Management of Wind Farms at the End of Their Lifetime

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Abstract:

Portugal, historically a pioneer in investing in renewable energies, is today in a paradoxical situation. While wind energy has consolidated itself as a fundamental part of the national electricity system, supplying around 25% of the country's electricity consumption, the sector is going through a phase of worrying stagnation in the development of new capacity. The owners of the parks find themselves in a "strategic limbo": the wind turbines reach the end of their projected lifespan (20-25 years) and the guaranteed remuneration contracts expire, but regulatory and economic uncertainty paralyzes action. The renewal of wind farms is considered "vital" for the new era of energy transition, but the lack of clarity prevents the decision making. This problem is compounded by the lack of decision support tools adapted to the Portuguese market. It is not possible to directly apply generic financial models or those imported from other jurisdictions, since Portuguese wind farms have a unique and heterogeneous "regulatory heritage". The motivation for this work, therefore, lies in the need to fill this gap: to develop a methodology that can reconstruct this complex history to rigorously quantify the economic viability of end-of-life scenarios, allowing developers to overcome uncertainty and decide the future of their assets. The main alternatives stand out: Life extension; Repowering; Dismantling. Two case studies were analyzed: a 5-turbine wind farm with a total installed power of less than 10 MW (Wind Farm A) and a wind farm with more than 35 wind turbines and an installed capacity of more than 100 MW (Wind Farm B). The results demonstrate that the feasibility of end-of-life strategies strongly depends on local wind conditions and terrain complexity. In Wind Farm A, characterized by moderate wind conditions, turbines operate below their design limits, resulting in reduced fatigue and preserved structural integrity. This confirms that life extension is a technically safe and viable option, although repowering could improve energy efficiency. In contrast, the analysis of Wind Farm B reveals non-compliant extreme wind speeds and turbulence levels, leading to accelerated structural degradation and reduced safety margins. In this scenario, life extension is not recommended and repowering or selective dismantling emerges as the only technically feasible solutions.

Keywords:

Wind farms; Site assessment; Life extension; Repowering; Decommissioning.

1. Introduction

The amount of energy that a wind farm can produce depends on several factors, namely the location, the number and size of the turbines, and the span of their blades. Over the years, the power of wind turbines has increased due to research and development in this field. In 1985, the most common turbine model had a capacity of 0.05 MW and a rotor diameter of 15 meters. Large wind energy projects currently are centered around turbines whose capacity exceeds 5 MW. In 2021, European wind farms generated 437 TWh of electricity, covering 15% of demand. Nonetheless, in several countries it exceeded 20% of electricity coverage, such as in Portugal (26%), Spain (24%), and Germany (23%) [1].

By 2030, approximately 65% of the installed wind capacity in mainland Portugal will reach or will be close to the end of its useful life. This scenario highlights the critical importance of studying and implementing strategies for the end of the life cycle of wind farms. [2].

Solutions such as life extension, repowering (replacement of equipment with more advanced technologies), and responsible dismantling might be key to ensuring the sustainability of the sector, maximizing the use of wind resources, while sustaining energy transition objectives [3,4].

1.1. Wind End-of-Life Options

When the farms approach the end of their useful life, 20 to 25 years, there is a need to pay attention to some strategies to know how the wind farm will be managed afterwards. The main alternatives stand out: Life Extension, Repowering and Dismantling. This is a complex decision, strongly conditioned by the availability of capital, the current state of the wind turbines involved, and the country where the park is located, since each one has its own regulations and specific remuneration mechanisms [5].

1.1.1. Life extension

The wind farms Life Extension aims to maximize the profitability of turbines through their improvement or replacement of certain components that allow the extension of its useful life. It is necessary to balance the annual income and the operating and maintenance costs. Extending the life of a wind power plant is not only an economic issue, but also a safety one. In this sense, the DNVGL-ST-0262 standard provides principles, technical requirements and guidelines to extend the useful life of onshore and offshore wind turbines [6–8]. To extend the life of wind turbines for each park, the feasibility of this alternative must be studied. For this purpose, there is a combination of methods and tools that aim to determine whether wind turbines can continue to operate safe and efficiently after the end of their projected useful life, which is typically 20 to 25 years.

To carry out this evaluation, several methods can be used, such as inspections, measurements, simulations and detailed analysis of the condition of the turbines and their components. To assess the overall condition of wind turbines, both visual and technical inspections are essential. These include direct observation of critical components such as blades, gearboxes, generators and towers [6].

Non-destructive inspections (NDT) consist of methods such as ultrasound, radiography, magnetic particle inspection or thermal imaging cameras (for detecting thermal failures) to identify internal defects without damaging the components. These techniques are especially valuable for verifying the structural integrity of blades and towers [9]. In addition, the use of drones equipped with high-resolution cameras or thermal sensors is increasingly used in the inspection of turbine blades. This technology makes it possible to detect failures and wear without the need to stop operation or expose technicians to risky situations.

Another approach is to carry out measurements and continuous monitoring of the performance and condition of turbines over time, a crucial factor in assessing the feasibility of extending the useful life. For this purpose, conditional monitoring is used, where sensors are installed in the turbines (such as vibration, temperature, pressure, torque and acceleration sensors) that allow continuous monitoring of the condition of the machines. These sensors help to identify anomalous conditions that may indicate excessive wear or impending failure. The data collected can be analyzed to predict failures and calculate the remaining service life of the components [10]. Vibration monitoring is also an important technique for detecting faults in rotating components, such as the generator and the main shaft of the turbine. Vibration analysis can identify wear on components such as blades, hubs, gearbox and main bearings [11].

