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Dependability Assessment of a Blade Pitching Mechanism in Tidal Stream Turbines

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To achieve sustainable energy goals, marine renewable resources particularly tidal stream turbines are expected to contribute to the next generation ocean energy systems. The reliability and performance assessment of tidal stream turbines require an integrated modelling framework that captures both mechanical component degradation and environmental variability. The study aims to analyse the effects of seal-bearing coupling on the dependability of the blade pitching mechanism in tidal stream turbines. The operational behaviour of the pitch bearing and seal assembly, critical components of the simplified blade pitching mechanism that experience continuous marine environmental stresses, is modelled by a Markov model. The model explicitly captures the physical dependency between the bearing and seal processes, acknowledging that these subsystems interact rather than degrade independently. The seal prevents seawater ingress and lubricant loss, while the bearing supports cyclic mechanical loads and enables controlled blade rotation. When the seal degrades, contamination and lubricant depletion can accelerate bearing deterioration. Therefore, seal repair is usually prioritized to prevent cascading degradation; however, if the bearing has already sustained major damage, it becomes the priority for maintenance and structural integrity concerns. A numerical study of the proposed unified stochastic framework is developed and presented, illustrating the dependability assessment of the simplified blade pitching mechanism. Results show that energy losses persist even at high tidal current velocities and the energy produced by the system is shown to increase with tidal current speed, rising steeply in the sub-rated region (2.2-2.4 m/s), yet never attaining the theoretical maximum due to degradation.

Keywords: Tidal Stream Energy, Marine energy systems, Markov modelling, Dependability assessment.

1. Introduction

Tidal Stream Energy has emerged as one of the most predictable renewable energy sources, owing to the astronomical forcing of tidal constituents and the resulting regularity of tidal currents (Neill and Hashemi 2018). Compared with wind and solar power, which exhibit high short-term variability due to meteorological fluctuations, tidal flows offer multi scale predictability from seconds to decades. This inherent predictability suggests that tidal Stream Energy could make a disproportionately valuable contribution to future low carbon electricity systems, particularly for regions with high renewable penetration where dispatchability and forecast accuracy are critical (Neill, Vogler, et al. 2017).

Tidal stream turbines operate in harsh marine conditions and under high hydrodynamic loads, placing major mechanical and reliability demands on mechanical transmission components (drivetrain components) (Zhang, et al. 2025). Despite favorable resource characteristics, the long-term viability of tidal stream devices depends strongly on their reliability and maintainability (Walker and Thies 2021). Components such as pitch bearings, dynamic seals and lubrication systems are exposed to continuous cyclic loading, turbulence induced vibration and hydrodynamic variability.

Bearings are particularly vulnerable to progressive wear and frictional heating, while seals are prone to degradation, leakage and water ingress, which can contaminate lubricant systems and accelerate bearing damage ((Xu, et al. 2023); (Khonsari and Booser 2017); (SKF 2025)). Such failures commonly require retrieval of the turbine or nacelle, resulting in multi month downtimes. Seal degradation usually results from abrasion, pressure induced deformation, or erosion from suspended sediments (Yonezawa and Watamura 2022). Unlike bearing degradation, the immediate effect of seal degradation is primarily *reliability-driven* rather than *performance-driven*: a worn seal increases the probability of lubricant leakage and water ingress, which accelerates bearing degradation. Preventive interventions are typically triggered when degradation becomes evident, though logistical delays, part availability and weather windows often lead to prolonged operation in degraded states (McMorland, et al. 2022). Corrective maintenance, especially for bearing replacement, is resource intensive and may require complete device retrieval, resulting in extended downtime.

These subsystems frequently constitute dominant failure modes, with bearing failures leading to prolonged outages due to retrieval requirements and seal failures posing risks of lubricant contamination and accelerated wear (Lee, Chen and Liu 2025).

To address the interplay between component health and energy efficiency, probabilistic degradation modelling provides a suitable framework. Continuous-time Markov Chains (CTMC) enable systematic representation of subsystem health transitions, healthy, degraded, maintenance and failed, together with repair processes and accelerated deterioration phenomena. In particular, seal degradation can substantially increase the likelihood of bearing degradation due to contamination and lubrication loss (Xia, et al. 2025). Integrating this CTMC with a health-dependent power-derating model allows the combined estimation of expected energy produced (EEP), expected energy not supplied (EENS) and their direct effects on power generation. EEP quantifies the expected energy delivery under stochastic degradation and maintenance conditions, while EENS measures the expected energy shortfall relative to a specified demand. Together, these measures connect component-level reliability behavior to system-level energy adequacy, making them well suited for assessing the operational implications of degradation in tidal stream turbines.

