Limitations and Opportunities in PHM for Offshore Wind Farms: A Socio-Technical-Ecological System Perspective

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ABSTRACT

The burgeoning importance of offshore wind farms (OWFs) in the transition to sustainable energy systems underscores the need for effective Prognostics and Health Management (PHM) strategies. While the current PHM framework demonstrates its prowess in enhancing the reliability and operational efficiency of OWFs, this paper contends that its potential remains largely untapped due to certain inherent limitations. This study casts a comprehensive spotlight on the limitations and untapped opportunities within the PHM framework for OWFs from a Socio-Technical-Ecological Systems (SETS) perspective.

The limitations, as identified, are threefold. First, the existing framework exhibits an over-reliance on technical factors, thus prioritizing maximization of Remaining Useful Life and cost minimization. This emphasis disregards crucial Non-Technological Factors (such as community impacts, stakeholder engagement, Human and Organization Factors (HOFs)) and uncertainty arising from them, which can exert significant influences on OWF's health and performance. Second, the PHM approach often adopts a component-centric view, with focus on dominant degradation modes, thus undermining the intricate interdependencies among diverse components and failure modes. This lack of a System Level Perspective (SLP) and Multi-Modal Degradation (MMD) hampers a comprehensive understanding of how component degradation cascades through the entire system. Third, the current framework largely ignores the ecological considerations, despite compelling evidence that the current monitoring, assessment, and maintenance activities has significant ecological consequences.

By addressing the identified limitations and leveraging the opportunities together with AI, the PHM framework for OWFs can evolve into a more comprehensive, inclusive, and resilient approach. The proposed paradigm shift resonates deeply with the contemporary drive towards sustainability, not only in terms of technical efficacy but also in terms of social acceptance and ecological compatibility.

1. INTRODUCTION

Offshore wind energy has a huge potential as an alternative to fossil fuels in regard to decarbonizing, mitigating greenhouse gas emissions (International Energy Agency, (2019)) and contributing to achieving the United Nations SDG#7 "affordable and clean energy" & SDG#13 "climate action" (United Nations, (2016)). With an annual electricity generation capacity of 12GW from offshore wind farms (OWFs), the European Union (EU) leads the tally and has plans to ramp up the generation to 60GW by 2030 and 300GW by 2050 for a climate-neutral future (European Commission, (2020)). Norway's ambitions align with that of the EU, as the target is to generate 30GW by operating 1500 offshore wind turbines (WTs) within 2040 (Norwegian Government, (2022)). Ongoing development of Hywind Tampen (Equinor, (2022)) followed by tendering of Sørlige Nordsjø II and Utsira Nord (Norwegian Government, (2022)) marks the first step in this direction.

To remain economically attractive for investors and consumers, it is vital to decrease the levelized cost of energy from OWFs (Mai, Lantz, Mowers, & Wiser (2017)). In order to achieve these significant technical developments have been made in blade, drivetrain and foundation design of WTs (IRENA, (2019)), however still challenges related to system dynamics, optimization and control of wind farms are being actively researched (Clifton, A., Barber, S., Bray, A., Enevoldsen, P., Fields, J., Sempreviva, A. M., Williams, L., Quick, J., Purdue, M., Totaro, P., & Ding, Y. (2023)). Another approach of reducing LCoE, is to increase availability of wind turbines 24/7, by optimal O&M activities, as it can account up to 35% of running cost of the OWFs (Sarker, B. R., & Faiz, T. I. (2016). This is achieved due to the timely inspection and maintenance (I&M) based

