PANEVĖŽIO KOLEGIJA ISSN 2029-1280, eISSN 2669-0071. Taikomieji tyrimai studijose ir praktikoje – Applied Research in Studies and Practice, 2024, 20.

# REVIEW OF AUTOMATED WIND TURBINE BLADE MAINTENANCE

***Kristupas PETRAUSKAS[a], Daiva STANELYTĖ[ab]***

*[a] Klaipedos valstybine kolegija / Higher Education Institution, Lithuania*
*[b] Lithuanian Energy Institute, Lithuania*

**Annotation.** Wind turbines are one of the most popular solutions for generating and using renewable energy. But studies have shown that wind turbine blade maintenance is essential for the longevity of blades and the whole power plant. The maintenance itself is basically cleaning of wind turbine blades from contamination, which consists of dust, salt, and icing on the surface of blades. If wind turbine blades are not properly cleaned by the schedule, then these three factors of contamination—dust, salt, and icing—cause blade deformation, a double-stall effect, and reduce the efficiency of wind turbine power plants by 10 to 40%. Since most of the cleaning is done manually by humans, which is dangerous for human life, takes more time, and requires more equipment and water usage, this article proposes an automated and autonomous wind turbine maintenance system. The studies have found that using SCADA for monitoring blade condition and integrating automated elements for maintenance itself, such as lifting arm, cleaning robots, and guide rails, makes the whole maintenance cheaper, safer, and more efficient, as it is unstoppable and uses less, if any, economic and human recourses.

**Keywords**: maintenance robots, automated lifting arm, SCADA, wind turbine blades

## INTRODUCTION

Wind farms are being developed more intensively as demand for renewable energy increases. However, there are factors that reduce the efficiency of this renewable energy source. Forced stall is the loss of blade lift due to a change in the aerodynamic properties of the blade itself. In the absence of forced stall, the rotor speed would increase without limit, which would cause mechanical damage to the engine. This stop is therefore foreseen. The double forced stop is an unforeseen change in aerodynamic properties, which reduces the amount of electricity produced and the power of the engine. Dust, salt, and icing on wind turbine blades, without proper maintenance, cause blade erosion, deformation, and a double-forced stopping effect, which reduces the efficiency of the wind turbine between 10 and 40% (depending on the climatic conditions, the geographical location, and the condition of the blades). Wind turbine blade erosion is not a new problem, but damage to blades has increased recently, especially for offshore wind turbines (Papi, Balduzzi et al., 2021). Therefore, wind turbines require specific maintenance. Maintenance does not require the intervention of technical staff, so cleaning is carried out manually or semi-manually, which is already the case in some wind farms. Manual maintenance has many disadvantages. Manual maintenance is dangerous for the operators because of the changing weather conditions and the high altitudes involved. For example, regular maintenance requires equipment consisting of a crane that lifts a platform on which operators are hoisted to the top of the plant, special ropes that hold the operators at a high altitude, and in some cases, a large amount of water to wash the blades. The biggest financial loss is the need to completely shut down the plant while cleaning is carried out. During manual cleaning, two to four operators carry out the maintenance. It takes at least four hours per blade to carry out the maintenance. Thus, such cleaning is very wasteful. In order to solve the problem of cleaning the blades of wind turbines with a minimum of resources and without stopping the turbine at all, a fully automated blade cleaning system is proposed, which will be analyzed later in this article.

**Subject.** Wind turbines.

**The aim of the research:** To analyze and provide recommendations for integrating autonomous and automated wind turbine maintenance system.

**The objectives of the research:**

1. To provide a framework for fully automated wind turbine maintenance.
2. To analyze the implementation of fully automated maintenance of wind turbines.
3. To review the effectiveness of fully automated maintenance of wind turbines.