For tidal stream systems, understanding how component degradation influences delivered power is essential (Lewis, et al. 2019). In this study by combining a component-level reliability model with a power curve framework, we provide a unified method for quantifying the coupled effects of degradation, maintenance strategies and tidal resource variability on long-term energy yield.

The primary objective of this paper is to develop and apply a CTMC model representing the joint degradation of a tidal turbine's pitch bearing and seal subsystems and to evaluate how subsystem failures and preventive along with corrective maintenance influence long-term energy delivery. Using tidal stream speeds representative of the Orkney region (2.2-3.2 m/s), we evaluate the EEP and EENS across a range of operational scenarios. Three demand levels are considered: the main community electricity demand, a demand level that can be met only when both the bearing and seal are healthy and a second reduced level that can be met whenever the bearing is healthy or degraded. This integrated reliability-power modelling approach enables us to quantify how subsystem degradation pathways and maintenance strategies influence the ability of a tidal turbine to supply electricity reliably over extended operational horizons, including assessing its capability to meet the annual electricity requirements of approximately 2,000 homes.

The remaining sections are structured as follows. Section 2 presents the modelling of the subsystems. In Section 3, the power modelling and the main dependability measures are described. A case study is presented in Section 4, and the conclusion is presented in Section 5.

2. Continuous-Time Markov Model of Pitch Bearing and Seal Degradation

2.1. Subsystems Condition States Formulation

To capture the essential reliability behavior of the pitch bearing and seal subsystems, the health evolution and maintenance actions of the two components are represented using a CTMC model.

It is assumed that the health condition of the components can be categorized as "healthy", "degraded", "maintainable" and "failed". The time spent in each of these components' condition is assumed to be exponentially distributed and thus a CTMC $\{X(t), t \geq 0\}$ can be used to model the evolution of components' condition. This approach accounts for the stochastic nature of components' degradation. Given that tidal stream generators are intended to operate continuously in time, in our approach, we are interested in the long-run behavior of the turbine. Thus, we are interested in the steady state probability distribution $\boldsymbol{\pi}$ of the Markov process $X(t)$, which can be derived by solving the following system of linear equations:

$$\boldsymbol{\pi}\mathbf{Q} = 0, \sum_{i=1}^{n} \pi_i = 1 \qquad (1)$$

where $\mathbf{Q} = [q_{ij}]$ is the $(n \times n)$ generator matrix, with q_{ij} denoting the transition rate from state i of $X(t)$ and n denoting the total number of states.

The proposed combinations of healthy, degraded, failed and under maintenance conditions in Fig. 1 are designed to capture the healthy operation of both components (H^B, H^S), isolated degradation of either component (H^B, D^S) or (D^B, H^S), concurrent degradation of both (JoPM), reflecting increased risk and reduced operational efficiency, failure states (F^B, H^S) and (H^B, F^S), where the turbine must shut down and enter corrective maintenance, maintenance state (PM^B, H^S) and (H^B, PM^S), in which power production is zero.

2.2. Degradation, Failure and Maintenance Transitions

Transitions between states encode degradation progression, failure mechanisms, maintenance initiation and maintenance completion.

In Fig. 1, we consider that the blade pitching mechanism is in state (H^B, H^S), where H^B is the healthy condition of the pitch bearing and H^S is the healthy condition of the seal. If degradation occurs in either subsystem, the process transitions out of this state via one of two degradation rates: pitch bearing degradation with rate λ_D^B, moves the system to state (D^B, H^S), while seal degradation, occurring with rate λ_D^S, moves the system to the state (H^B, D^S). Furthermore, once in a degraded condition, each subsystem may continue to deteriorate or may enter maintenance. The pitch bearing may fail from the degraded condition with rate λ_F^B sending the system to the state (F^B, H^S), or maintenance may be initiated with rate μ_{PM-E}^B (Enters PM) transitioning to the bearing preventive maintenance state (PM^B, H^S). Similarly, from the degraded state the seal may fail and enter from state (H^B, D^S) with rate λ_F^S to (H^B, F^S) or enter maintenance with rate μ_{PM-E}^S transitioning to the state (H^B, PM^S).