Thermography can be used to identify anomalous heating points in critical components (such as the generator or gearbox), is an effective tool to detect problems before they become serious, helping to plan interventions before the total failure of components.

Computer simulation is a powerful tool for assessing the feasibility of extending the lifespan of wind turbines. It can be used to predict the behavior of turbines under different operating and environmental conditions. One of the types of modeling is fatigue modeling, since fatigue is one of the main factors that limits the useful life of turbines. Simulation, usually using finite element analysis, allows the structural response of turbines to operate under certain conditions, as well as different climatic loads. This process helps to estimate the remaining lifespan of key components such as the blades and turret [12].

To predict the remaining useful life and identify recurring failure patterns, the analysis of historical operational data plays an essential role. This analysis include reviewing the turbine's operational data, such as energy production, wind speed, hours of operation and maintenance. It should be analyzed if the turbine is undergoing accelerated degradation, in order to identify the need for maintenance or the replacement of critical components. A failure analysis can be carried out, where previous failures as well as the behavior of the components can provide information regarding the parts of the turbines that are most degraded [11].

1.1.2. Repowering

Repowering requires the total turbine replacement by new and more efficient ones, possibly with an increase in installed power. When turbines reach their lifespan, it is expected that the new wind turbines will allow a better use of the wind resources and, thus, an increase in production. This strategy has few advantages, as the oldest wind farms are usually in the best locations, but have the least efficient wind turbines [13].

The development of wind turbines designed for low wind speeds stands out, which allowed the use of areas previously considered inadequate. It is also important to note that these new machines are larger and have higher rated powers, replacing several old and lower power wind turbines that are at the end of their useful life. The replacement of several old wind turbines with a smaller number of more advanced units has major implications for operation and maintenance, reducing the operational complexity of the farms and reducing, above all, the costs associated with maintenance [5,14].

The possibility of relocating the turbines is another advantage of repowering. Based on the analysis of the wind data collected over the years, it is possible to install a new turbine in a different position in the same wind farm where the wind is stronger, increasing the energy yield. In addition, with the new technology, the connection to the power grid becomes safer, significantly reducing the occurrence of voltage peaks and frequency variations. In this context, the site assessment is particularly relevant. Nowadays, site assessment and resource analysis techniques are more advanced as they were at farm construction date, which may have led to installation decisions that today prove to be poor, or even risky, in terms of turbine performance and service life. Site assessment has evolved significantly over the past two decades, providing more accurate and personalized analysis to optimize turbine choice [15].

Repowering can result in a higher generation of electricity, which may require an evaluation of the transmission capacity and the grid infrastructure. For this there is a need to verify if the local electricity grid can accommodate the higher energy production of the new turbines without overload [16]. It is also necessary to evaluate whether the substations and electrical interconnection systems are available, in order to ensure that they can handle the increase in capacity without the need for major infrastructure upgrades. Finally, it is important to evaluate the stability of the grid as the most modern turbines require different forms of control [17].

1.1.3. Dismantling

The dismantling of the park occurs mainly when there is no capital for the maintenance of the park, or if it is no longer profitable. One of the challenges for correct dismantling is to ensure the best use of end-of-life equipment, whether it is the sale of the equipment in secondary markets or recycling. Currently, about 85-90% of the content of wind turbine dismantling can be recycled, including the towers, foundations, generators and gearboxes. One of the most challenging components to disassemble are wind turbine blades due to their size and material. Most of these components are concrete, cast iron and steel, which are easy to recycle, but blades are still a big problem. To combat this difficulty, a new "melting-turbine-blade" composite thermoplastic is being developed, using a thermoplastic resin that can be melted and reused, unlike thermoset resins [18,19].

The dismantling of a wind farm is a complex and highly technical process, which involves the dismantling and disposal of the equipment and infrastructure of a wind farm, with due consideration for environmental, economic, social and legal aspects [20,21]. This option involves the installation of substations, underground or overhead cables, transmission lines and the removal of the electrical cables connecting the wind turbines to the power grid. The foundations of wind turbines are robust structures that require specialized methods for their removal or destruction. Concrete can be reused for other purposes, while steel can be recycled [22].

1.2. Framework and Relevance of End-of-Life Assessment

The strategic decision on the end-of-life strategy of a wind farm cannot be based solely on economic and financial criteria. Before validating any profitability scenario, it is imperative to ensure the technical feasibility and structural safety of the assets in their specific operating context. It is in this context that the Site Assessment arises, a critical step to mitigate the uncertainty associated with the aging of wind turbines [23].

Unlike greenfield projects, where the evaluation of the resource is primarily aimed at estimating energy production, the re-evaluation of end-of-life parks has a dual purpose: safety verification and correction of historical inefficiencies. The need for a new site assessment is based on the issue that many of the pioneering wind farms in Portugal, installed more than 20 years ago, were designed without the specific assessment of site conditions that is required nowadays. As a result, there is a risk that some turbines are operating under high turbulence conditions or extreme gusts above those predicted in their original design, which can accelerate the degradation of components [3].

