

## TECHNICAL AND ENVIRONMENTAL ASPECTS OF WIND FARM MAINTENANCE

Andrei-Cristian BĂDESCU<sup>1</sup>, Bilghe SULIMAN<sup>1</sup>

<sup>1</sup> PhD Students, Faculty of Power Engineering, National University of Science and Technology POLITEHNICA Bucharest, 060042 Bucharest, Romania; andrei.badescu@stud.energ.upb.ro; bilghe.suliman@stud.energ.upb.ro

**Abstract:** *This paper provides a concise analysis of current trends in the maintenance of wind turbines and highlights how modern maintenance strategies contribute to operational sustainability and environmental protection. Based on extensive documentation and practical experience from wind energy projects, the main development directions are identified: the transition from corrective to predictive maintenance, process digitalization through SCADA systems and AI-based platforms, and the integration of circular economy principles in component management.*

*In parallel, the study emphasizes the importance of environmental impact and life-cycle assessment (LCA) as integral parts of a sustainable maintenance strategy. The conclusions show that data-driven and predictive approaches can significantly reduce O&M (Operation and Maintenance) costs, increase equipment availability, and lower the ecological footprint of wind farms.*

**Keywords:** *Predictive maintenance, wind energy, sustainability, environmental impact*

### 1. Introduction

Wind energy has become one of the main pillars of the global energy transition, contributing significantly to the reduction of greenhouse gas emissions and to the diversification of the energy mix. However, the operation of wind farms involves major challenges related to maintenance, reliability, and operational efficiency. Maintenance and repair costs can account for between 15% and 30% of the total Levelized Cost of Energy (LCOE) [1], [2].

In this context, companies and research centers continuously develop advanced maintenance methods aimed at minimizing unplanned downtime, extending equipment lifespan, and optimizing resource consumption. The current trend is toward intelligent, data-driven maintenance capable of anticipating failures before they occur and proposing optimal actions from both cost and environmental perspectives [3], [4].

Properly planned maintenance is no longer just a technical matter but also a key component of sustainability. Modern O&M strategies can directly reduce the carbon footprint by extending component lifetimes, reducing the need for new materials, and minimizing industrial waste [5]. Moreover, assessing the environmental impact of maintenance activities is becoming an integral part of decision-making, enabling simultaneous optimization of technical and ecological performance.

### 2. Current trends in wind farm maintenance

The evolution of maintenance in the wind sector has followed a clear trajectory—from corrective (reactive) maintenance to preventive, predictive, and finally prescriptive maintenance.

#### 2.1 Corrective maintenance

This is the oldest form of maintenance, based on intervention only after a failure occurs. Although initially less costly, this approach carries high risks of unplanned downtime, production losses, and further damage to adjacent components [6].

In the wind industry—where access to turbines is often difficult due to remote locations and weather conditions—corrective maintenance is the most expensive long-term strategy.

## **2.2. Preventive maintenance**

This strategy involves performing maintenance at regular intervals regardless of the actual condition of the equipment. While it reduces the risk of major failures, it can lead to premature replacements and inefficient use of resources. In recent years, preventive approaches have been refined through reliability analyses and historical data modeling to adjust maintenance intervals dynamically [7].

## **2.3. Predictive and prescriptive maintenance**

The most advanced approach is predictive maintenance, based on real-time data from sensors, SCADA systems, and Condition Monitoring Systems (CMS). These monitor vibration, temperature, pressure, and oil quality to detect early signs of component degradation (gearbox, generator, bearings, blades).

By integrating artificial intelligence and machine learning algorithms, maintenance becomes prescriptive—not only predicting failures but also recommending the most efficient corrective actions based on cost, downtime, and ecological impact [8], [9].

Such systems are increasingly supported by digital twins and integrated analytics platforms that simulate the turbine's behavior under real conditions to guide optimal O&M decisions.

## **2.4. Reliability-Centered Maintenance (RCM)**

The RCM approach relies on the functional analysis of each subsystem and the identification of critical components. Its purpose is to prioritize maintenance tasks based on risk level and operational importance. This methodology has become a standard tool for industrial-scale O&M optimization [10].

# **3. Correlation between maintenance and sustainability**

The concept of sustainability in wind energy extends beyond the generation of clean electricity; it also encompasses how equipment is operated, maintained, and decommissioned. Therefore, maintenance activities play a crucial role in reducing environmental impact throughout the turbine's life cycle.

## **3.1. Impact of maintenance on the turbine life cycle**

Life Cycle Assessment (LCA) analyses show that a significant portion of a turbine's environmental footprint is concentrated in the manufacturing and maintenance phases, rather than during operation [11].

Unplanned interventions often lead to additional material consumption, repeated transport to remote sites, and increased logistical emissions. Conversely, predictive maintenance mitigates these effects by enabling efficient planning and extending component lifetimes [12].