**Research methods:** analysis of scientific literature.

**Value of research:** this article primary objective is to close the research gap, as there haven't been many studies that are entirely focused on automating wind turbine blade maintenance and implementing autonomous balde condition monitoring. Therefore, this article introduces new looks and solutions considering automated wind turbine blade maintenance, examines an existing blade condition monitoring system, and proposes an additional monitoring system, SCADA, to fill the gap between real-time condition tracking and data transfer, and briefly and methodically discusses the effectiveness of an automated and autonomous wind turbine blade maintenance system if integrated. The article's analysis can be used as a theoretical foundation and offer useful solutions for creating a safe, cost-effective, and low energy-loss maintenance system for wind turbine blades.

## RESEARCH METHODOLOGY

The implementation of automated wind turbine blade maintenance and condition monitoring was examined through a review of scientific literature sources. This study combined secondary data from multiple main studies and analyzed it using a quantitative research approach. Foreign authors' works were among the sources analyzed, allowing for a detailed analysis of the use of automated wind turbine blade maintenance and condition monitoring using one of the most popular condition monitoring systems, which is SCADA. To provide the most thorough literature search possible in databases, research data and theoretical reviews from IEEE and Science Direct were examined. By looking over the titles, abstracts, and full texts, the scientific article's suitability for analysis was evaluated. Because the most pertinent databases were chosen, where research findings on the adaptation of automated wind turbine maintenance and condition monitoring systems were published, a global literature search was carried out, and every search term that could be used to describe the concept under investigation was used. The search of scientific literature was methodical, accurate, detailed, and comprehensive. The used keyword combinations led to the identification of 114 924 publications. Table 1 displays the findings of the databases' search for scientific publications.

1 Table

**Findings from a database search for scientific articles**

| **Keywords** | **Science Direct** | **IEEE** | **SUM** |
|---|---|---|---|
| Maintenance robots | 50 382 | 4593 | 54975 |
| Automated lifting arm | 7283 | 44 | 7327 |
| SCADA | 12 871 | 6033 | 18 904 |
| Wind turbine blades | 29 823 | 3895 | 33 718 |
| **Sum** | 100 359 | 14 565 | 114 924 |

Source: made by an authors, 2024

The interpretation of the results obtained comes next: How can the results be applied? What relevance do the results obtained have for future research? Since the data needed for the study is found in scientific databases, the research is conducted in accordance with research ethics guidelines.

## AUTOMATED BLADE MAINTENANCE METHODOLOGY

The wing is the part of the blade that maintains the structural integrity of the blade as a whole, and if the failure factors continue to develop, the blade will no longer be usable and will need to be replaced (Lopez et al., 2021). So, the whole manual maintenance is done on wind turbine blades, but as mentioned before, manual maintenance is dangerous, so automated maintenance is proposed. Automated maintenance of wind turbines improves plant efficiency because it keeps the plant running without interruption while also cleaning the wind turbine blades with less water equipment and technical staff involvement, which puts operators at risk, (Yaqub et al., 2017). The main risk for technical staff that is mentioned here is hight and moving parts of the plant. Manual cleaning of wind turbine blades is shown in Figure 1.

Figure 1. **Manual cleaning of wind turbine blades.**

Improving wind turbine performance, operation, and efficiency requires evolving Operation and Maintenance (O&M) methods, (El-Naggar et al., 2023). A new maintenance system is proposed. The automated maintenance system consists of three maintenance robots, guide rails, and an automated lifting arm, (Dipankar et al. 2017). Actually, each element has its own operational system, which makes them three separate subsystems of one common automated maintenance system. The automated blade cleaning system components are shown in Figure 2.

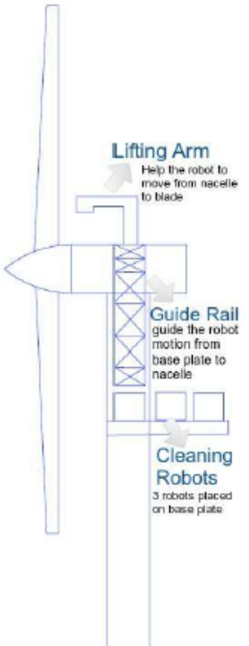


Figure 2. **Automated blade maintenance system components**.