As established by the IEC 61400-1 standard and detailed in the life extension specifications DNVGL-SE-0263, it is mandatory to revalidate extreme weather loads and accumulated fatigue. Studies such as those by [4], demonstrate that computer simulation of site conditions is crucial to safely estimate the remaining useful life.

Alongside safety, re-evaluation plays a key role in the analysis of energy efficiency. In the early stages of wind development, the selection of wind turbines was often based on a conservative approach or limited availability of models, leading in many cases to an oversizing of the rated power compared to the actual available wind resource. This mismatch means that the park does not take advantage of the full energy potential of the place. Modern Site Assessment allows us to quantify this deficit, demonstrating that repowering is not only aimed at renewing assets, but also at correcting design inefficiencies, allowing the installation of turbines more suitable for the actual wind profile and maximizing production [24].

Wind farms site assessment underpins key decisions such as turbine selection, layout optimization, and long-term performance evaluation. It ensures technical compatibility and regulatory compliance, whereas during operation, it supports assessments for life extension, repowering, or overpowering opportunities. The site assessment evaluates the suitability of a specific wind turbine model for a given location by analyzing local atmospheric and terrain conditions. Key parameters include average wind speed, extreme gusts, turbulence intensity, vertical shear, flow inclination, and directional variability [25]. These are assessed against the turbine's design limits and IEC Wind Class criteria to identify any potential risks or constraints. The analysis also considers topographic features and surface roughness that may influence wind flow and turbine performance. Thus, accurate assessment of site-specific wind conditions ensures that selected turbines operate within their design envelope, minimizing technical risk and supporting optimal energy production [26].

The methodology for site assessment varies depending on the project phase, with different data sources used depending on the project [27]:

- When the wind farm is in the development stage, wind data is generally available only at the measurement station. As such, it is generally necessary to use appropriate wind flow models to perform both horizontal and vertical extrapolation – from the location and height of the measurement station to that of the wind turbines. This allows for the estimation of key wind parameters, including mean and extreme wind speeds, effective turbulence intensity, maximum flow angle, and wind shear.
- For operational wind farms, SCADA data is usually available for each wind turbine. This data may be used to determine the mean and extreme wind speeds directly at each wind turbine’s location and height – e.g., for a life extension, repowering, or overpowering analysis. However, this requires a sufficiently long dataset to characterize the long-term mean wind conditions at the site.

Thus, this research aims to obtain a comprehensive view of the state and future needs of wind farms in Portugal, based on effective and sustainable management of wind assets, especially in the context of their discontinuation or revitalization phase. Thus, a technical evaluation methodology was applied to specific wind farms in mainland Portugal to identify technical conditions for their respective scenarios. Two case studies were analyzed: the first one corresponds to a small size park, consisting of less than 5 wind turbines and with a total installed power of less than 10 MW and with an orography of moderate complexity, whereas the second wind farm corresponds to a park with more than 35 wind turbines, and an installed capacity of more than 100 MW, operating in a region of high orographic complexity in central Portugal.

2. Site Assessment Methodology

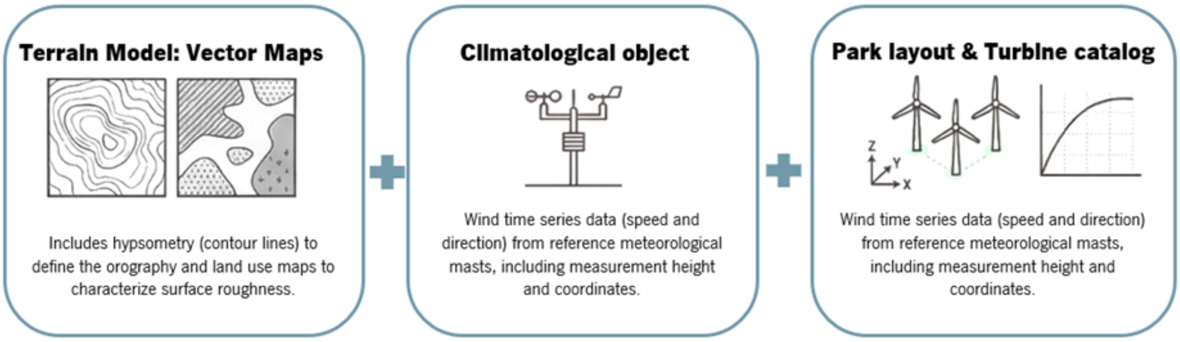
The assessment of wind potential and site conditions is based on a combination of analysis of observed data and computer modelling. However, the specific methodology varies depending on the stage of maturity of the project and the type of data available for the characterization of atmospheric flow. Within the scope of this research, the methodology adopted favors the use of meteorological mast data.

This approach allows the creation of a reference wind statistic model, Observed Wind Climate, which is extrapolated to the entire park through computational models. This option ensures that the validation of safety classes (IEC) and production estimation are based on calibrated meteorological measurements, which are critical for reliable life extension analysis. For the operationalization of this analysis, the computational workflow is structured in the sequential interconnection of four main modules, using the software suite developed by EMD International and DTU Wind Energy [28]. The specifics of each module and its application in this study are detailed in the following sections.