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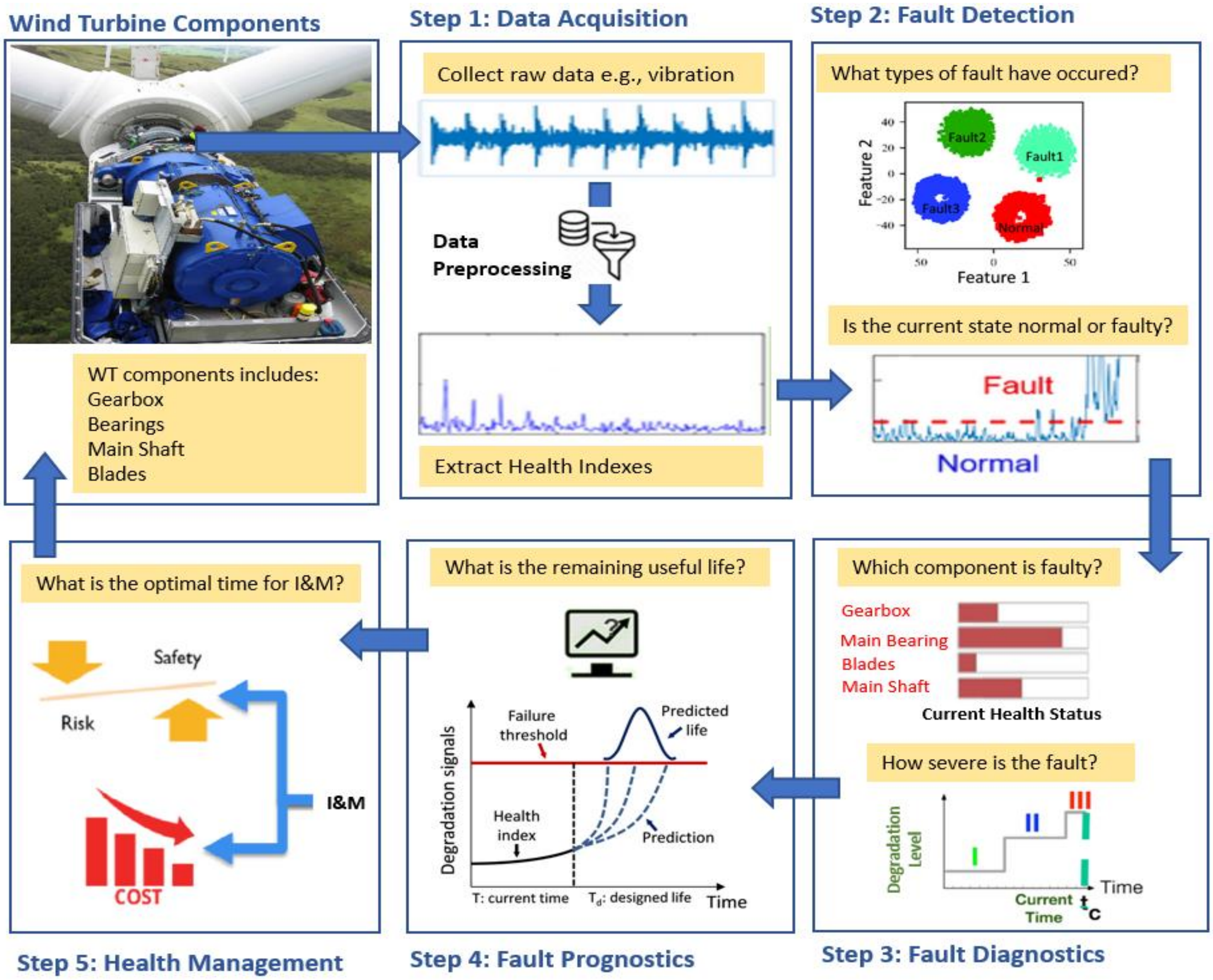

Figure 1. A typical PHM framework for wind turbine.

upon the performance monitoring of the WTs.

Performance monitoring leverages the Supervisory Control and Data Acquisition (SCADA) system to establish correlations between various parameters, such as wind speed and power output. This approach develops models to define normal operational states, utilizing them to pinpoint abnormal behaviors and activate alarms sent to operators, signaling the need for Inspection and Maintenance (I&M) activities (Jansen, M., Staffell, I., Kitzing, L., Quoilin, S., Wiggelinkhuizen, E., Bulder, B., Riepin, I., & Müsgens, F. (2020)). Nonetheless, this methodology grapples with two pivotal challenges. Firstly, the triggered alarm does not provide any insight into the causality of the abnormal behavior, in layman's terms it does not provide answers to the questions like "How severe is the fault?" or, "When will the degrading component fail?", or "Which component is failing?". Secondly, SCADA-generated alarms rely on the past degradation state of components. This temporal constraint often leads to insufficient time for equipment upkeep or replacement due to logistical complexities linked to operational weather constraints and the remote nature of OWFs (Sheng, S. (2017)).