To fulfil automated blade maintenance system, whole new construction is needed alongside the wind turbine tower, because automated system needs to be mounted at the top of the tower and if any installation or update is needed for any of mentioned parts, there has to be an option for technical staff to get up there, so some kind of lift form might be required.

## STRUCTURE OF ROBOTS

Since maintenance robots will be used outside and sometimes in harsh conditions (depending on where the wind farm is located), these robots have to have enough sensors to work reliably and confidently. To do that, robots have to scan and gather information about the terrain and environment in which they are. Each robot contains five sensors: two distance measure sensors, a pressure sensor, an edge detection sensor, and a thickness measuring sensor, (Dipankar et al., 2017). Sensors are the main output signals for robots to understand the movement in space. But those five sensors might not be enough for reliable work since distance, pressure, and other physical quintity measuring sensors cannot define environment and terrain type. As mentioned before, wind turbine blades might be dusted, covered in ice, or already deformed. So there is a solution to how wheeled robots could scan and analyze the environment to correct their movements.

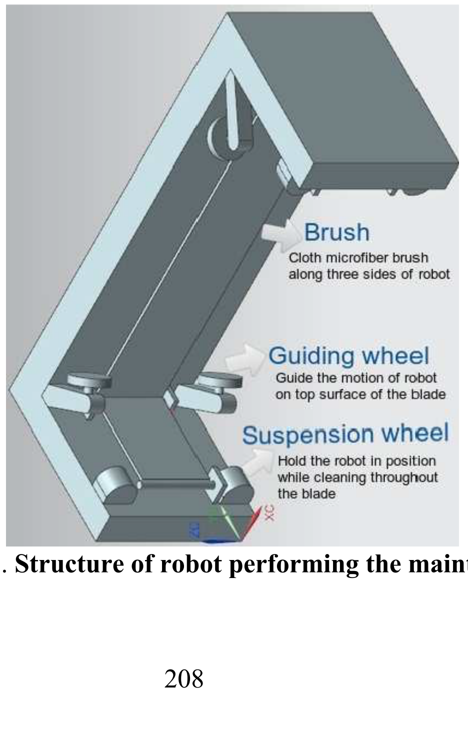


Figure 3. **Structure of robot performing the maintenance**

Accelerometer and gyroscope could be added in addition to those five already existing sensors. The data of the accelerometer and the gyroscope were tested separately and together, and different processing window sizes were also applied. Data from inertial sensors were collected for different outdoor terrain types using a prototype measurement system. The achieved results show that above 99% classification efficiency can be achieved using the collected data, (Csík et al., 2021). So, the gyroscope and accelerometer do not actually scan the environment; SCADA does that. The gyroscope and accelerometer are just additional sensors for all wheeled robots to help them to control their movement and correct their trajectory.

Four DC motors rotate the steering wheels that move the robot on the blade's surface, stop wheels keep the robot still while cleaning, and microfibre brushes attached on the base of the robot body are used for cleaning itself, (Nisarg et al., 2017). The robot performing the technical cleaning is shown in Figure 3.

To prevent varying blade moments of inertia, which could result in structural damage to the blade, the robots must be the same size, weight, and shape (Nisarg et al., 2017).

## STRUCTURE OF GUIDE RAILS AND LIFTING ARM

Five sensors are required for guide rail functioning, which also includes three stands connected to the individual robot systems, (Nisarg et al., 2017). Guide rails are actually part of the construction shown in Figure 2, because, as it can be seen, there is a lift-type construction from the base plate up to the nacelle. And the guide rails are mounted inside that construction together with the robot detecting sensors and pressure sensors.

The automated lifting arm, which is built of a high-resolution camera, a spacial sensor, and pressure and maintenance sensors for robot detection, is intended to move the robots from the top position of the guide rails to the wind turbine blade itself (Nisarg et al., 2017). Though in this study there is little information on how the sensors were picked, it seems that some sensors could be replaced with a simpler and cheaper alternative; for example, for robot detection, a simple movement sensor could be used instead of pressure and maintenance sensors. A tiny subsystem consisting of the camera and the spatial sensor seeks to precisely position the wind turbine blade in various weather scenarios (Dipankar et al., 2017).