2.1. Average Wind Resource (WAsP) Modelling

The Wind Atlas Analysis and Application Program (WAsP) is the industry standard for flow modeling in terrains of moderate complexity. Integrated into the WindPRO workflow, this module uses a linear flow model (BZ-model) to solve the atmospheric flow equations, applying the "Wind Atlas" methodology. The operating principle is based on "cleaning" the local effects (orography, roughness and obstacles) of the data observed on the meteorological mast to generate a Generalized Wind Climate (Atlas). Then, the process is reversed to extrapolate this climate to the specific coordinates and hub height of each wind turbine, reintroducing the effects of the local terrain [29].

For the WAsP calculation and subsequent modeling of the resource, the software requires the integration of three fundamental categories of input data, shown in Figure 1 previously structured in the WindPRO interface.



Includes hypsometry (contour lines) to define the orography and land use maps to characterize surface roughness.

Wind time series data (speed and direction) from reference meteorological masts, including measurement height and coordinates.

Wind time series data (speed and direction) from reference meteorological masts, including measurement height and coordinates.

Figure 1. *Inputs for WAsP modeling architecture.*

WAsP is fundamental to characterize the average wind regime to which each turbine is exposed. The results obtained in this phase, which subsequently fed the compliance analysis, include [30,31]:

1. **Minimum inter-turbine distance**: Geometric verification of the layout to ensure that the spacing between wind turbines meets the minimum requirements (usually expressed in rotor diameters), preventing excessive losses due to wake effect and induced turbulence loads.
2. **Air density**: Calculation of the air density specific to the altitude of each turbine (corrected for local temperature and pressure), a variable that linearly affects the power curve and aerodynamic loads.
3. **Mean wind speed**: Calculation of the average annual speed at cube level, being the primary indicator of the energy potential and wind class of the turbine.
4. **Wind shear**: Estimation of the vertical wind speed profile, which directly influences the asymmetric loads on the rotor.
5. ***Weibull* parameters**: Determination of the scale and form factors of the *Weibull* probability distribution for each directional sector. These parameters define the long-term wind statistic at the turbine position.
6. **Frequency and directional distribution:** Characterization of the compass rose at each location, indicating the percentage of time that the wind blows from each sector (essential inputs for the calculation of fatigue due to turbine alignment).
7. **Energy contribution:** Estimate of gross and net Annual Energy Production (AEP), allowing the identification of turbines with a low-capacity factor (potentially oversized).

These parameters provide the park's climate "baseline". Yet, as the linear model of WAsP does not solve for weather-dependent turbulence or complex extreme winds, this data is complemented by WAsP Engineering.

2.2. WAsP Climate Analyst Modelling

While the classical WAsP focuses on the characterization of the mean wind regime (Weibull distribution), in this study, the WAsP Climate Analyst module is used with a specific objective for life extension evaluation. In this scenario for which the analysis of time series for the extreme winds' determination is of utmost importance. The correct estimation of extreme speeds is essential to verify whether the structural integrity of the turbines has been compromised. To do so, it was necessary to set up an analysis that would allow the statistical treatment of the raw data with the temporal resolution level [32].

While importing the data files, a filter of consistency needs to be applied, based on a certain threshold. A cut-off value of 0.5 m/s is defined for the velocity and direction channels. This filtering is technically necessary because, at very low wind speeds (below the threshold), the direction sensors tend to present erratic or stationary readings that do not reflect the actual flow, which may bias the directional statistical analysis.

For extreme winds the methodology considers the triangulation of different statistical approaches to mitigate uncertainty, namely, the Peak Over Threshold (POT), Annual Maxima (AM) and Spectral Correction (SC). The acceptance of the final values of extreme winds depend on the verification of internal consistency criteria.

In this study, a comparative analysis was carried out between the results obtained by the POT method and by the AM method. It was considered as a validation criterion that the final estimates for the same location should show convergence. Thus, discrepancies between the models were treated as indicators of potential anomalies, triggering a review of the process. Also, an analysis of the directionality of extreme winds was carried out to verify whether the turbines are exposed to storms coming from sectors where the orography can aggravate the loads (acceleration effects).

2.3. WAsP Engineering

WAsP Engineering (WEng) is the tool used to characterize instantaneous and extreme wind conditions that affect the structural integrity of turbines. This module uses the LINCOM[1] linearized flow model to solve the equations of conservation of mass and momentum over the terrain, allowing to estimate parameters such as flow inclination and environmental turbulence.

A key parameter at this stage is the grid resolution. To minimize discretization errors, the horizontal resolution was defined in line with the hub height of the turbines under analysis. Methodologically, the criterion was adopted that the grid resolution must be identical to or higher than the height of the machine. In addition, the boundaries of the domain have been adjusted to cover the complete area of influence of the park, ensuring that the boundary conditions do not interfere with points of interest. The simulations generate a set of spatialized physical variables critical for normative validation [29]:

- **Extrapolation of extremes:** The model projects the extreme wind field (calculated via POT) to the position of each turbine, combining climatological statistics with orographic acceleration factors. The final vertical profile is analytically adjusted with the local shear coefficient.
- **Flow inclination:** Mapping of wind incidence angles. Significant deviations from the horizontal, common in complex terrain, can induce aerodynamic loads for which the rotor was not designed for.
- **Environmental turbulence:** Estimation of turbulence intensity, isolating disturbances caused only by roughness and topography, serving as the basis for the subsequent calculation of total turbulence.