Both of the subsystems can enter into concurrent degradation. Thus, if degradation propagates while the other subsystem is already degraded, the system transitions from the states (H^B, D^S) and (D^B, H^S) to the joint degraded state (JoPM) with λ_D^B and λ_D^S, correspondingly. State (JoPM) captures the situation where both components are degraded simultaneously and may initiate joint preventive maintenance, which reduces downtime relative to sequential interventions. Once joint maintenance is completed, the system then returns from the state (JoPM) to the fully healthy state of both components (H^B, H^S) with rate $\mu_{PM-C}^{S,B}$ (Completed PM). Finally, subsystem specific maintenance states also restore both components to full health: from (H^B, PM^S) at rate μ_{PM-C}^S and from (PM^B, H^S)

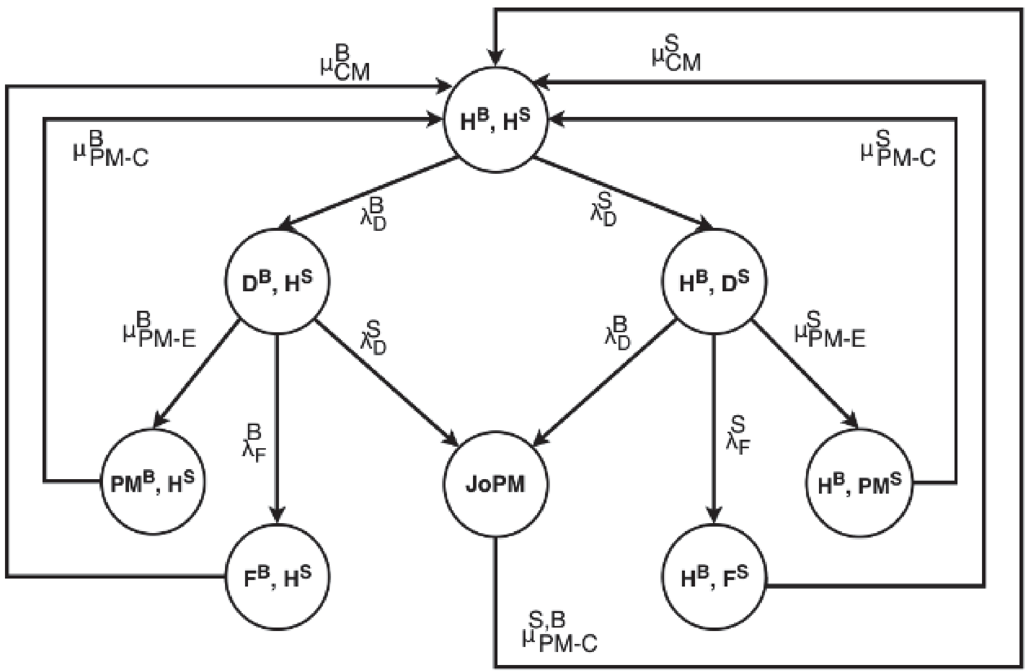

Fig. 1. State transition diagram for the deterioration pitch bearing-seal under maintenance.

at rate μ^B_{PM-C}, both transitions lead back to the healthy state (H^B, H^S).

2.2.1. *Seal-Driven Acceleration of Bearing Degradation*

Seal degradation has a direct influence on the degradation rate of drivetrain bearings. When the seal loses integrity due to wear or material fatigue, it can no longer maintain an effective separation between the lubricated bearing environment and the surrounding seawater. Even modest degradation of the seal increases the probability of lubricant contamination by water or suspended particles. As the seal condition worsens, the pitch bearing experiences elevated friction, increased vibration, all of which significantly accelerate its deterioration (Xia, et al. 2025).

To capture this physical coupling in our reliability model, the transition rate for pitch bearing degradation is made *conditional on seal health*. Specifically, the transition from a healthy pitch bearing (H^B, D^S) to a degraded pitch bearing (D^B, D^S) is assigned an accelerated rate multiplier, reflecting the reduced protective function of the seal and the increased likelihood of contamination induced wear. By embedding this dependency directly in the transition structure, the model reproduces the nonlinear failure dynamics that arise from interacting components and more accurately represents the operational risks associated with combined mechanical and sealing degradation in tidal stream turbines.