To surmount these challenges, OWF operators recognize the potential of integrating the Prognostics and Health Management (PHM) approach to formulate optimal I&M strategies for OWFs. As illustrated in Figure 1, PHM leverages sensor data from in-situ SCADA systems or retrofitted Condition Monitoring (CM) systems. These data sources, combined with diverse analytics and machine learning (ML) techniques, facilitate fault detection, diagnosis, prognosis, and health management across OWFs. Recent years have witnessed notable progress in deploying various methodologies, including stochastic modeling (Cao, L., Qian, Z., Zareipour, H., Wood, D., Mollasalehi, E., Tian, S., & Pei, Y. (2018)), machine learning (Elforjani, M., & Shanbr, S. (2018)), physics-based techniques (Breteler, D., Kaidis, C., Tinga, T., & Loendersloot, R. (2015)), and hybrid approaches (Wang, P., Long, Z., & Wang, G. (2020)), to diagnose and prognose critical wind turbine (WT) components.

A comprehensive evaluation of these techniques, encompassing an assessment of their strengths, limitations, and potential for hybrid models, has been meticulously presented by (Zhang, W., Vatn, J., & Rasheed, A. (2022)). Additionally, (Rinaldi, G., Thies, P. R., & Johanning, L. (2021)) provides an exhaustive survey of state-of-the-art strategies governing the operation and maintenance (O&M) planning, as well as the CM of OWFs. This review expounds upon benefits, limitations, and envisions prospective horizons entailing robotics, artificial intelligence, and data analytics. Moreover, (McMorland, J., Flannigan, C., Carroll, J., Collu, M., McMillan, D., Leithead, W., & Coraddu, A. (2022)) undertakes an extensive analysis of the O&M modeling landscape, accounting for innovative WT concepts like X-rotor and multi-rotor designs. The study pinpoints factors such as weather dynamics, failure and degradation patterns, vessel logistics, cost estimation, and maintenance tactics, as pivotal for O&M modeling. Equally noteworthy is (McMorland, J., Flannigan, C., Carroll, J., Collu, M., McMillan, D., Leithead, W., & Coraddu, A. (2022)) which elucidates O&M challenges and research opportunities inherent to WT systems. Notable opportunities encompass integrating diverse data sources to fine-tune O&M strategies, precise inventory management, nuanced uncertainty modeling, the pressing need for standardized open data frameworks, and pivotal reference software development.

To the author's best understanding, the existing exploration of challenges and opportunities associated with WTs/OWFs is primarily limited to treating them as purely technical systems. However, this perspective falls short, given that OWFs have far-reaching impacts on both society and ecology, rendering them as intricate social-ecological-technical systems (SETS). Consequently, a comprehensive examination and analysis of OWFs as SETS is imperative. This paper serves as a foundational step, presenting a paradigm shift where OWFs are approached from the SETS framework. We present an exploration of these complex systems, unveiling knowledge gaps and charting a trajectory for future advancements within the realm of PHM.

The subsequent sections of this paper are delineated as follows. In Section 2, we delve into main constituents of SETS and describe it in context to OWFs. Section 3 outlines and discuss the limitation within PHM research as applied to OWFs while Section 4 expounds upon prospective avenues for future research. Ultimately, Section 5 present important conclusions from the study.

2. SOCIAL- ECOLOGICAL-TECHNOLOGICAL SYSTEMS

2.1. General

Urban areas, as intricate hubs of human activity, infrastructure, and ecological dynamics, epitomize the interwoven interactions between social, ecological, and technological components (McPhearson, T., Cook, E. M. (2022). Recently, SETS research has gained traction as a new approach to understand urban complexity. SETS are characterized by their inherently interdisciplinary nature, drawing from a diverse array of disciplines, including engineering, ecology, social sciences, economics, and policy analysis (Ahlborg, H., Ruiz-Mercado, I., Molander, S., & Masera, O. (2019)). It holistically brings together over two decades of interdisciplinary work on social-ecological systems (SES) and socio-technical systems (STS) to advance interdisciplinary and critical systems approaches to urban sustainability and resilience (Branny, A., Møller, M. S., Korpilo, S., McPhearson, T., Gulsrud, N., Olafsson, A. S., Raymond, C. M., & Andersson, E. (2022)).