So, to conclude the structure of guide rails and lifting arm, the statement can be made that guide rails and lifting arm together form a one maintenance robot transportation system, but the same system could be realized with a smaller number of sensors, which are overused in this case, and that means a higher price.

## AUTOMATED MAINTENANCE

Before initiating automated maintenance, information and signals about bad wind turbine blade conditions are required. There are a lot of information and data gathering sources, but most of them are pretty expensive to install and maintain. Minimization of the maintenance costs requires as precise as possible maintenance scheduling (Nurseda et al., 2020). So, the proposal is to use SCADA. Moreover, the proposed solution implies low deployment costs because it relies solely on the information collected from the widely available supervisory control and data acquisition (SCADA) system (Yingying et al., 2017). Therefore, the SCADA-based condition monitoring is mostly performed by using an industrial standard, which is data averaging on a ten-minute basis. However, such an averaging time leads to the drawback that SCADA-based methods are considered to provide a late-stage indication of incoming faults (Murgia et al., 2023). But as mentioned earlier, it is cheap and quite effective.

All the cleaning events are triggered by the scheduling function. When the scheduler prompts that scheduled cleaning time has reached, the ODS (Operations and Decision-making Subsystem) sends a message to NCS (Network Communication Subsystem). NCS activates the communication link and acquires necessary information from the local sensors and remote servers. So, in this whole SCADA, ODS, and NCS communication system, the real-time information is acquired and evaluated.


Figure 4. **Local network communication subsystem**

When a signal is applied to the microcontroller to perform maintenance, the microcontroller sends a signal to the maintenance robots to take positions on the guide rail (Dipankar et al., 2017). The robot and pressure detection sensors detect that the robots have taken up positions on the stands and start their movement up until a second robot detection sensor at the top of the system is activated, which sends a signal that the robots have reached a set height and the guide rail system stops moving (Nisarg et al., 2017). In this case, the most basic automation principles are used for starting and stopping the process, making this system very easy to install because basically there are two position sensors at the top and at the bottom of the system, which start and stop the movement of the guide rail, but no emergency stop is provided. When the guide rails stop, the microcontroller sends a signal to the automated lifting arm, whose camera and spacial sensor subsystem detects the positioning of the robots and accurately moves them from the guide rails to the surface of the blade (Dipankar et al., 2017). On the blade surface, the robots adjust their direction of movement with the guide and stop wheels and with an attached microfibre brush. The blade is cleaned. Instead of the microfibre brush, sponge pads can be used with sensor nodes that measure the thickness of the plaque on the surface of the blade that needs to be cleaned (Yaqub, 2017).

Once cleaning is complete, the same operation is executed, but in reverse. Execution is initiated by feedback – an automated lifting arm picks up the robots from the blades and moves them onto the guide rails, where object detection and pressure sensors detect that the robots have taken up positions on the stands, and the system starts moving downwards until it reaches the base plate (Nisarg, 2017).

The individual components of the automated system form a single system whose purpose is to autonomously monitor the condition of the wind turbine blades and carry out regular maintenance.

## EFFICIENCY OF AUTOMATED MAINTENANCE

The fault mode of interest can incur a long period of downtime if not detected and acted upon before the functional failure of the generator, forcing the wind turbine to a standstill until the failed generator has been replaced (Hansen et al., 2024). Also, depending on the geographical location, dust, icing, and salts cause blade erosion, which has a negative effect on the aerodynamic performance of wind turbine blades (Mishnaevsky Jr. et al., 2020). Erosion degrades the aerodynamic performance, reduces the maximum lift force, increases the total drag force at all values of blade angle, and reduces the forced stop threshold, which is dependent on the reduction of blade angle and wind direction (Castorrini et al., 2023). So as mentioned before, the main goal of an automated maintenance system is to prevent wind turbines from causing double-stall effects, failure of the generator, and blade erosion, considering all the effects and risks of damaged blades. Since downtime of wind turbines is a loss in energy and finances, the automated system has to be effective enough to prevent wind turbines from stopping at all. To understand the actual losses of wind turbine failures, some numbers will be provided.

