between inspections, which may already bring relevant economic benefits, around EUR 41 million alone (an increase of almost 13% in the non-discounted cash flow;
- The opportunity of extending the operation of the farm for 5 years, which may only be possible with SHMs, will provide the biggest economic advantages to the farm owners. Doing so could add more than EUR 300 million of added revenue estimated on that operational extended period alone (an increase of almost 100%).

4. Discussion and Conclusions

This study has presented the development of a multidisciplinary and holistic research which was produced to understand the viability of structural health monitoring systems on the support structures of bottom-fixed offshore wind.

The costs associated with the implementation of SHMs on OSW support structures are relatively small when compared to the overall CAPEX of a certain farm, but are still relevant and were, therefore, discussed and estimated. Contacts with insurance experts were conducted, with diverging opinions on the topic. The present research assumes that marginal benefits can be obtained on the operational insurance costs by implementing SHMs, but these are probably not sufficient to totally compensate for their implementation.

The impact on maintenance expenditures may be relevant, as the intrinsic maintenance strategy can be shifted from a preventive into a predictive one. The produced Monte Carlo model provided results indicating that SHMs with good detection efficiencies can raise the necessary interval between inspections (IbI), whilst guaranteeing the same farm energy output. Moreover, when potential revenues and maintenance journey costs are included, the benefits of installing SHMs and increasing IbIs grew considerably. Furthermore, as operational extension life of existing farms can only be consented after the validation of several licensing and certifying bodies, and the respective equipment manufacturers, the data gathered by these systems can be used to provide the detailed condition and remaining useful life to these entities.

Whilst the implementation of SHMs has proved to bring relevant advantages by changing the maintenance strategy and by allowing the use of bigger intervals between inspections, the biggest economic benefit from implementing SHMs seems to come from generating the opportunity to extend the operational life of a certain OSWF. For the tested case-study, this opportunity resulted in additional non-discounted cash inflows of more than EUR 300 million for the Kaskasi OSWF. This value is not marginal and leaves no room for doubt: life extension should only be considered if enough turbines are still operating and if the SHMs installed on the support structures indicate that there are still relevant remaining useful lives to guarantee adequate operation for further years.

The findings of this study significantly contribute to and expand upon the existing literature in the field of offshore wind energy. Through the comprehensive techno-economic analysis produced, this paper proved the feasibility of implementing SHMs on the support structure of bottom-fixed offshore wind farms. In comparison to previous research, the main conclusions highlight the impact of SHMs on capital expenditure (CAPEX) by considering the cost of the system. However, the benefits derived from SHMs, including mitigating operational risk and optimizing maintenance operations, prove to outweigh the initial capital costs. Furthermore, this study goes beyond existing literature by emphasizing the potential for SHMs to provide valuable insight into acknowledging damage accumulation on the structures to support life extension decisions. By extending the operational lifetime of the wind farm, the true benefits of implementing SHMs emerge, leading to the generation of hundreds of millions in added revenue. Thus, this research fills a gap in the current understanding of the field by offering new perspectives and practical implications for future studies and the implementation of offshore wind projects. SHMs may also have impacts that are not immediately quantifiable, such as allowing for the iteration and improvement of current support structure's mechanical design. Moreover, offshore wind farms will continue to become bigger in capacity and farther from shore than the existing ones, and eventually unconstrained by the water depth with floating foundations. Eventually, regularly inspecting each turbine individually using technicians may become an impractical task, not humanely achievable nor economically viable. In the end, as the society converges into the concept of the Industry 4.0, the fourth industrial revolution, the OSW-related industries will need to keep up with the current industrial trends. It does not seem adequate to possess turbines more than 50 km off the coast, and not be able to acknowledge in real time the condition of the support structures that hold the turbine equipment in place.

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