At the core of SETS lies the recognition that the interactions between social, ecological, and technological elements are far from isolated; rather, they constitute a dynamic and integrated network. Social dimensions encompass human behavior, cultural norms, governance structures, and economic systems. Ecological aspects encompass biodiversity, ecosystems, and environmental processes. Technological elements comprise innovations, infrastructure, and engineering solutions. The essence of SETS is the acknowledgement that interventions in one dimension inevitably reverberate across the entire system, triggering cascading effects and influencing the equilibrium of the entire interconnected network. Prominent frameworks, such as the Social-Ecological System (SES) (Partelow, S. (2018)) framework and Transition Management Theory (Rotmans, J., Kemp, R., & van Asselt, M. (2001)), facilitate the analysis of adaptive capacity, transformation pathways, and governance structures within SETS.

The versatility of SETS is evidenced by its wide-ranging applications across various domains. Urban planning and design, for instance, benefit from SETS-based assessments that optimize human well-being, resource efficiency, and ecosystem health (Colléony, A., & Shwartz, A. (2019)). Agricultural systems leverage SETS insights to devise sustainable farming practices that harmonize productivity, biodiversity, and socioeconomic equity (Durán, Y., Gómez-Valenzuela, V., & Ramírez, K. (2023)). In the context of energy systems, SETS-driven analyses guide the integration of renewable technologies, grid management, and community engagement. We shall next discuss the various SET interactions happening while operating and maintaining a typical OWF.

2.2. Social-Technological-Ecological Interactions in OWFs

A typical OWF is a complex SETS (as shown in Figure 2) implying that its functioning and performance are influenced by not only the technical aspects but also by the

Non-Technological Factors (NTFs), such as the policies/regulations governing the wind farm development, the involvement of stakeholders (including local communities, government agencies, industry players, management), ethical considerations, and decision-making processes throughout the lifecycle of the wind farm. For e.g., while selecting a potential site for OWFs, it is necessary to couple technical-engineering terms (e.g., high wind energy efficiency, bottom suitability, inland infrastructures) with ecological–environmental considerations (e.g., the least possible impact on biodiversity, ecosystem functioning) and socio-economic aspects (e.g., effects on coastal and marine activities, development of marine spatial planning) (Soukissian, T., & Reizopoulou, S. (2016)).

The integration of SETS insights into OWF O&M strategies has far-reaching implications for sustainability and resilience. As offshore wind energy continues to expand globally, the SETS approach offers a roadmap for navigating complex socio-ecological-technical trade-offs. By fostering dialogue, collaboration, and adaptive governance, OWFs can evolve as catalysts for sustainable energy transition, harmonizing human needs, ecological conservation, and technological progress. The integration of ecological assessments in decision-making processes ensures the long-term coexistence of offshore wind farms with marine ecosystems. Hence, it is important to recognize that OWFs necessitates not only technical prowess but also a wider spectrum of attributes, including transparency, enhanced social acceptance, and judicious resource allocation. By addressing these facets, OWFs can not only thrive technically but also thrive holistically, ultimately contributing to a more encompassing sustainability paradigm.

3. LIMITATIONS IN CURRENT PHM FRAMEWORK FOR OWFS

The PHM framework for a typical OWF is currently facing the following research gaps:

1. **Lacking Non-Technological Factors (NTFs):** The present state of affairs reveals that the I&M plans derived from the PHM approach predominantly hinge on technical variables such as maximizing Remaining Useful Life (RUL) and economic considerations centered around cost minimization. This approach, however, exhibits a notable gap by failing to account for other important sustainability parameters. other NTFs such as community impacts, stakeholder engagement, regulatory requirements, and ethical considerations which are vital for holistic health management of OWFs have not been integrated into the PHM framework. As a result, the current framework might lack the inclusivity needed to comprehensively assess the health and performance of the OWFs. Overemphasizing technical factors could lead to an incomplete assessment of risks associated with OWF operation. While technical failures are significant, the tendency to ignore other important NTFs could potentially translate into suboptimal I&M decision-making, diminished operational efficiency, and even expose the system to latent safety hazards. For instance, a turbine failure causing noise pollution in proximity to residential areas might result in community backlash, regulatory fines, and project delays, all of which may have far-reaching consequences beyond the technical domain.

