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Design for Repowering of Wind Farms: An Initial Framework

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Design for Repowering of Wind Farms: An Initial Framework

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Abstract. The need for clean and cost-effective energy sources is more pertinent than ever. Wind energy positions itself as a global contender in this role, offering a cost-effective and environmentally-friendly energy option. Furthermore, the wind energy industry is already starting to see numerous wind farms reaching 20+ years of life that require either repowering or decommissioning decisions to be made. Repowering offers many potential economic and sustainable benefits; however, many operators are faced with challenging decisions regarding whether to repower and how to optimally repower. This paper aims to address these challenges by introducing a novel comprehensive framework, known as "Design for Repowering". In Design for Repowering, wind farms of the future would be designed with planned repowering in mind. Through integration of multiple criteria, including health monitoring/sensors, digital twins, and social/environmental factors, we aim to address open questions about repowering, such as the optimal timing, strategy, and economics of repowering decisions. Furthermore, the framework is applied to several case studies, illustrating its potential for solving some of the long-term challenges expected in the future of wind energy.

1. Introduction

Globally, the need for renewable energy is growing, and wind energy serves as a frontrunner aiming to fill this need. The Global Wind Energy Council estimates that 680 GW of global wind capacity will be added between 2023 and 2027 [1]. At the same time, many wind farm fleets around the world are aging. In countries like Denmark and Spain, more than half of the cumulative capacity of onshore wind energy consists of turbines greater than 10 years old [2]. Close behind is the United States, where over 40% of turbines are more than 10 years old and approximately 6.5% are more than 20 years old [3]. Consequently, increased focus must be given not only to new installations, but also to end-of-life (EOL) considerations for existing projects.

When wind turbines reach EOL, there are three main options: 1) decommissioning, 2) life-extension, or 3) repowering [4]. The primary focus of this paper is on repowering, which refers to the process of retrofitting wind farms with new components/technologies or refurbishing existing wind turbines in some capacity. This can either include a full repowering process (replacement of the entire wind turbine) or a partial repowering process (replacement of only certain components) [5], as illustrated in Figure 1.

Repowering is of particular interest due to the unique benefits it can provide for an existing wind farm. Because wind farm repowering projects can utilize existing infrastructure and investments (grid connections, land leases, etc.), repowering greatly simplifies the process of installing or upgrading wind farm capacity [6]. This process can also overcome the economic, regulatory, and societal barriers that typically come with installing new wind farms. Despite the benefits of repowering, there is still uncertainty in decisions regarding repowering to be made by wind farm operators.

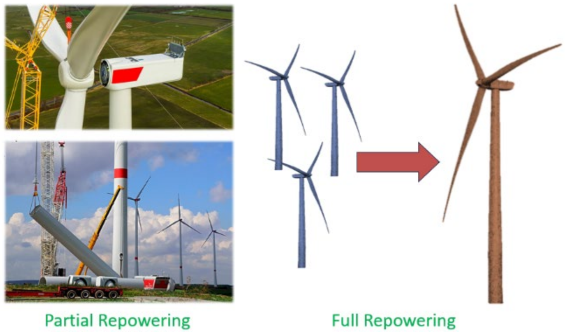

Figure 1: Partial Repowering vs. Full Repowering Process

This paper aims to develop a comprehensive repowering framework that can be used to "Design for Repowering" and thus address the uncertainties faced in repowering decisions. The benefits of such a framework are twofold: 1) this framework can be applied to existing wind farms to address open questions about repowering and best understand how to maximize real-time repowering benefits, and 2) the Design for Repowering framework has the potential to aid decision-making by wind farm operators and revolutionize the way we design future wind farms, with ultra-long life and planned repowering.

Ultimately, the full scope of this Design for Repowering research effort entails five key parts: (1) development of a Design for Repowering (DFR) framework, (2) initial LCOE screening to prioritize case studies, (3) development of DFR framework technical elements (e.g., over-building, health audit), (4) technical analysis of case studies including quantifying benefits of the technical elements (e.g., over-building, health audit), and (5) exercising the framework to optimize a repowering strategy. The scope set forth in this paper focuses primarily on points (1) and (2), laying out the initial repowering framework and LCOE screening to identify key case studies for Design for Repowering.

