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IMPORTANCE AND COST OF MAINTENANCE PRACTICES IN WIND TURBINES

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Abstract

The daily increase in global demand for energy the use of renewable energy sources. Global warming, environmental pollution, and the depletion of fossil fuels require energy production sources to be clean and renewable. Among the renewable energy technologies wind energy is the most preferred technology after solar. Advancements in technology, increases in capacity factors, and decreases in initial investment costs contribute to the growing number of wind energy facilities. The most important component of wind energy facilities is the wind turbine. As with any operating device, wind turbines can face malfunctions for various reasons. Ensuring that turbines operate safely, efficiently, and with longevity is possible through regular maintenance and repairs. Mechanical and electrical malfunctions can cause interruptions in energy production and financial losses. Planned maintenance practices can ensure the continuity of energy production and prevent losses. It has been determined that if the necessary maintenance are not carried out on time, a financial loss of 613.2 $ / per day will occur for 1 MW wind power plant operating with %35 capacity factor, based on the unit energy production pricing of 73 $/MWh as listed in the Electricity Market YEKDEM and according to Law No. 3453. This study examines the importance of maintenance practices and the cost of maintenance in wind energy facilities.

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RÜZGAR TÜRBİNLERİNDE BAKIM UYGULAMALARI VE BAKIM MALİYETİ

Anahtar Kelimeler

Rüzgar enerjisi, rüzgar türbini verimi, rüzgar türbin santrali, rüzgar türbini bakımı, bakım maliyeti

Öz

Tüm dünyada enerjiye olan talebin günden güne artması yenilenebilir enerji kaynaklarının kullanımını zorunlu kılmaktadır. Küresel ısınma, çevre kirliliği, fosil yakıtların tükeniyor olması; enerji üretim kaynaklarının temiz ve yenilenebilir olmasını gerektirmektedir. Yenilenebilir enerji teknolojileri arasında rüzgar enerjisi güneşten sonra en çok tercih edilen enerji teknolojisidir. Gelişen teknoloji, kapasite faktörlerinin her geçen gün artması, ilk yatırım maliyetlerinin azalması rüzgar enerjisi santrallerinin kurulumunu her geçen gün arttırmaktadır. Rüzgar enerji santrallerinin en önemli bileşeni rüzgar türbinleridir. Çalışan her cihaz gibi rüzgar türbinlerinde de çeşitli nedenlerle zaman zaman arızalar meydana gelmektedir. Türbinlerin uzun ömürlü, güvenli ve verimli şekilde çalışmaya devam edebilmesi, düzenli şekilde bakım ve onarımlarının yapılması ile mümkündür. Meydana gelebilecek mekanik ve elektriksel arızalar enerji üretiminde kesintiye ve maddi kayıplara sebep olmaktadır. Planlı bakım uygulamaları, enerji üretiminin devamlılığını ve kayıpları engelleyebilmeyi mümkün kılmaktadır. Bu çalışmada rüzgar enerji santrallerinde bakım uygulamalarının önemi ve bakım maliyeti incelenmiştir.

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1. Introduction

The global wind energy sector is poised for substantial growth in the coming years. According to the Global Wind Energy Council (GWEC), annual wind energy installations are projected to double from 78 GW in 2022 to 155 GW by 2027, bringing the total global wind capacity to approximately 1,581 GW(URL-1). By technological advancements, increasing demand for renewable energy, and supportive government policies worldwide, the global wind energy market was valued at $62.1 billion in 2019 and is expected to reach $127.2 billion by 2027(URL-2).

The gradually increasing use of fossil fuels causes global warming, disrupting the natural balance, leading to rapid melting of glaciers, temperatures deviating from seasonal norms, droughts in some regions, and floods in others. All these negative effects can be reduced by obtaining the energy needed from renewable sources and using it efficiently.

Türkiye is abundant in renewable energy sources. As stated in data reported by official sources, the potential for wind energy is 48,000 MW(URL-3; Republic of Türkiye Ministry of Energy and Natural Resources (2023). The first wind energy facility in Türkiye began operating in 1998 in Çeşme, İzmir, with a capacity of 55 kW (Çanka Kılıç, 2012). Investments have increased since 2005, and many wind energy facilities have been established (İlkılıç, 2009; Koç and Şenel, 2013; Hayli, 2001). Today, the installed capacity has exceeded 10 GW (URL-4). While the number of onshore/offshore wind turbine increasing daily, 2 MW onshore and 5 MW offshore are being projected (URL-5).