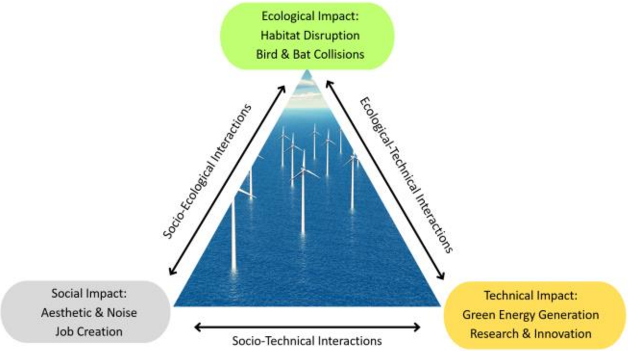

Figure 2. OWF viewed as a complex SETS.

2. **Lacking System Level Perspective (SLP):** A WT is a complex electro-mechanical-hydro system having multiple (approximately 8500) components that function collectively to convert wind energy to electrical energy. Some of the vital subsystems and components of a typical WT are blades, rotor, gearbox, generator, yaw, tower, controller, anemometer, break, etc. as shown in Figure 3. Current application of PHM approach for OWFs have been component-centric primary focusing on critical components such as generators, drivetrain, blades etc. However, in practice OWFs have many interdependent components where degradation of one component (e.g., main shaft) has a cascading effect on other components (e.g., main bearing). Simultaneously, the quality of I&M activities, performed by technicians also affects the degradation rate of the entire system. Nevertheless, currently the PHM framework lacks SLP as it fails to integrate the interactions between different machine/social elements of an OWF.
3. **Lacking Multi-Modal Degradation (MMD):** Each WT component exhibits significant variation in terms of how they degrade/fail, due to factors including manufacturing variations/defects, operational loading, material imperfections, human performance variability etc. In practice, a component undergoes multimodal degradation due to failure modes such as cracking, fatigue, corrosion, erosion etc., even though it undergoes the same operation. However, until now most prognostics models have been developed for

single degradation modes (e.g., fatigue, erosion) by using 'machine related' quantitative information available from sensors and almost no use of quantitative or qualitative information derived from human sources is taken into consideration.

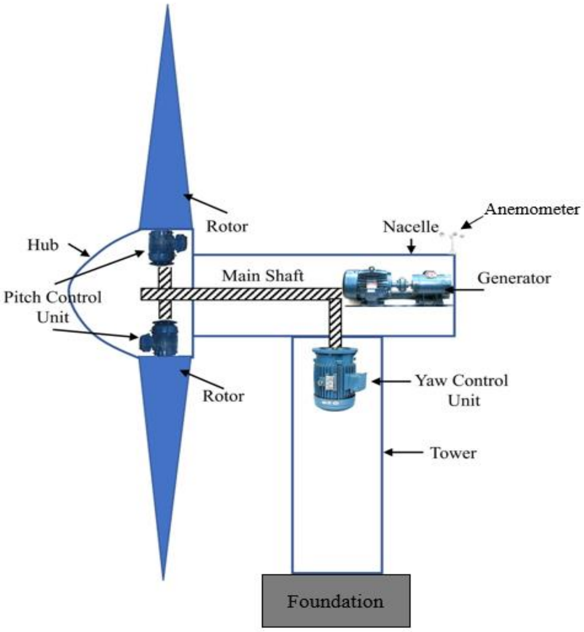

Figure 3. Typical components of Horizontal Axis WT

4. **Non-inclusion of Human and Organizational Factors (HOF) Data:** HOF encompass the interactions among various components within a system and individuals, considering their behaviors. This interaction takes place across different levels, including individual, situational, group, organizational, or cultural levels (Human and Organisational Factors, (2019)). Instances of these interactions can be observed in various aspects, such as job design, workload, procedures, competence management, working conditions, reporting culture, systemic investigations, audits, and the safety culture of the organization. As depicted in Figure. 4, the enhancement of railway safety, akin to other high-risk industries, initially centered on technical reliability (period from 1960-1980). Subsequently, there was an emphasis on formalizing processes through safety management systems (1980-2000). While significant strides have been made in enhancing safety, progress has begun to stabilize, leading to a plateau effect. Presently (2000 onwards), the integration of HOF has emerged as paramount to sustaining the trajectory of safety improvement.

   However, as currently practiced, the PHM approach prioritizes the hardware aspects of OWFs by collecting CM data from physical components and employing data analytics/ML techniques to predict and manage its performance and maintenance needs. Nevertheless, statistics from the WT manufacturers indicate that 40% of WT failures emanate due to HOFs (Interreg IVB North Sea Region Programme 2007-2013, (2015)). These statistics serves as a reminder that, while the hardware aspect is undoubtedly important, the human dimension also has a significant influence on the overall health and performance of the system. Thus, the current trend of neglecting the HOF data within the PHM framework limits the effectiveness and holistic understanding of the system's health and performance.