The remaining structure of this paper is as follows. Section 2 reviews current repowering literature and recent repowering decisions, drivers, and barriers. Section 3 discusses the need for a comprehensive repowering framework and outlines the initial development of such a framework. Section 4 illustrates several case studies to which this framework is applied. Section 5 discusses the results of the analysis, and Section 6 presents final conclusions on the topic.

2. Literature Review

While repowering is attractive as an option for extending or renewing wind farm service life, several aspects of repowering necessitate further study: 1) the financial benefits of repowering have yet to be quantified through a well-defined financial model, 2) repowering carries inherent risk due to the uncertainty in the reliability of age to-be-reused components (such as towers and foundations), and 3) the optimal timing and strategy for repowering projects has yet to be explored.

To better understand the repowering process, including what factors can affect repowering activity, it is necessary to conduct a thorough review of existing repowering and wind energy literature. The authors have identified six key topics pertaining to repowering that require further study, which are as follows: (1) Drivers, Barriers, and Feasibility, (2) Component Remaining Useful Life, (3) Health Monitoring and Sensors, (4) Optimal Strategy and Planning, (5) Techno-Economic Analysis, and (6) State of Wind Energy Reports. We address each of these in the following sections.

2.1. Drivers, Barriers, and Feasibility

Repowering as an EOL option necessitates a driver to guide the decision — in essence, there should exist some factors that guide developers towards repowering. Compared to decommissioning (the complete removal of a wind farm project) or life-extension (slightly increasing the lifespan of a wind farm), repowering holds many benefits, namely that existing project infrastructure coupled with reduced maintenance costs of new machines lead to higher returns on investments for project owners.

Purely economic or time-related considerations, however, may not be sufficient to fully understand repowering activity. In areas like Europe, non-price criteria such as sustainability, system integration, and European supply chain development are becoming increasingly popular for awarding permits for wind farms [8], demonstrating the importance of considering externalities for repowering decisions. Kitzing et al. [2] argue that in Denmark, repowering is far more complex than purely end-of-life considerations due to the influence of additional factors such as noise regulations, aesthetic concerns, political pressures, and space requirements. These factors, coupled with the fact that turbines in Danish repowering projects are dismantled an average of 5.8 years earlier than those in non-repowering projects, illustrates the complexity of making repowering decisions. Moreover, changing land restrictions can impede the widespread adoption of repowering, as in the case of Unnewehr et al. [16] where newly enacted exclusion criteria decreased projected repowering operating capacity by 40%. Still, repowering does have many decision drivers: Martínez et al. [7] conducted a life-cycle assessment of a repowering process and found that repowering old wind farms provides significant environmental benefits (approximately an order of magnitude of kg CO_2 savings) due to the increased capacity for clean energy production.

Studies focusing on the feasibility of repowering projects showed varied results: Jadali et al. [6] show repowering as an attractive option for offshore wind farms, leading to a 35-36.5% reduction in the levelized cost of energy (LCOE) compared to partial or full decommissioning scenarios. de Bona et al. [9] find that repowering in Brazil is most sensible for turbines that have nominal power below 2.0 MW. Some studies like Lantz et al. [5] find that in the United States, repowering becomes economically viable after around 20-25 years of wind farm operation. Other authors suggest shorter timespans for repowering that can even be as little as 10 years when economically incentivized [10].

2.2. Component Remaining Useful Life
One of the key metrics related to repowering is the remaining useful life (RUL) of a wind turbine component [11]. For partial repowering, RUL is essential to informing whether an aged component can function safely as required if reused, or whether it must be replaced during the repowering process. Typically, full repowering provides more value to a project than partial repowering [5, 12], in which case it is not as important to track RUL of components, as they are all replaced at end-of-life. However, tracking RUL for “planned repowering” cases can prove beneficial even in full repowering cases, as turbines can be replaced earlier than EOL if the RUL shows signs of degradation.

2.3. Health Monitoring and Sensors
In order to best inform a repowering decision, there exists a need for a proper health audit of a repowered farm, which ultimately necessitates strong health monitoring (HM) systems. HM systems are not currently widespread in most wind turbines, though Wymore et al. [14] find that economic benefits are likely to provide the greatest motivation for adopting health monitoring systems into these machines. Properly monitoring the health of a turbine allows for more informed maintenance, leading to a reduction in unexpected costs and downtime. Similarly, when it comes time to repower a wind farm, repowering can be done on a case-by-case basis as in the case of Liu et al. [13], where turbines in the most critical health categories are repowered first.