2.4. Wind Farm Assessment Tool

The final step of the computational workflow is performed in WAsP Assessment Tool (WAT). This module acts as the normative integration tool, where the modeled wind data (WAsP and WAsP Engineering) are cross-referenced with the design curves of the turbines to verify compliance with the safety requirements stipulated in the IEC 61400-1 standard.

The primary focus of this analysis lies in the calculation of the Effective Turbulence Intensity. Unlike environmental turbulence, effective turbulence results from the quadratic sum of background turbulence with additional turbulence induced by the wake of neighboring turbines. This parameter represents the actual aggressiveness of the flow to which the components are subjected.

The quality of the structural integrity assessment intrinsically depends on the robustness of the Ambient Turbulence Intensity matrix introduced in the model. To ensure the numerical stability of the model in extreme wind regimes, a conservative extrapolation technique was applied to the higher wind speed bin, discrete velocity intervals typically of 1 m/s, extending the validated turbulence curve to 30 m/s by replicating the last statistically significant values.

The final validation consists of the direct comparison between the effective turbulence curve calculated for the site and the certified design curve of the turbine (Class A, B or C). The verification that the local turbulence does not exceed the design limits in any speed bin is the vital technical indicator that underlies the physical feasibility of the asset's life extension.

3. Case Studies Parametrization

Following the computational workflow described above, this section provides a detailed technical characterization of the sites, including specific park specifications, turbine technology, and terrain constraints. For each case study, the results of the Site Assessment are presented in three steps:

1. Site Characterization: General description of the terrain and turbine technology.
2. Wind Resource Verification: Comparison between the measured conditions and the limits of the IEC Class (Oversizing Test).
3. Structural Integrity Check: Effective Turbulence Check (Safety Test).

The objective is to verify the technical feasibility of the service life extension by comparing the actual conditions of the site with the design specifications. In order to comply with the confidentiality restrictions requested by the wind farm operators, the specific names and exact coordinates of the sites have been anonymized.

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[1] LINCOM (Linearized Computation) is a spectral linear flow model that solves the linearized Navier-Stokes equations over complex terrain, specifically designed for turbulence and extreme wind estimation.

3.1. Wind Farm A: Small Capacity Park

The first case study is a Portuguese wind farm, with a small size, consisting of less than 5 wind turbines and with a total installed power of less than 10 MW, starting between 2005 and 2012, in operation in the Central Interior region of Portugal.

The site of implantation is characterized by an orography of moderate complexity, defined by smooth ridge lines and open valleys, with a land cover predominantly composed of undergrowth and shrubs, typical of transition zones to drier climates.

The park's infrastructure consists of a linear alignment of wind turbines. The technology selected for this project is based on a platform with 2.0 MW of nominal power, with a variable pitch regulated power adjustment system. The turbines installed are certified to IEC Class IIA, which means they are designed to withstand average winds of up to 8.5 m/s and extreme gusts ($Vref$) of 42.5 m/s. The main technical specifications of the fleet are presented in Table 1.

Table 1. *Technical characterization and turbine specifications of Wind Farm A.*

Specification	Value
Number of Wind Turbines	<5
Rated Power	2.0 MW
Total Installed Capacity	<10.0 MW
Design Class	IEC Class IIA
Hub Height	80 m

For the purposes of this evaluation, a time series of wind data from a meteorological mast installed on site (referred to as the Met Mast), located in a central position in relation to the layout of the turbines, was used, ensuring a high correlation with the wind resource felt by the machines. The schematic representation of Wind Farm A is represented in Figure 1.

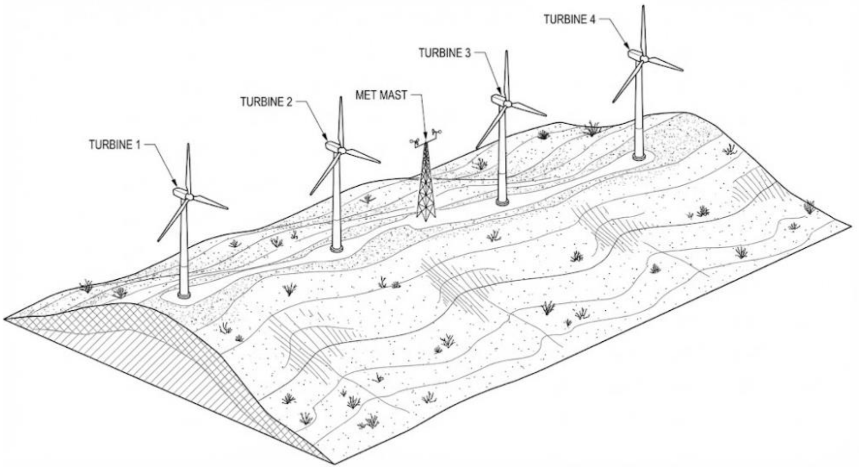

Figure 1. *Schematic representation of the layout of Wind Farm A and the meteorological tower (Image generated by computer model for anonymity preservation).*

3.2. Wind Farm B: High Capacity Park

Wind Farm B corresponds to a large wind farm, with more than 35 wind turbines, and an installed capacity of more than 100 MW. It operates in a region of high orographic complexity in central Portugal. This site is characterized by steep slopes and abrupt variations in terrain, factors that drastically influence wind runoff and the intensity of turbulence. Wind farm B is much larger than the previous one. This park consists of > 35 wind turbines, each with a nominal power of 3.0 MW. The turbines installed are certified to IEC Class IIA, which means they are designed to withstand average winds of up to 8.5 m/s and extreme gusts of 42.5 m/s. The main technical specifications of the fleet are presented in Table 2.