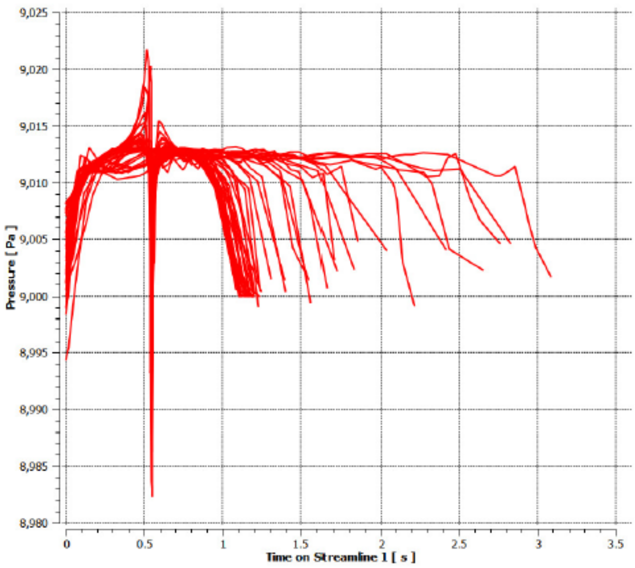


Figure 5. **Wind pressure of uneven dust deposition.**

More than 3800 failures are reported annually; over a 20-year period, downtime for a 500 MW offshore wind farm can result in production losses of approximately 12 million euros per year (So Young Oh et al., 2024). Also, it should be mentioned that if a wind farm is located on an offshore site, maintenance is even more expensive. Offshore wind farms are located in remote areas that are often subjected to harsh conditions; therefore, they require special equipment for maintenance (e.g., vessels), which significantly increases the operation and maintenance (O&M) costs (Saleh et al., 2023). Therefore, early detection of failures and decreasing downtime is crucial to minimize losses and ensure the longevity of the system. Also, some simulations were done to show the difference in wind pressure to wind turbine blades depending on dust deposition if an automated maintenance system was integrated.

Figure 5 illustrates the wind profile that is impacted by uneven deposition density, with two blades having dust depositions that are 1 mm thick and the third blade having dust that is 1.5 mm thick. This diagram illustrates the connection between wind pressure and time. The abrupt shift in pressure suggests the existence of a positioned wind turbine blade in the hollow cylinder of the simulation. Because of the unequal distribution of dust, the wind pressure does not, in contrast, converge after passing the wind turbine to the one in Figure 6 that converges in the clean blade simulation.

Figure 6 displays the wind pressure profile caused by clean blades. After the incoming wind force has interacted with the cleaned wind turbine blades, this profile amply illustrates the convergence of wind pressure.