2.4. Optimal Strategy and Planning
In some repowering studies, the literature has attempted to develop and apply optimal strategies towards repowering wind farms. Liu et al. [13] describe an optimal repowering plan which evaluates turbine health based on dynamic degradation, taking the relative error between predicted and actual health values to determine the priority of turbine replacement. Their proposed method successfully lowers the LCOE of the wind farm by 2-8% relative to the baseline case where turbine health is not considered. Given these scenarios where some turbines in a farm may have poor health, non-EOL repowering shows promise as a repowering strategy.

2.5. Techno-Economic Analysis
Several studies exist on the techno-economic analysis of repowering scenarios. Abadie et al. [12] find that decommissioning is not a common option unless owners explicitly choose to do so or

permits/licensing expire. Villena-Ruiz et al. [15] conduct a techno-economic analysis of a real repowered project and conclude that the project yields satisfactory profitability, even without reliance on public subsidies. In this case, 69 wind turbines were replaced by just 7, with the same net capacity and double the Annual Energy Production (AEP).

2.6. State of Wind Energy Reports

Various reports on the state of wind energy focus not only on the projected growth in wind energy, but also the expected growth in repowering activity. According to WindEurope [17], yearly repowering volume is expected to grow from 1-2 GW in 2017 up to 5.5-8.5 GW by 2027, and over half of Europe's currently installed wind capacity will reach end-of-life by 2030. Wind energy installations and renewable energy needs are clearly growing, and the development of a repowering framework is needed to address the future of these wind energy projects.

3. Development of the "Design for Repowering" Framework

Repowering is a pressing topic in the wind energy community and will only become more pertinent as wind fleets around the world continue to age out. Given the growing significance of wind farm repowering, it is necessary to consider the long-term outlook of the repowering project space. To address this, we introduce a "Design for Repowering" (DFR) framework, in which the wind farms of the future are designed such that repowering becomes increasingly viable.

At a high level, DFR is a multi-criteria decision-making method used to design a wind farm with considerations for future repowering activity. DFR integrates the technical, economic, and social design criteria needed to support a farm over an extended project lifetime. The eight main factors considered for the DFR framework are shown in Figure 2 below and further discussed in the following subsections.