## **3.2. Resource optimization and waste reduction**

In modern O&M strategies, resource optimization and spare parts management are key elements of sustainability. Scheduled replacements based on actual equipment condition enable reuse and refurbishment, minimizing waste generation.

For example, gearbox reconditioning and industrial oil filtration can lower environmental impact by up to 20%, according to NREL studies (2023) [13].

## **3.3. Digitalization and energy efficiency in maintenance**

The digitalization of maintenance processes not only enhances reliability but also improves the overall energy efficiency of wind farm operations.

Modern SCADA platforms collect and process data from hundreds of turbines simultaneously, allowing for optimized crew routing, reduced travel times, and lower fuel consumption [14]. Furthermore, predictive analytics can evaluate cost-benefit ratios between replacing or continuing to operate a component based on current performance and environmental risk.

### 3.4. Circular economy strategies

An increasingly important aspect is the integration of circular economy principles. Instead of a linear model (“produce–use–discard”), sustainable maintenance encourages recycling, refurbishing, and material recovery.

Manufacturers and operators now collaborate on blade recycling programs, a key step toward achieving climate neutrality in the wind industry [15].

Thus, sustainable maintenance becomes a central pillar of the circular economy, directly contributing to the UN Sustainable Development Goals (SDGs).

## 4. Analysis and Discussion

### 4.1. Relevant technical indicators

Maintenance performance can be evaluated through indicators such as:

1. MTTF (Mean Time To Failure) – average time before a failure occurs;
2. MTTR (Mean Time To Repair) – average repair duration;
3. Availability (A) – proportion of operational time, calculated as:

$$A = \frac{MTTF}{MTTF+MTTR} \quad (1)$$

These indicators were applied in the author’s previous case studies, showing that predictive maintenance can increase turbine availability from 92% to over 97%, while reducing annual maintenance costs by 10–15%.

### 4.2. Comparative analysis of maintenance strategies

**Table 1:** Comparative analysis of maintenance and environmental impact

| Maintenance Type | Advantages                       | Disadvantages                       | Environmental Impact                       |
|------------------|----------------------------------|-------------------------------------|--|
| Corrective       | Low initial costs                | High downtime, failure risks        | High – frequent transport and replacements |
| Preventive       | Operational stability            | Premature replacements, fixed costs | Moderate – constant resource use           |
| Predictive       | High reliability, optimized cost | Requires sensor/AI investment       | Low – optimized logistics and material     |

This comparison shows that, although predictive maintenance involves higher initial costs (monitoring equipment, software), its long-term benefits in energy efficiency and environmental performance make it the most economically and ecologically viable strategy [16], [17].

### 4.3. Correlation model between maintenance and environmental impact

Based on LCA methodology, a simplified risk matrix can be used to assess how maintenance affects environmental parameters:

**Table 2:** Risk matrix – assessment of maintenance impact of the environment

| Evaluated Factor             | Probability | Consequence | Risk Level |
|------------------------------|-------------|-------------|------------|
| Hydraulic oil leakage        | Medium      | High        | High       |
| Frequent maintenance trips   | High        | Medium      | High       |
| Poor recycling of components | Medium      | Medium      | Medium     |
| Continuous monitoring (CMS)  | Low         | Low         | Low        |

Implementing CMS systems reduces both technical and ecological risks, confirming international findings (IRENA, 2024) and aligning with observations from the author's dissertation.

#### 4.4. Economic considerations

From an economic perspective, predictive maintenance helps reduce the LCOE by minimizing production losses and improving maintenance scheduling.

Industry-wide data shows O&M cost savings of 10–20%, especially for wind farms above 100 MW [18].

Moreover, the reduction of waste and transport-related emissions supports ESG (Environmental, Social, and Governance) targets, increasingly required in energy sector reporting.

#### 5. Conclusions

The analysis demonstrates that maintenance is a critical component for optimizing the performance, sustainability, and profitability of wind farms.

The transition from corrective to predictive and prescriptive maintenance has been driven by the need to enhance turbine availability, lower O&M costs, and align with global environmental goals.

The implementation of CMS systems and AI-based predictive models enables early fault detection and optimal intervention planning, directly reducing LCOE and the carbon footprint.

These technologies foster a sustainable approach by extending component lifetimes and minimizing resource consumption and waste generation.

The key outcomes are:

1. Predictive maintenance increases average turbine availability by up to 5 percentage points;
2. Annual maintenance costs can be reduced by 10–20%;
3. CO<sub>2</sub> emissions and waste from premature replacements can decrease by up to 25%.

Integrating circular economy principles and LCA-based decision-making provides a holistic perspective on wind farm sustainability.