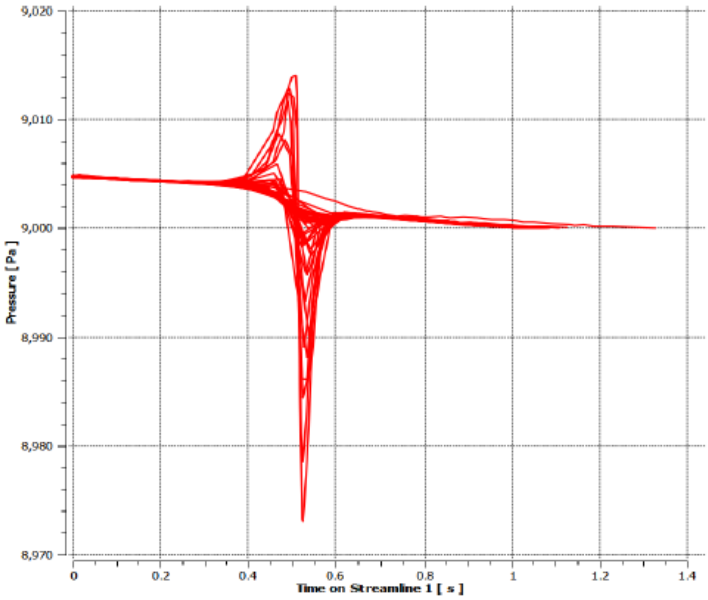


Figure 6. **Wind pressure of clean blades.**

So, the simulation above showed the importance of clean blades, because in the case where blades are clean, the pressure of the wind on the blades is not so abrupt and scattered. If the proposed automated maintenance system is used, the risk and danger to the technical staff are reduced, the consumption of water resources and equipment is reduced, the operation of the wind turbine is not interrupted, and breakdowns are avoided, resulting in no losses (Nisarg et al., 2017). Below, there is a table that compares the existing maintenance and proposed solutions.

2 Table

**Comparison of existing and proposed solutions.**

| Specifications | Manual | Semi-automatic | Automatic |
|---|---|---|---|
| Cleaning time | 4x3 hours | 1.5x3 hours | ½ or ¾ hour |
| Intensity of work | High | Medium | Low or none |
| Water consumption | High | Medium | Low or none |
| Operational status | Suspended | Suspended | Working |
| Safety | Unsafe for blades and staff | Safe | Safe |
| Cost-effectiveness | Not cost-effective | Not cost-effective | Cost-effective |

Manual maintenance of wind turbine blades is costly, inefficient, and dangerous for staff, so the proposed automated wind turbine maintenance system helps to solve the problems of cost-effectiveness, safety, and efficiency. As it can be seen from the table, that automated wind turbine blade maintenance system reduces cleaning time to half a time compared to manual cleaning. Intensity of work, water consumption is very low, since there are no humans involved in the process, it is completely safe, and the most important thing is that wind turbine status is operational, so basically, if the proposed system were to be installed and with proper maintenance of the system itself, losses of 12 million euros per year per one wind turbine could be eliminated.

## CONCLUSIONS

Renewable energy sources are one of the fastest growing directions in electrical energy generation and consumption, but as demand for wind turbines grows, maintenance of these wind turbines becomes more and more complex because of manual maintenance dangers. Maintenance includes not only physical cleaning of wind turbine blades but also gathering and collecting real-time data on wind turbine blade condition to even prevent any known damage to blades from happening. So, as solutions were proposed and found for maintenance and condition monitoring for wind turbine blades, the conclusions of this study are:

1. The automated wind turbine maintenance structure consists of three maintenance cleaning robots, an automated lifting arm, and guide rails. All components are separate subsystems that, combined, build one whole functioning automated blade cleaning system.

2. The execution process consists in making the maintenance of wind turbines as automated and autonomous as possible and requiring minimal, if no, intervention by technical staff. Blade condition is monitored using the widely used SCADA system, which makes condition monitoring cheap and effective, despite it's minor flaws. Also, a local network communication subsystem makes maintenance fully autonomous and, combined with the SCADA real-time monitoring system, is implemented.

3. As mentioned in this article, wind turbine standstill is huge power and financial losses, and since renewable energy sources are in high demand, on-time maintenance is very important to prevent wind turbine failures. Now more and more people depend on this energy, so considering the effectiveness of automated maintenance systems, it is clear that these systems have to be in higher priority of development and research. But as of now, all the studies have shown that automated maintenance is a more efficient, cost-effective, less resource and time-consuming, and safer solution compared to manual maintenance.

## REFERENCES


Brahmbhatt, N. Mrunal, P. Dipankar, D. (2017). Micro-controller Driven Wind Turbine Blade Cleaning Peripheries. International Conference on Advances in Computing, Communications and Informatics (ICACCI). 847-851. Retrieved from: https://doi.org/10.1109/ICACCI.2017.8125947

Castorrini, A. Ortolani, A. Campobasso Sergio, M. (2023). Assessing the progression of wind turbine energy yield losses due to blade erosion by resolving damage geometries from lab tests and field observations. Renewable Energy, 218, 119296. Retrieved from: https://doi.org/10.1016/j.renene.2023.119256

Csík, D., Odry, Á., Sárosi, J. Sarcevic, P. (2021). Inertial sensor-based outdoor terrain classification for wheeled mobile robots. 2021 IEEE 19th International Symposium on Intelligent Systems and Informatics (SISY). 159-164. Retrieved from: doi: 10.1109/SISY52375.2021.9582504.