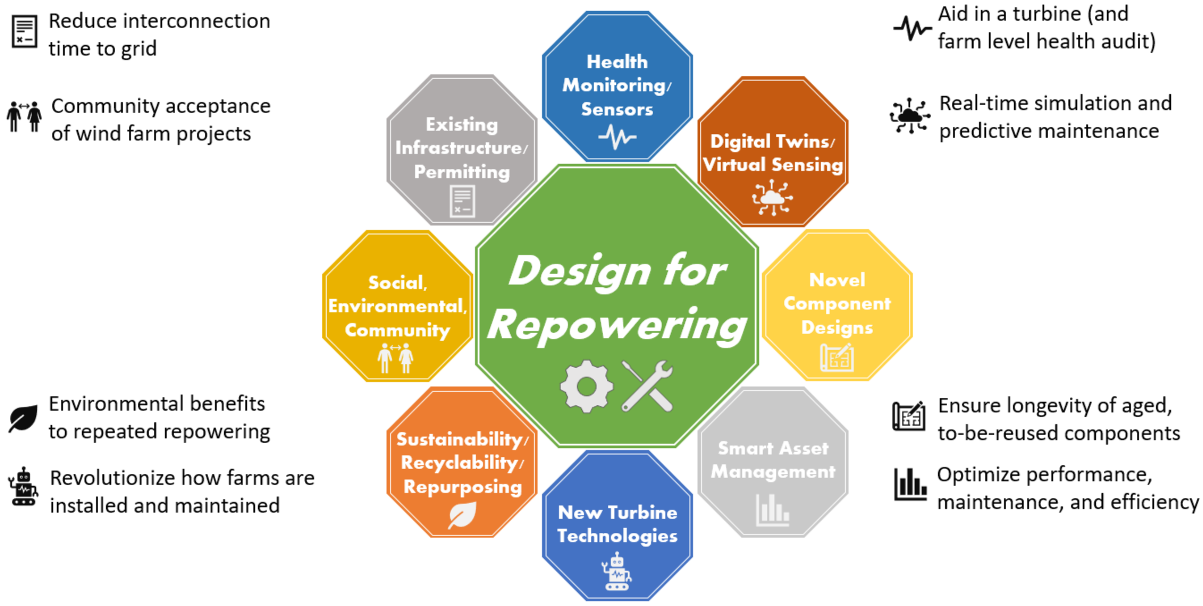

Figure 2: Considerations for Design for Repowering of Wind Plants

Given the wide range of turbines, siting factors, and uncertainties in future wind farm and turbine growth, DFR cannot entail a "one-size-fits-all" approach. Instead, the framework is developed as a broad guide aiming to integrate the various factors that go into repowering decisions. Although a wind farm designed for planned repowering may experience higher initial capital costs, we expect DFR to provide both economic benefits and non-financial benefits to wind farm owners/operators.

To account for future growth, we introduce the concept of "Future-Proof Structural Engineering" (FPSE), in which turbine components such as towers and foundations are over-built (i.e., over-designed) for a longer lifetime in the initial design phase, lending to increased re-usability for repowering projects, even if the turbine capacity is later upgraded.

Furthermore, the Design for Repowering philosophy holds significant merit even in scenarios where full repowering at EOL is common. These wind farms can avoid the inefficiencies and higher costs associated with unplanned repowering or decommissioning. In essence, DFR offers a strategic framework that maximizes the operational lifespan and efficiency of wind farms, either through repeated partial upgrades or comprehensive full repowering.

In the sub-sections that follow, we step through each of the eight aspects of the framework and elaborate upon its influence and integration into DFR.

3.1. Health Monitoring / Sensors

Central to the idea of “Design for Repowering” is the idea of continuous health monitoring and sensing to aid in a turbine (and farm level) health audit. Typically, the health of a wind turbine is assessed through manual inspection [19], which can be a time-consuming process prone to human error. Recent advances in inspection technologies have allowed for safer, more efficient inspection, such as drone-based turbine inspections, but this process is still tedious for a large wind farm and cannot provide continuous data on the health of a wind farm.

To facilitate efficient, real-time health monitoring, the DFR framework proposes the embedding of a sensor network within each turbine across the wind farm. This on-line sensor network enables continuous, automated monitoring, yielding advantages in terms of enhancing maintenance strategies and allowing for more informed repowering decisions. Knowing each turbine’s state of health allows for an optimal repowering decision to be made and takes out the majority of guesswork regarding when each component should be replaced. A wide range of sensing systems is proposed to provide a comprehensive understanding of each turbine’s health, including vibration monitoring, oil quality monitoring, strain sensing, SCADA data collection, blade root sensing, and wind speed (LIDAR) sensing [14, 21-22]. The integration of a comprehensive sensor network into each turbine, while incurring a higher capital expenditure (CapEx), has potential to provide significant cost-savings in terms of operational expenditures (OpEx) [20, 21-22]. These savings manifest primarily through the shift from reactive to preventative maintenance, which reduces both downtime and labor as well as their associated expenses. Nilsson and Bertling find that for a wind farm with 30 turbines, increasing uptime by 0.43%, or changing 47% of the corrective maintenance into preventive maintenance, would be enough to recoup the cost of a condition monitoring system [20]. Thus, the sensor-driven approach in the DFR framework is not just a technological upgrade, but a strategic investment into the long-term health, efficiency, and profitability of future repowered wind farms.

3.2. Digital Twins / Virtual Sensing

Coupled with health monitoring of individual turbines is the idea of using digital twins to maintain virtual, on-demand models of wind turbines. The advantage of using digital twins, particularly in the context of repowering, is that digital models allow for real-time simulation, predictive maintenance, and performance optimization of wind turbines and wind farms [23, 24].

The primary simulation tool envisioned within the DFR framework is OpenFAST, an open-source wind turbine simulation tool developed and maintained by the National Renewable Energy Lab [25]. OpenFAST provides an interface to several computational models for aerodynamics, control systems, and structural dynamics, among others. Coupled with condition monitoring data, these digital twin models can be augmented to better reflect their physical counterparts [19].