To carry out this analysis, wind data from a meteorological tower installed within the perimeter of the wind farm under study were used. Because it is a very complex terrain, the data from the Met Mast was extrapolated, through the WAsP, to calculate the specific conditions for each turbine. This step ensure that the effects of wind acceleration at the top of the ridges and in the steep slope areas, where the most exposed turbines are located, are correctly quantified.

Table 2. *Technical characterization and turbine specifications of Wind Farm B.*

Specification	**Value**
Number of Wind Turbines	> 35
Rated Power	3.0 MW
Total Installed Capacity	> 105.0 MW
Design Class	IEC Class IIA
Hub Height	80 m

4. Results and Discussion

This section presents the main results regarding the site assessment of both case studies under analysis. The analysis is based on wind resource verification and the application of WAsP Assessment Tool. The evaluation of the life extension potential begins by comparing the extreme weather conditions measured on site with the design limits set by the manufacturer for the turbine class.

4.1. Wind Farm A

Regarding wind resource verification of Wind Farm A, data analysis confirms that the site has Class IEC III characteristics (moderate winds, $V_{average}$< 8.5 m/s), despite being equipped with Class II machines (strong winds).This discrepancy highlights a structural oversizing of the wind turbines, in terms of safety it becomes positive, since the turbines have always operated below their load limits, saving the materials from excessive fatigue.

However, this compromises the efficiency of the park, since the turbines have rotors smaller than ideal for the site, wasting energy production potential. Figure 2 presents the structural graph for the representative turbine. The graphics were generated by the WAT software.

It shows the verification of structural integrity by comparing the site-specific conditions and the turbine design limits of a wind turbine representative of the wind farm under study. The blue curves shown in the figure illustrate the design boundary defined by the Normal Turbulence Model (NTM) according to IEC standards (in the case under study, Class IIA), representing the maximum turbulence loads that the turbine was sized to withstand. In contrast, the red line represents the Effective Turbulence Intensity (I_{eff}) of the location, calculated based on historical wind data.

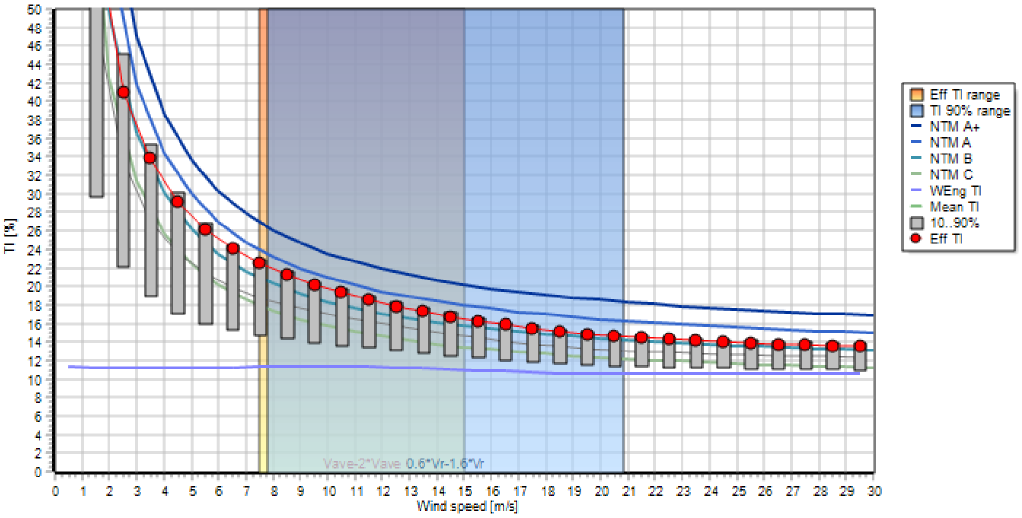

Figure 2. *Comparison between the site's Effective Turbulence Intensity (red line) and the IEC IIA Class Design Curve (NTM A line).*

The analysis demonstrates that the turbulence levels of the site remain below the design limit at all analyzed wind speeds (0 to 25 m/s). Given that turbulence is one of the main drivers of cyclic aerodynamic loads and fatigue on critical components (such as blades, turret, and transmission), this positive deviation between the actual loads (red line) and the design limits (blue lines) confirms the existence of a considerable margin of safety. This indicates that the turbine has been subjected to less fatigue data over its lifetime than its IEC class is able to withstand.

The preservation of structural capacity provides the technical validation needed to support the Life Extension strategy, confirming that the asset maintains sufficient structural integrity to operate safely beyond its initial 20 years. Table 3 summarizes the parameters calculated by WAsP Engineering at hub height.