Dipankar, D. Mrunal, P. Himmat, S. (2017). Automated cleaning of wind turbine blades no downtime. 2017 IEEE International Conference on Industrial Technology (ICIT). 394-399.

El-Naggar, M. Sayed, A,. Elshahed, M,. EL-Shimy, M,. (2023). Optimal maintenance strategy of wind turbine subassemblies to improve the overall availability. Ain Shams Engineering Journal, 14(10), 102177. Retrieved from: https://doi.org/10.1016/j.asej.2023.102177.

Hase, H.H. MacDougall, Jensen, C.D., Kulahci, M., Nielsen, F.B. (2024). Condition monitoring of wind turbine faults: Modeling and savings. Applied Mathematical Modelling, 130, 160-174. Retrieved from: https://doi.org/10.1016/j.apm.2024.02.036.

Yaqub, R. Heidary, K. (2017). Autonomous Wind Turbine Blades Cleaning System. 2017 IEEE International Conference on Smart Energy Grid Engineering (SEGE). 394-399.

Yürüşen, N.Y., Rowley, P.N., Watson, S.J., Melero, J.J. (2020). Automated wind turbine maintenance scheduling. Reliability Engineering & System Safety, 200, 106965, Retrieved from: https://doi.org/10.1016/j.ress.2020.106965.

Lopez, C.J., Kolios, A. (2022). Risk-based maintenance strategy selection for wind turbine composite blades. Energy Reports, 8, 5541-5561. Retrieved from: https://doi.org/10.1016/j.egyr.2022.04.027.

Mishnaevsky, L. Hasager, C.B, Bak, C., Tilg, A.M., Bech, I.J. Doagou Rad, S., Fæster, S. (2021). Leading edge erosion of wind turbine blades: Understanding, prevention and protection. Renewable Energy, 169, 2021, Pages 953-969. Retrieved from: https://doi.org/10.1016/j.renene.2021.01.044.

Murgia, A. Verbeke, R. Tsiporkova, E. Terzi, L. Astolfi, D. (2023). Discussion on the Suitability of SCADA-Based Condition Monitoring for Wind Turnbine Fault Diagnosis through Temperature Data Analysis. Energies, 16(2), 620. Retrieved from: https://doi.org/10.3390/en16020620. 1-20.

Nurseda, Y. Rowlay, P. Watson, S. Melero, J. (2020) Automated wind turbine maintenance scheduling. Reliability Engineering & System Safety, 200, 106965. Retrieved from: https://doi.org/10.1016/j.ress.2020.106965.

Oh, S.Y., Joung, C., Lee, S., Shim, Y.B., Lee, D., Cho, G.E., Jang, J., Lee, I.Y., Park, Y. (2024). Bin Condition-Based Maintenance of Wind Turbine Structures: A State-of-the-Art Review. Renew. Sustain. Energy Rev. 204, 114799. Retrieved from: https://doi.org/10.1016/j.rser.2024.114799.

Papi, F., Balduzzi, F., Ferrara, G., Bianchini, A. (2021). Uncertainty quantification on the effects of rain-induced erosion on annual energy production and performance of a Multi-MW wind turbine. Renewable Energy, 165(1), 701-715. Retrieved from: https://doi.org/10.1016/j.renene.2020.11.071.

Saleh, A. Chiachío, M. Fernández Salas, J. Athanasios, K. (2023). Self-adaptive optimized maintenance of offshore wind turbines by intelligent Petri nets. Reliability Engineering & System Safety, 231, 109013. 1-20. Retrieved from: https://doi.org/10.1016/j.ress.2022.109013.

Zhao, Y. Dongsheng, L. Dong, A. Kang, D. Qin Lv. Shang, L. (2017). Fault Prediction and Diagnosis of Wind Turbine Generators Using SCADA Data. Energies 2017, 10(8). Retrieved from: https://doi.org/10.3390/en10081210. 1-17.