The relative difference of the turbine’s virtual, predicted state and its actual, monitored state provides the basis for a detailed turbine-level health audit. This methodology aligns with the approach taken by Liu et al. [13]. At a high level, the approach functions as follows: 1) the predicted and actual health of the turbine are evaluated, which provides the health condition estimation, 2) wind turbines are grouped into different health conditions based on threshold values, and 3) the wind turbines with the worst health are scheduled for maintenance or set to be decommissioned or repowered the soonest.

3.3. Novel Component Design Strategies
Given that the "Design for Repowering" approach considers significantly increasing wind farm lifespan, new component design strategies may be needed to ensure longevity of aged components such as towers and foundations. Typically, components are designed for a nominal 20-to-30-year lifespan, after which they must be replaced. With the implementation of FPSE, these components can be built stronger from the onset. In a scenario where repowering is planned for the project from the start, this allows for larger rotors and new technology to be implemented on top of the same structural components, even in the case where the turbine capacity is upscaled during repowering. Such a design approach can enable cost savings in the tower and foundation, enhancing the usefulness of DFR.

3.4. Smart Asset Management
Smart Asset Management (SAM) in the context of wind energy refers to the process of integrating smart sensors and advanced data analytics to optimize the performance, maintenance, and overall efficiency of a wind farm and its assets. One key aspect of SAM is predictive maintenance, which relies on data collected from smart sensors. As discussed in Section 3.1, these sensors continuously monitor the health and performance of each turbine, providing real-time data that can be used to predict potential failures or maintenance needs. Another critical aspect of SAM is performance optimization. These optimizations can manifest either through intelligent control strategies for wind farm power generation [26, 27], or by increasing the overall reliability of the farm [28, 29].

3.5. New Turbine Technologies
New turbine technologies have the potential to revolutionize the way wind farms are currently installed, maintained, and repaired. These technologies, when coupled with the DFR framework, can significantly enhance the efficiency and feasibility of repowering initiatives.

One innovative approach is the on-site deployment of crawler (self-hoisting) cranes as opposed to hiring large, traditional cranes [30]. This strategy could substantially reduce the costs and logistical complexities associated with replacement of large wind turbine components that have traditionally relied on enormous cranes to complete construction. Other technologies of note include hybrid energy storage solutions. Integrating wind energy with storage systems, such as battery storage, hydrogen production, or compressed air energy storage can allow for more consistent energy output and storage of excess energy [31]. Additionally, advancements in aerodynamic technology (e.g. vortex generators, plasma actuators, trailing edge modifications), have shown significant promise in increasing turbine performance [32] and/or extending operational lifetime by reducing stresses on turbine components [33]. Similar modifications on the trailing edge of wind turbine blades can be further employed to reduce their acoustic effects.

3.6. Sustainability / Reusability / Repurposing
The environmental advantages of the DFR approach are demonstrated in many of the following ways. First, the implementation of DFR can lead to reduced material usage and lower carbon emissions by optimizing the use of existing infrastructure, thereby diminishing the need for new materials and their associated environmental impact [34]. In addition to re-usability of existing infrastructure, turbine components (such as foundations and towers) can be re-used to provide even further cost savings and environmental benefits [35]. In general, wind farm repowering projects lead to higher capacity factors, generating additional energy while reducing land use [36]. Repowering also shows benefits to wildlife in terms of lower fatality rates compared to greenfield projects [37].

3.7. Social Concerns and Community Engagement / Benefits
In addition to technical and economic considerations, wind energy projects (whether new or repowered) should encompass a collaboration between project developers and community members. One challenge that greenfield developers face can be backlash from community members. In contrast, communities with existing wind projects are more accustomed to the presence of wind farms [17]. One benefit of

DFR is therefore the added community and social acceptance of renewing existing wind projects via repowering actions compared to engaging in greenfield development. Furthermore, DFR ensures job security for local communities through long-term job creation and providing continuous long-term revenue relative to a scenario where a wind farm is decommissioned after 20 years.