Table 3. *Climatological comparison between Wind Farm A site versus Design limits*

Wind Parameter	Site Max Value	Design Limit	Verification
Extreme Wind Speed (V_{ref})	< 42.5 m/s	42.5 m/s	Compliant
Annual Average Speed ($V_{average}$)	<8.5 m/s	8.5 m/s	Compliant
Effective Turbulence (I_{eff})	≅17%	20%	Compliant

It is possible to verify that the IEC class of the table complies with the specific location of the wind farm. Although this result demonstrates a technically safe operation within the nominal parameters, it requires a strategic interpretation that transcends mere compliance.

It should be noted that structural validation focuses on the 15 m/s speed bin, which is critical for the definition of loads in the IEC standard. The software converts the reference face value (I_{ref}) into a Representative Turbulence limit applicable to this bin, which is 20%. Given that the Effective Turbulence of the site at 15 m/s is approximately 17%, it is confirmed that the wind turbine operates below the maximum expected fatigue limit. This technical compliance demonstrates safe operation and paves the way for a life extension strategy, allowing to maximize the return on the initial investment. However, the feasibility of this route requires in situ audits to validate the real state of conservation.

On the other hand, Repowering also reveals a missed opportunity in terms of aerodynamic efficiency (rotors too small for the existing wind). Repowering would emerge as the ideal solution to correct this, installing machines corresponding to the class of the site. However, this option faces barriers that transcend engineering. Licensing process for repowering is extremely lengthy and demanding, which combined with the high CAPEX, makes repowering a considerable strategic challenge given the simplicity of maintaining current assets.

In sum, Wind Farm A presents a scenario of high decision-making flexibility. The robustness of the technical results allows the asset manager to opt for life extension to minimize immediate costs, repowering to maximize technological efficiency (despite bureaucratic and financial obstacles), or planned dismantling if contractual or ground impediments arise. Thus, the final decision is not imposed by a failure in the integrity of the machines but requires a cost-benefit analysis that balances the technical health of the asset, the economic viability of the investment and the current legal framework.

4.2. Wind Farm B

The application of the site assessment process in Wind Farm B presents significant differences when compared to the Wind farm A. Although the average annual speeds remain in compliance with winds below 8.5 m/s, the analysis of extreme winds is no longer compliant.

During the simulations it was possible to observe that the orography induces extreme gusts that exceed that supported by wind turbines. Within this analysis, it was possible to observe that two of the wind turbines present in the park under study have gust values (return period of 50 years) higher than 52 m/s. This value classifies these positions as Class S (Special), far exceeding the safety limit of Class II (42.5 m/s) and even Class I (50 m/s). Figure 3 presents the structural graph (generated by the WAT software) for the representative turbine.

The blue curve represents the standard design boundary (NTM Class IIA), while the red line indicates the Effective Turbulence Intensity (I_{eff}) measured at the site. Unlike the previous case, the site conditions (red line) exceed the design threshold, particularly around the wind speed range of 15 m/s. This confirms that the turbines are operating outside their design envelope, subjecting the components to fatigue loads significantly higher than the certified limits. It is important to note that the effects of effective turbulence are not only due to the complexity of the site, or the high number of wind turbines, but also from the interference of neighboring turbines, which had to be considered in the study. Given the high density of installation in the region, the site assessment study must consider the impact of adjacent wind farms for the calculation of loads.

The analysis concludes that the Cumulative Wake Effect, coming from both the park's own 35 turbines and neighboring units, severely aggravates the intensity of incident turbulence. In the innermost positions of the layout, this effect adds to orographic turbulence, leading to high values of I_{eff}, which far exceed the design capability of Class IIA, accelerating fatigue wear far beyond what was predicted in an isolated scenario.

Consequently, this analysis demonstrates that the structural lifetime consumption was severely accelerated, and the safety margin observed in Wind Farm A did not exist.

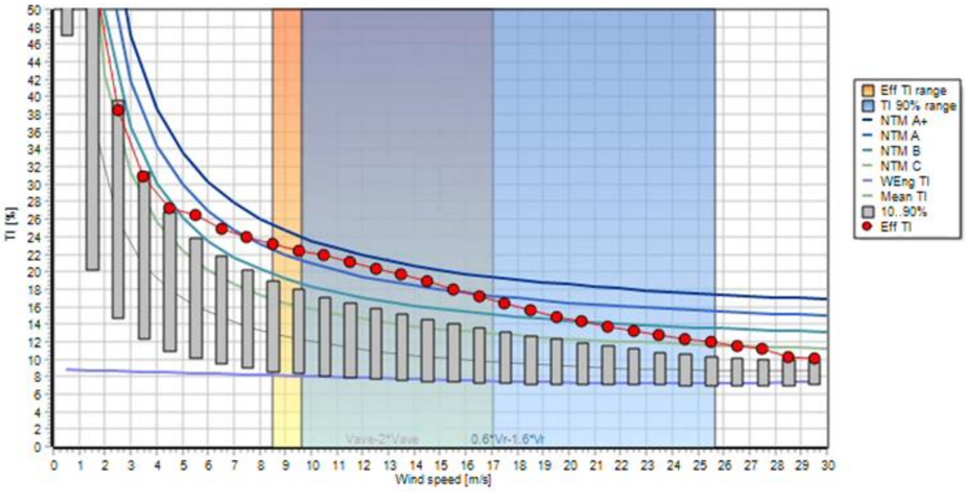

Figure 3. *Comparison between the site's Effective Turbulence Intensity (red line) and the IEC IIA Class Design Curve (NTM A line).*

From the point of view of the end-of-life decision, these results strongly advise against the Life Extension strategy, since continued operation under these excessive loads would exponentially increase the risk of catastrophic component failure. This scenario validates the need to transition to Repowering (with new technology adapted to higher turbulence classes) or Decommissioning as the only technically safe options. Table 4 summarizes the critical parameters calculated by WAsP Engineering at cub height.