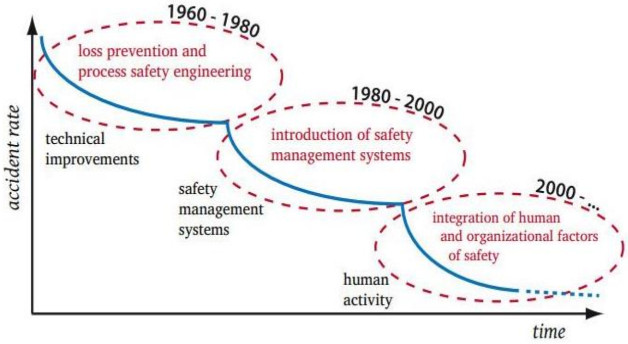

Figure 4. Factors responsible for reducing accident rate in high-risk industries (Human and Organisational Factors, (2019)).

5. **Inefficient Uncertainty Management:** In the context to PHM of an OWF, uncertainty can arise from various sources, such as measurement/modelling errors, limited data, variability in operating conditions and errors during human interaction with WT. Although, many researchers have focused on analyzing uncertainty arising due to technological factors [12, 28], still none of the studies have quantified uncertainties emanating due to NTFs. Furthermore, uncertainty propagation and management while considering SLP also requires thorough investigation and research.

6. **Lacking Ecological Considerations:** OWFs are often part of larger marine environments, and it is vital to comprehend their interactions with adjacent ecosystems (Galparsoro, I., Menchaca, I., Garmendia, J. M., Borja, N., Maldonado, A. D., Iglesias, G., & Bald, J. (2022)). It is a consensus that the growth of OWFs should not lead to significant environmental harm nor compromise environmental objectives, rather its O&M should be compatible with biodiversity protection and conservation objectives (e.g., SDG 14, Life Below Water). The current monitoring, assessment, and maintenance strategies fail to adequately address the potential ecological consequences due to these activities; thus, further research is needed to assess the cumulative impacts of multiple wind farms in an area, considering factors such as habitat fragmentation, displacement of species, and changes in ecological dynamics. Integrating ecological considerations into a

PHM framework would preserve ecosystem connectivity, promote biodiversity, mitigate potential negative cumulative effects of OWFs on multi-species populations, and ensure the long-term viability of offshore wind energy as a renewable and ecologically friendly power source.

In light of these examples, it is clear that a recalibration of PHM approach for OWFs is imperative. Recognizing the multifaceted interactions between technical, non-technical, and socio-ecological components can lead to more holistic and effective PHM strategies that address the complexities of offshore wind energy systems comprehensively. With this as background author now discusses the future research directions in the PHM domain in context to OWFs.

4. FUTURE DIRECTIONS

Applying the SETS framework to O&M of OWFs necessitates a multidisciplinary perspective, drawing from fields such as environmental science, engineering, economics, sociology, and policy studies. The SES framework, combined with Complex Adaptive Systems theory, provides a robust foundation for comprehending the resilience, adaptability, and transformative potential of OWF O&M systems. Ethical considerations, stakeholder engagement, and ecosystem-based management would further contribute to a holistic understanding of O&M strategies for the OWF within SETS context. There is the need to transcend disciplinary silos and facilitate an integrated approach that aligns technological developments with ecological sustainability and social well-being.

In line with the limitations in the PHM framework, possible future research direction along with relevant methods are given in Table 1. AI and ML would also play a pivotal role in advancing each of these research directions as they enable the analysis of large datasets, pattern recognition, and predictive modeling, enhancing the accuracy and efficiency of PHM strategies. Some examples of AI/ML integration include:

1. **Lacking Non-Technological Factors (NTFs):** Natural Language Processing (NLP) techniques, sentiment analysis, and social network analysis can be used to analyze stakeholder sentiments, engagement patterns, and communication effectiveness. Machine learning algorithms like Random Forest and Gradient Boosting can quantify the impact of NTFs on overall system performance.
2. **Lacking System Level Perspective (SLP):** Complex system modeling techniques such as Agent-Based Modeling and System Dynamics can simulate interdependencies between components and assess their effects on system health. Machine learning methods like Autoencoders can capture hidden relationships between components.
3. **Lacking Multimodal Degradation:** Multimodal AI models using Generative Adversarial Networks (GANs) can learn the multimodal degradation patterns from combined sensor data and human feedback. Supervised machine learning algorithms like Support Vector Machines (SVMs) can classify different degradation modes using a variety of input features.
4. **Non-inclusion of HOF Data:** NLP can extract insights from textual data such as incident reports, maintenance logs, and safety culture assessments. Supervised Machine Learning models can predict failure probabilities considering both technical and HOF features.
5. **Inefficient Uncertainty Management:** Bayesian networks can model uncertainties arising from both technological and NTFs. Deep Learning methods like Long Short-Term Memory (LSTM) networks can predict uncertainty propagation over time.
6. **Lacking Ecological Considerations:** Geographic Information System (GIS) combined with AI can analyze spatial and temporal ecological impacts. Machine Learning algorithms like Gaussian Process can predict ecological changes based on various factors including wind farm operations and marine ecosystem dynamics.

Incorporating AI/ML techniques with the respective methods would enhances the accuracy, speed, and scalability of PHM strategies, leading to more effective and sustainable O&M practices in OWFs.

Table 1. Future research directions and associated methods.

Future Research Direction	Methods
Integrating NTFs	Social Impact Assessments, Stakeholder Engagement Models, Ethical Decision-Making Frameworks
Adopting a SLP	Structural System Decomposition, System Dynamics Modeling, Integrated Risk Assessment
Embracing MMD	Multimodal Degradation Models, Physics based modeling
Incorporating HOFs	Human Factors Engineering, Organizational Behavior Analysis, Safety Culture Assessments, Safety Fractal Analysis
Enhancing Uncertainty Management	Uncertainty Quantification, Probabilistic Risk Assessment, Scenario Analysis.
Incorporating Ecological Considerations	Environmental Impact Assessments, Ecological Modeling, Ecosystem Services Valuation.

5. CONCLUSION

In conclusion, this study sheds light on the limitations and untapped opportunities within the PHM framework for OWFs, viewed through a Socio-Technical-Ecological System (SETS) perspective. The identified research gaps underscore the necessity for a paradigm shift in the approach towards OWF management. The existing over-reliance on technical factors in the PHM framework presents a pressing need to integrate NTFs encompassing socio-cultural and organizational aspects. Such inclusion would broaden the scope of decision-making by accounting for community impacts, stakeholder engagement, regulatory compliance, and ethical considerations, which collectively contribute to the holistic health and performance of OWFs.

Furthermore, the current framework's limitation in considering the system as a whole (System Level Perspective) accentuates the requirement for a comprehensive approach that captures the intricate interdependencies among various components and their cumulative impact on system health. This entails embracing a holistic viewpoint that fuses machine-related data with human-related data, thereby fostering a more accurate representation of system behavior and degradation modes. Additionally, managing uncertainty stemming from both technological and NTFs emerges as an imperative and needs further exploration. Since OWFs coexist within larger marine ecosystems, integrating ecological considerations into the PHM framework will be crucial in aligning OWF operations with biodiversity protection objectives, thereby ensuring their long-term sustainability.

In this pursuit, author emphasized on not only advancing the existing technical models but also embracing AI/ML methods for effective integration of NTFs and ecological parameters. The path forward entails forging collaborations among engineering, social sciences, and environmental disciplines to devise a comprehensive PHM framework that upholds the complex interplay of technical, social, and ecological factors. This transformative approach stands poised to charter new horizons for advancing the PHM framework for OWFs, enhancing their reliability, sustainability, and contribution to the clean energy landscape.

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BIOGRAPHIES

Arvind Keprate received his B. Tech in Mechanical Engineering (2007) from Himachal Pradesh University, M.Sc. in Marine & Subsea Technology (2014), and PhD (2017), in Offshore Engineering from the University of Stavanger, Norway. He is currently an Associate Professor at Oslo Metropolitan University where he teaches Machine Design, Process & Piping Design to Mechanical Engineering students. Besides this, he also teaches Machine Learning, Probability & Statistics at Kristiania University College in Oslo. He has been a visiting researcher at the Prognostics Center of Excellence, NASA Ames Research Center, USA. Currently, his research is focused on Digital Twins, and PHM of complex Socio-Ecological-Technical Energy Systems such as Wind Farms.