3.8. Existing Infrastructure and Planning

One of the main benefits of repowering projects is the ability to reuse existing wind farm sites, which provides a well-characterized wind resource, allows for reuse of existing electrical infrastructure, and greatly reduces or eliminates the time needed for permitting or grid interconnection. In the United States alone, over 8,000 energy projects were waiting for permission to connect to the electric grid at the end of 2021, and it takes on average four years for developers to get approval for this process [38]. One of the most crucial benefits therefore of the Design for Repowering framework is the ability to minimize the time spent waiting for permitting and regulatory decisions.

4. Application of the Design for Repowering Framework: Initial Economics Screening

The Design for Repowering framework is intended to be applied to gain insights on viability of different repowering options (e.g., to consider a novel, long life (40-100 year repower) wind farm concept, in which repowering is built in as a key consideration in the design of the farm) and, as noted in the Introduction, ultimately to optimize repowering strategies. However, it can also be applied to standard repowering cases (where a farm is repowered after 20 years, leading to a 40-year lifetime).

To analyze how the DFR framework can be applied to repowering, it is necessary to develop a series of "repowering scenarios" based on the assumptions and elements built into the framework. Here we introduce several scenarios and present an initial screening of the economics. Table 1 shows several repowering scenarios for evaluating the framework, ranging in repowering activity from partial repowering up to full repowering, and in lifespan from a baseline, 20-year wind farm all the way up to an advanced, planned repowering of a 100-year wind farm. Along the upper portion of the table is where most traditional repowering activity falls. To encompass the wide range of repowering activities, the "Conventional Repower" row assumes a repower at EOL while varying the level of repower from partial (blade replacement) all the way up to full (new machines and foundations).

Table 1: Repowering Scenarios for Evaluating the Design for Repowering Framework

Baseline	20-year wind farm with decommissioning				*20-year lifespan*
Conventional Repower	Replace blades only	Replaces blades + nacelle	Replace turbine, re-use foundation	New machines and foundations	↓
Intermediate Repowering	Periodic repowering (blades in year 15-20; blades + generator in year 30-40 …)		Full repower every 15-20 years		↓
Advanced Repower	Repeated partial repowering	Heterogeneous repower	Periodic full repowering	Informed/ planned full repowering	*100-year lifespan*
	Partial Repowering	→	→	*Full Repowering*	

To analyze the commercial / economic viability of the different repowering cases, a simple "Repowering Screening" tool was used to analyze and compare the levelized cost of energy (LCOE) of each case. The formula used is as follows:

$$LCOE = \frac{\sum_{year=0}^{20} \frac{CapEx + OpEx}{(1+r)^{year}}}{\sum_{year=0}^{20} \frac{AEP}{(1+r)^{year}}} \tag{1}$$

In this formula, CapEx refers to the initial installed project cost, while OpEx refers to operational expenditures. The AEP is the annual energy production of the farm (in kWh), and the r term refers to the discount rate (%). Some new repowering scenarios have been introduced, such as a "heterogeneous repower" where some turbines are given a full repower and some are partially repowered. Using such a screening tool allows for rapid determination of how the estimated LCOE changes in response to changing the repowering case and its underlying financial assumptions, and provides a means to prioritize cases for further study withing the DFR framework.

Given that wind turbine rotors continue to grow, it is also important to note the increase in AEP that comes with subsequent repowers. For this reason, the repowering screening includes an additional "Increased AEP factor" that acts as a multiplier on the wind farm AEP compared to a modern baseline windfarm. This factor can be changed to account for both a "continued growth" scenario where wind turbine rotors grow at the same pace, and a "slow growth" scenario where turbine growth slows.

5. Results of the Design for Repowering Framework Analysis

To investigate the economic impacts of Design for Repowering, an advanced repowering scenario for a wind farm designed to be repowered three times was analyzed. The results of this analysis are included in Table 2 below. The term "LCOE" refers to the levelized cost of energy for the current operational period (nominally 20 years), which can include either the original construction or a subsequent repowering event. On the other hand, the term "Cumulative LCOE" encompasses the entire operational lifetime of the wind farm, aggregating the costs over all the phases (including the time periods for the initial 20 years plus all subsequent repowers).