3. Power Modelling under Component Health Uncertainty

The electrical power that a tidal stream turbine can produce depends not only on the external hydrodynamic resource but also on the internal mechanical health of its critical subsystems. While the ideal turbine response is determined by the instantaneous flow velocity and the hydrodynamic power coefficient, real operating conditions involve deviations from this ideal due to subsystem degradation and efficiency reductions caused by mechanical wear. To capture these effects quantitatively, the present study integrates a set of health-dependent derating multipliers, representing the joint degradation of the subsystems in power output.

3.1. Health-Dependent Multipliers

The baseline power output is defined by the standard tidal stream turbine power curve $F_0(V)$, which maps the instantaneous flow speed V to mechanical power under fully healthy operating conditions (Lewis, Murray, et al. 2021). The curve is constructed using the turbine's cut-in velocity, rated velocity range and rated power. Following established practice for tidal resource and turbine performance modelling, power increases approximately with the cube of flow velocity between the cut-in and rated speeds, after which it saturates at the rated power through blade pitch and generator torque control. The ideal power curve is defined analytically as:

$$F_0(V) = \begin{cases} 0, & V < V_{ci}, \\ F_r \frac{V^3 - V_{ci}^3}{V_r^3 - V_{ci}^3}, & V_{ci} \le V < V_r, \\ F_r, & V_r \le V \le V_{co}, \\ 0, & V > V_{co} \end{cases} \quad (2)$$

where V_{ci} is the cut-in speed, V_r is the rated speed, V_{co} is the cut-out speed and F_r is the rated power output.

Subsystem degradation affects turbine performance through several mechanisms: increased mechanical losses, vibration-induced control limits, reduced drivetrain efficiency and operational safety constraints. To incorporate these effects without rederiving the full mechanical model of the turbine, each health state in the CTMC model is assigned a derating multiplier $\alpha_i \in [0, 1]$ applied multiplicatively to the ideal power curve. These multipliers act as derating factors that scale the ideal power curve according to subsystem health. Accordingly, the instantaneous power output in health state *i* is defined as the Eq. 3 below:

$$F_i(V) = \alpha_i F_0(V) \quad (3)$$

This structure ensures that the baseline hydrodynamic dependence on tidal speed is preserved, the loss of performance due to degradation is explicitly represented and maintenance and failure states naturally lead to zero output. Table 1 presents the derating factors α_i, consistent with typical tidal turbine practice where minor degradation reduces efficiency, while maintenance/failed states produce zero output.

Table 1. Derating factors α_i for each state.

State	Interpretation	Multiplier α_i
(H^B, H^S)	Full rated curve	1.00
(H^B, D^S)	Small derating	0.9
(D^B, H^S)	Larger derating, friction, vibration	0.8
(JoPM)	Combined effect	0
(F^B, H^S)	Offline	0
(H^B, F^S)	Offline	0
(PM^B, H^S)	Offline	0
(H^B, PM^S)	Offline	0

Because bearing degradation primarily affects mechanical efficiency, vibration and allowable loading, we assume a stronger derating for degraded bearings (0.8 $F_0(V)$) in state (D^B, H^S) than for degraded seals (0.9 $F_0(V)$) in (H^B, D^S), for which the primary effect is increased failure risk rather than immediate performance loss. By assigning differentiated multipliers to bearing and seal related degradation, the model captures the asymmetric influence of mechanical versus sealing defects on power production.

3.2. Dependability Measures

3.2.1. *Expected Energy Produced*

The EEP is a prediction of the overall output performance of the tidal stream turbine and the estimated amount of electrical energy the system is expected to produce over a given period. The maximum potential output under ideal operational conditions and resource availability is the primary concern of EEP and is considered the sum of the performance rate of the total system and its related state probability, and it can be expressed as follows:

$$EEP(t) = \sum_{i=1}^{K} P_i(t) \cdot F_i \quad (4)$$

where F_i is the power output in state *i* and P_i is the corresponding state probability. Asymptotically, Eq. 4 can be rewritten as follows:

$$EEP = \lim_{t\to\infty} EEP\,(t) = \lim_{t\to\infty} \sum_{i=1}^{K} P_i(t) \cdot F_i$$
$$= \sum_{i=1}^{K} \lim_{t\to\infty} P_i(t) \cdot F_i = \sum_{i=1}^{K} \pi_i \cdot F_i \quad (5)$$

3.2.2. *Expected Energy Not Supplied*

EENS is the expected quantity of energy that will not be delivered by the system to consumers during a certain period because of the lack of system power or an unexpected major shutdown (Platis, Limnios and Le Du 1998). Therefore, we define a subset B that contains all of the operational states i for which the generated power F_i is less than the demand DE. The subset is defined as follows: $B = \{i \in U \mid DE > F_i\}$.