In conclusion, the future of wind farm maintenance will be defined by:

1. Advanced digitalization – through data analytics and digital twins;
2. AI and machine learning integration – for prescriptive decision-making;
3. Operational sustainability – through reduced environmental impact and circular economy implementation.

These developments make maintenance not only a technical process but a strategic driver for clean, efficient, and sustainable energy.

#### References

- [1] Stehly, Tyler, Patrick Duffy, and Daniel Mulas Hernando. "2022 Cost of Wind Energy Review." National Renewable Energy Laboratory (NREL), 2023. Accessed October 30, 2025. <https://docs.nrel.gov/docs/fy24osti/88335.pdf>.
- [2] International Renewable Energy Agency (IRENA). "Renewable Power Generation Costs in 2023," 2024. Accessed October 30, 2025. <https://www.irena.org/Publications/2024/Sep/Renewable-Power-Generation-Costs-in-2023>.
- [3] Ren, Zhengru, Amrit Shankar Verma, Ye Li, Julie J.E. Teuwen, and Zhiyu Jiang. "Offshore wind turbine operations and maintenance: A state-of-the-art review." *Renewable and Sustainable Energy Reviews* 144 (2021): 110886.

- [4] Fox, Harriet, Ajit C. Pillai, Daniel Friedrich, Maurizio Collu, Tariq Dawood, and Lars Johanning. "A Review of Predictive and Prescriptive Offshore Wind Farm Operation and Maintenance." *Energies* 15, no. 2 (2022): 504.
- [5] Bădescu, A.-C. "Trends in the Evolution of Wind Turbine Maintenance. Case Study – Environmental Impact Assessment for a Wind Farm / Tendințe în evoluția întreținerii turbinelor eoliene. Studiu de caz – Evaluarea impactului asupra mediului pentru un parc eolian." Master's Thesis. Maritime University of Constanța, 2025.
- [6] Carroll, J., A. McDonald, and D. McMillan. "Failure rate, repair time and unscheduled O&M cost analysis of offshore wind turbines." *Renewable Energy* 19, no. 6 (2016): 1107–1119.
- [7] Kusiak, A., and A. Verma. "A data-driven approach for monitoring blade pitch faults in wind turbines." *IEEE Transactions on Sustainable Energy* 2, no. 1 (2011): 87–96.
- [8] Ng, Eddie Yin-Kwee, and Jian Tiong Lim. "Machine Learning on Fault Diagnosis in Wind Turbines." *Fluids* 7, no. 12 (2022): 371.
- [9] Davidsson, S., M. Höök, and G. Wall. "A review of life cycle assessments on wind energy systems." *The International Journal of Life Cycle Assessment* 17 (2012): 729–742.
- [10] Atilgan Turkmen, Burcin, and Fatos Germirli Babuna. "Life Cycle Environmental Impacts of Wind Turbines: A Path to Sustainability with Challenges." *Sustainability* 16, no. 13 (2024): 5365.
- [11] Tchakoua, Pierre, René Wamkeue, Mohand Ouhrouche, Fouad Slaoui-Hasnaoui, Tommy Andy Tameghe, and Gabriel Ekemb. "Wind Turbine Condition Monitoring: State-of-the-Art Review, New Trends, and Future Challenges." *Energies* 7, no. 4 (2014): 2595-2630.
- [12] Tchakoua, P., R. Wamkeue, M. Ouhrouche, F. Slaoui-Hasnaoui, T. A. Tameghe, and G. Ekemb. "Wind turbine condition monitoring: State-of-the-art review, new trends, and future challenges." *Energies* 7, no. 4 (2014): 2595–2630.
- [13] National Renewable Energy Laboratory (NREL). "Gearbox Reliability Collaborative Update." Technical Report, 2023.
- [14] Jani, H. K., S. S. Kachhwaha, G. Nagababu, and A. Das. "A brief review on recycling and reuse of wind turbine blade materials." *Materials Today: Proceedings* 62, Part 13 (2022): 7124-7130.
- [15] Jensen, J. P., and K. Skelton. "Wind turbine blade recycling: Experiences, challenges and possibilities in a circular economy." *Renewable and Sustainable Energy Reviews* 97 (2018): 165-176.
- [16] García Márquez, F. P., A. M. Tobias, J. M. Pinar Pérez, and M. Papaalias. "Condition monitoring of wind turbines: Techniques and methods." *Renewable Energy* 46 (2012): 169-178.
- [17] Ding, F., Z. Tian, and T. Jin. "Maintenance modeling and optimization for wind turbine systems: A review." Paper presented at the 2013 International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering (QR2MSE), Chengdu, China, 15-18 July, 2013.
- [18] WindEurope. *O&M and Asset Management Report 2023*. WindEurope, Brussels, 2023, 84 pp.