Table 2: Advanced Repower Scenario – LCOE Screening

Assumption	Baseline (no repower)	Baseline (advanced repower)	First repower	Second repower	Third repower
CapEx ($/kW)	1000	1500	750	750	750
OpEx ($/kW-yr)	35	35	38	41	44
Inspection Costs ($/turbine)	N/A	N/A	1000	2000	4000
Discount Rate (%)	5.50	5.50	5.50	5.50	5.50
Increased AEP factor (total)	N/A	1.2	1.32	1.45	1.45
Payback Period (yr)	12	17	6	5	5
LCOE ($/kW-hr)	0.0320	0.0358	0.0207	0.0194	0.0200
Cumulative LCOE ($/kW-hr)	N/A	0.0358	0.0279	0.0248	0.0235

Cost estimates for the table were obtained based upon the Land Based Wind Market Report: 2023 Edition [18], then modified in accordance with the different assumptions underlying an advanced repower case. Based upon these cost breakdowns, for the baseline case with no repower, installed project cost is $1,000/kW while operations and maintenance costs are $35/kW-yr in the initial 20-year period. To determine the payback period associated with each scenario, the national average market value of $32/MW-hr was used for the sale price of generated energy. These numbers form the basis for which the advanced repowering assumptions can be applied, and all values are reported in 2023 USD.

Now advanced repowering cases are examined where the cost estimates for the initial 20-year period for baseline (with advanced repower) case were then modeled as follows: CapEx for the baseline (with advanced repower) case was increased by 50% to account for FPSE (Future Proof Structural Engineering, or over-building) of the turbine towers and integration of a comprehensive health monitoring and sensor network. AEP for the baseline repower case was increased by 20% based on a higher (+20%) hub height having 5-7% higher wind speeds of an "over-built" FPSE tower.

The cost estimates for subsequent repowers assumed the following. CapEx was reduced by 25% assuming a future-proof tower that does not need replacement for partial repowering. OpEx increases with each repower, considering that some components are aging and continue to be re-used with a higher risk of failure and increased maintenance requirements. AEP increased by an additional 10% for the first two repowers to account for an expected increase in rotor size of future turbines. Inspection costs increase significantly over the course of the life of the turbine as more frequent manual inspections are needed to validate the reusability of increasingly aged components (such as the tower).

As the results show, applying the Design for Repowering assumptions can lower the LCOE of a wind farm over time, which is reflected within the decrease in cumulative LCOE associated with subsequent repowers. Conversely, an initial bump in the LCOE is found, as expected, from the cost associated with FPSE in the baseline (with advanced repower) case as well as installing a sensor suite into each turbine. Subsequent reductions in the cost of energy are expected to come from the re-use of components (CapEx reductions) for longer periods of time in addition to the increased energy generation (AEP increase) from existing infrastructure and newer turbine technologies. The reduction in payback period also reflects the financial viability of repowering, with additional costs for replacing components being quickly offset by the increased generation and lifetime of the wind farm. Ultimately, we see that a design for repowering results in superior economic performance after a single repowering when compared to a non-repowered wind farm, and this benefit is expected to increase as further repowering is completed. However, further study is now needed to examine additional elements of the research plan, as outlined in the Introduction, to further develop and evaluate technical elements such as over-building (FPSE) and health audits, and the exercise the DFR framework to evaluate and optimize repowering strategies.

6. Conclusions

The Design for Repowering framework introduced in this work provides a comprehensive approach to addressing the challenges associated with wind farm repowering decisions. By integrating multiple criteria, such as health monitoring/sensors, digital twins, and social/environmental factors, the framework offers insights into the optimal timing, strategy, and economics of repowering decisions. Initial results implementing various considerations of the framework in a repowering economic screening indicate its potential for solving long-term challenges and driving down the levelized cost of energy in the wind energy industry. Still, LCOE is not the only metric to benefit from DFR. Benefits can arise in terms of reduced CO2 emissions from component re-use, ease of maintenance due to a comprehensive sensor suite, and enhanced grid penetration through smart asset management. In summary, the work presented here introduces a new "Design for Repowering" framework encompassing several key considerations for repowering, and an initial LCOE screening to identify key case studies for applying the framework. Future work includes further development of DFR framework technical elements (FPSE, health audit), technical analysis to quantify their benefits, and application of the framework for optimizing a real repowering strategy.

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