To describe the EENS let:

$$EENS(t) = \sum_{i \in B} max(DE - F_i, 0) \cdot P_i(t) \quad (6)$$

Because we are interested in the long-term behaviour of the described system, we need to calculate the EENS asymptotically. Using Eq. 6, we derive the following expression:

$$EENS = \lim_{t \to \infty} [\sum_{i \in B} \max(DE - F_i, 0) \cdot P_i(t)]$$

$$= \sum_{i \in B} \max(DE - F_i, 0) \cdot \lim_{t \to \infty} (P_i(t))$$

$$= \sum_{i \in B} \max(DE - F_i, 0) \cdot \pi_i \quad (7)$$

Then, the EENS in a time interval of T time units can be written as follows:

$$EENS(T) = EENS \times T$$

$$= \sum_{i \in B} \max(DE - F_i, 0) \cdot \pi_i \times T \quad (8)$$

4. Case study: Tidal Stream Turbine Performance at Orkney

This section evaluates the proposed reliability power model through a case study representative of the high energy tidal resource at Orkney, Scotland. The Fall of Warness test site exhibits strong and predictable tidal currents, with mean velocities of approximately 2.5 m/s and spring tide peaks regularly exceeding 3 m/s (Sellar, et al. 2018). These conditions make the specific site one of the most suitable European locations for assessing tidal stream turbine performance under realistic operational and maintenance constraints.

4.1. Orkney Site Characteristics

To reflect these hydrodynamic characteristics, the turbine's baseline power output is modelled using a physical tidal power curve $F_0(V)$ for a 2 MW tidal stream turbine with a cut-in speed of 1.0 m/s and a rated-speed of 2.5 m/s. The analysis is carried out across a representative speed band of 2.2-3.2 m/s, capturing the range in which the turbine transitions from sub-rated to consistently rated operation.

To evaluate the adequacy of the turbine under different operational assumptions, three demand scenarios are examined. The first corresponds to the comparison of the resulting energy yield against the annual power demand of 2,000 homes, which based on an average UK household consumption of approximately 2,700 kWh/year, corresponds to 5,400 MWh/year. The second demand level is defined such that only the fully healthy state of the turbine can meet it, thereby isolating the consequences of any deviation from optimal operating conditions. The third scenario reflects a more flexible demand that can be satisfied when the turbine is either fully healthy or operating with a degraded bearing, allowing assessment of the benefits of operational tolerance. This benchmark enables direct assessment of whether the turbine, when subject to realistic degradation pathways and downtime, can satisfy localised community scale energy needs.

The case study highlights the implications of subsystem degradation for the reliability-centred design of tidal stream turbines. By linking component health to power output through the power curve and derating formulation, the model reveals how even modest derating in degraded states can meaningfully influence the ability of the turbine to meet local demand, such as powering 2,000 homes and underscores the importance of targeted monitoring strategies, seal integrity and preventive maintenance in enhancing operational performance.

5. Dependability Assessment Results

The EEP expresses the mean annual energy generated by the tidal stream turbine as a function of the prevailing current speed, accounting for the stochastic degradation and failure behaviour of the bearing-seal subsystem. For each tidal speed in the range 2.2-3.2 m/s, the physical power curve $F_0(V)$ determines the maximum achievable output of a healthy turbine, while the CTMC model provides the steady state probabilities of being in healthy, degraded, maintenance or failed conditions. The EEP is therefore computed as a probability-weighted average of the energy produced.

In Fig. 2, the resulting EEP curve increases monotonically with current speed. This behaviour arises from the cubic dependence of available hydrodynamic power on current velocity below the rated point and the plateau in the power curve once rated power is achieved.

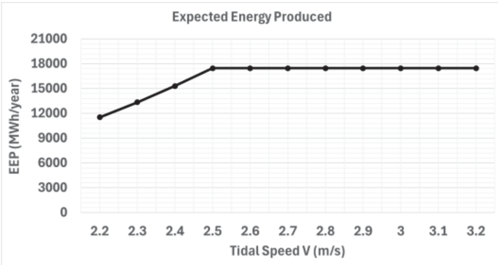

Fig. 2. Expected energy production of the tidal-stream turbine.