Table 4. *Climatological comparison between Wind Farm B site versus Design limits*

Wind Parameter	**Site Max Value**	**Design Limit**	**Verification**
Extreme Wind Speed (V_{ref})	52.9 m/s	42.5 m/s	Non-compliant
Annual Average Speed ($V_{average}$)	7.6 m/s	8.5 m/s	Compliant
Effective Turbulence (I_{eff})	>20%	20%	Non-compliant

The comprehensive assessment of all turbine positions reveals that approximately one-third of the wind farm operates outside the IEC safety thresholds. These results obtained from the study of the site assessment originated different strategies from those adopted in Wind Farm A.

In this case, Wind Farm B, the option of extending life to the entire park is not a promising one. The identification of class S in wind turbines, with gusts above 52 m/s, suggests that these active turbines are subject to higher loads than those supported. When a machine reaches this level of fatigue or overload, life extension is no longer a problem of management and starts to require interventions. This means that structural damage or components replacement led to a high OPEX.

In wind farm B, repowering appears as a clear advantage, given the high number of existing wind turbines. This option would allow for a substantial reduction in assets. For instance, the park could be reconfigured to just 3 or 4 larger turbines (considering over-equipment). Consequently, this strategy results in a significant reduction in the total number of machines. Despite the licensing barriers already mentioned, repowering may appear as an opportunity to bridge the end of the feed-in tariffs (guaranteed remuneration). In Portugal, the end of tariffs coincided with the end of the park activity's life, so, a way to also overcome the impact of price reduction is to levelized the turnover by doubling the production. In this way, parks like the one in the case study can see repowering as an opportunity to maintain cash-flow.

From a safety point of view, the dismantling of critical units (Class S) is a technical imperative to avoid catastrophic failures. However, assuming the total dismantling of critical units would be not taking advantage of the existing wind potential. Thus, it is concluded that the dismantling of Wink Farm B should not be seen as the preemptive option, but rather as a mandatory intermediate phase to unlock Repowering choice.

5. Main Conclusions

The objective of this study was to apply a methodology to support decision-making regarding the management of wind farms at the end of their operational lifetime in Portugal. In particular, the work sought to evaluate the technical feasibility of three main strategies: life extension, repowering and dismantling. Uncertainty associated with aging assets and the regulatory and operational context of Portuguese wind sector was considered.

A site assessment methodology was implemented, combining observed wind data with advanced computational modelling. Meteorological mast data were used to establish a representative wind climate, which was then extrapolated across each wind farm using WAsP-based models. Additional analyses were conducted to estimate extreme wind conditions through statistical approaches and to characterize turbulence, flow inclination, and structural loads using engineering flow models.

The final step involved comparing the calculated site-specific conditions with turbine design limits defined by IEC standards through the Wind Farm Assessment Tool. This integrated workflow enabled a detailed evaluation of structural integrity, fatigue exposure, and overall compliance with safety requirements.

The results highlight the importance of site-specific conditions in determining the most appropriate end-of-life strategy. In the case of Wind Farm A, the analysis revealed that the turbines operate under less demanding wind conditions than those for which they were designed, resulting in a structurally conservative scenario. Turbulence levels and extreme wind speeds remain below the design thresholds, indicating reduced fatigue accumulation and preserved structural integrity. Consequently, life extension emerges as a technically viable and safe option, although repowering could improve energy efficiency by better matching turbine capacity with the available wind resource. In this case, the final decision should probably be influenced by economic and regulatory considerations rather than technical limitations. In contrast, Wind Farm B presents a more challenging scenario due to its complex terrain and higher exposure to extreme wind conditions. The analysis showed that both turbulence intensity and extreme wind speeds exceed the design limits of the installed turbines in several locations, leading to accelerated fatigue and reduced safety margins. A substantial portion of the wind farm operates outside IEC compliance, making life extension technically unfeasible and potentially unsafe. Under these conditions, repowering or selective dismantling becomes necessary, with repowering offering a strategic opportunity to replace outdated turbines with more suitable technology while maintaining or increasing energy production. In sum, while life extension may be appropriate in low-stress environments, more demanding conditions require a transition toward repowering or partial dismantling to ensure continued safe and efficient operation of wind energy assets

Overall, the study demonstrates that end-of-life management decisions for wind farms cannot rely on generic assumptions but must be grounded in detailed technical assessments of site conditions and turbine performance. The proposed methodology provides a reliable framework for such evaluations, enabling asset managers to balance safety and performance factors.

As future work, it is intended to develop a quantitative model to evaluate the net present value, internal rate of return and payback period of different end-of-life scenarios, considering the legislation, historical tariff regimes and forecasts of future market prices. This model will therefore complement the technical analysis and better support the decision-making process.

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