At lower speeds (2.2-2.4 m/s), the turbine operates close to but below rated power, so even small increases in velocity significantly raise the baseline energy available in the healthy states. As speed approaches the upper part of the examined interval (2.5-3.2 m/s), the turbine consistently reaches rated output in healthy conditions and consequently, the EEP curve begins to flatten. However, the curve does not reach the purely deterministic theoretical maximum because the Markov model accounts for the probability of degraded, maintenance and failed states, which reduce the effective output even at higher speeds.

Overall, the EEP captures the combined effect of hydrodynamic resource intensity and component reliability. It illustrates that higher tidal speeds increase production but cannot eliminate reliability induced energy losses and therefore provides a realistic, reliability adjusted estimate of annual energy production.

The EENS in Fig. 3 quantifies the mean annual energy shortfall relative to a specified demand level. In this analysis, three demand scenarios are evaluated across the same range of tidal speeds.

Across all scenarios, EENS decreases systematically as tidal speed increases. At lower speeds, the turbine operates below rated power, and the combination of reduced hydrodynamic resource and reliability induced downtime results in significant unmet demand. As the speed rises into the rated region, the available power from the healthy states increases, reducing the magnitude of shortfalls.

Comparing the demand scenarios, the highest EENS values occur for the demand that can only be satisfied in the fully healthy state. This demand is set above the output capability of all degraded states, illustrating that even mild degradation of either component leads to unmet demand.

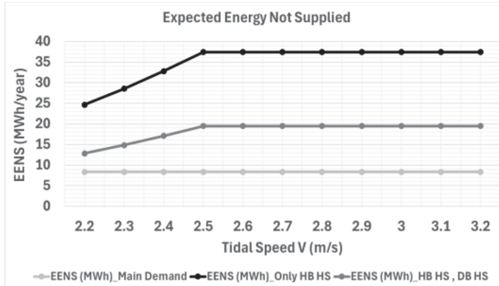

Fig. 3. Expected energy not supplied under three demand scenarios.

The second demand scenario, satisfiable by the healthy and degraded bearing state, shows substantially lower EENS across all speeds, demonstrating the sensitivity of energy adequacy to the operational tolerance of the system. Thus, the EENS curves demonstrate that system reliability is as influential as hydrodynamic resource intensity in determining energy adequacy. Even in tidally energetic sites, non-negligible energy deficits can occur unless maintenance policies and subsystem reliability are fully incorporated into performance assessments.

EEP shows that favourable tidal resource conditions do not fully compensate for reliability related losses. Even when current speed is high enough for the turbine to reach rated output under operational conditions, degradation and maintenance still reduce long-term energy delivery. This indicates that resource assessment alone is insufficient for estimating annual yield and that component-level degradation modelling is needed for realistic performance evaluation.

The comparison between demand scenarios shows that energy adequacy depends not only on mean resource intensity but also on the level of performance degradation that can be tolerated before demand is considered unmet. In this sense, the analysis highlights the importance of preventive maintenance for limiting the indirect degradation effect transmitted from the seal to the bearing.

Conclusion

This paper presented an integrated dependability and performance assessment framework for a simplified blade pitching mechanism in tidal stream turbines, with explicit consideration of the coupled degradation behaviour of the pitch bearing and seal subsystems. By employing a CTMC model, the proposed approach captured not only individual component deterioration, failure and maintenance processes, but also the physically motivated dependency whereby seal degradation accelerates bearing wear. This coupling reflects realistic marine operating conditions and addresses a key limitation of conventional independent-component reliability models.

The resulting EEP and EENS measures demonstrated that reliability induced losses persist even at high tidal current velocities, highlighting that resource abundance alone cannot guarantee energy adequacy. The case study for the Orkney tidal site showed that degraded operational states, particularly those associated with bearing deterioration, have a disproportionate impact on long-term energy delivery, while preventive and coordinated maintenance strategies can significantly mitigate energy shortfalls. Overall, the proposed modelling approach provides a structured framework for reliability-centred design and operational planning of tidal stream turbines. By explicitly linking component-level degradation to power output and demand adequacy, the approach supports more realistic assessments of long-term performance and offers valuable insights for maintenance optimization, monitoring prioritization and future turbine design.

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