Wind energy is an energy source that stands out among renewable energy sources with its environmental sustainability and economic benefits. Wind turbines play a key role in the production of this energy. However, regular maintenance is very important for the turbines to operate effectively and continuously. Due to the energy loss resulting from the failure of the wind turbine must be covered by fossil fuels.

Periodic maintenance in wind turbines ensures the smooth operation of these systems, the safety of the system and employees, the long life of the turbine components, the continuity of energy supply, the reduction of environmental impacts with less energy loss and maximum efficiency in energy production. Otherwise, energy losses occur and system performance is adversely affected (Öztürk, 2020). Maintenance costs, although they may seem high in the short term, will prevent the costs of possible problems in the long term (Mishnaevsky, 2019).

Wind turbines are complex systems subject to various types of failures, which can be broadly categorized into external and internal failures. Damage to the turbine's exterior components, usually the blades, named external failures(Bird strikes, Lightning strikes, rain, hail,..). And malfunctions within the turbine's mechanical and electrical systems named internal failures(Gearbox Failures, Generator Failures, Bearing Failures, Nacelle Fires,..). Understanding these failure modes is crucial for developing effective maintenance strategies and improving the reliability and longevity of wind turbines(Chen, 2018).

Mishnaevsky (2020) investigate the failure mechanisms of wind turbine blades by scale testing of blades in laboratories, a post-mortem analysis of failed blades, analysis of incident reports and computational modelling. high velocity region, transitional and tapered areas, interface and bonded regions determined the most endangered regions of the blades.

Tchertchian and Millet (2023) determined that a systematic maintenance organisation would be able to resolve the failure in a shorter time and shorten the energy downtime. Thus, energy production can continue with zero emission by ensuring that wind turbines are available as soon as possible.

The wind energy industry continuously improves its operation and maintenance practices to reduce the levelized cost of energy. Predicting failures in wind turbines enables early warning and timely intervention, thereby minimizing costly corrective maintenance as much as possible. Additionally, it helps prevent production losses due to prolonged downtime. Latiffianti, Sheng and Ding(2022), developed an early warning system that can detect gearbox failures in turbines by following 5 wind turbine data for 2 years.

The maintenance costs of wind turbines rise significantly when they operate under challenging and unpredictable conditions. Furthermore, the aging of wind turbines adds to the frequency of unplanned maintenance activities. Some components like gearbox, power generator, blades and control systems cover the %80 of the total maintenance cost according to Jimmy, McDonald, and Carroll, J. (2020), Dao, Kazemtabrizi, and Crabtree (2019) and Perez and Ntaimo(2015)

Santelo, Oliveira and Maciel (2021), consider that 2 MW wind turbine paid US$36.00/MWh for energy generation. According to the study, for 2 MW turbine, maintenance cost US$44,000.00/year if preventive interventions are not made and if one preventive maintenance is made US$8000.00/year.

Rezamand, Kordestani, Carriveau, Ting, Orchard and Saif (2020), search the effect of climatic conditions and turbine types over the reliability and availability behavior of the wind turbine. The results show that colder climates significantly affect rotor blade performance, leading to longer downtimes and higher failure rates. Additionally, lightning has emerged as a major cause of rotor blade failures in colder climate regions. It is concluded that the turbine type and installation location should be taken into consideration when determining the operation and maintenance strategy.

This study examines the malfunctions in wind turbines, their causes, detection methods, the importance of maintenance practices, the cost analysis of potential failures in wind turbines, and the energy losses that can be prevented through maintenance practices.

2. Materials and Methods

2.1 Conversion of Wind to Energy

Wind turbines are systems that convert the kinetic energy of the wind into mechanical energy and then into electrical energy. The mathematical formula expressing the portion of the theoretical power of the wind that converts into electrical energy is presented in Equation (1) (Yavuz and Özbay, 2020).

$$P = \frac{1}{2} \times \rho \times A \times \vartheta^3 \times C_P \tag{1}$$

P : Net power generated by the wind turbine (W)

ρ : Air density (kg/m^3)

A : Area swept by the wind turbine blades (m^2)

ϑ : Average wind speed at the turbine installation site (m/s)

C_P: Turbine efficiency percentage

According to the mathematical formula, the factors affecting the amount of energy produced include the wind speed at the installation site and the blade length of the wind turbine.

2.2 Maintenance Practices in Wind Turbines

Turbines with a capacity at the MW level and an average lifespan of 25 years are being produced nowadays. Factors determining the lifespan include the environment where the turbine is located, operating conditions linked to climatic factors such as wind, temperature, humidity, and lightning, material quality, and most importantly, regular maintenance and repair activities. The basic components of wind turbines; tower, rotor blade, nacelle, hub can be shown in Figure 1.

Adverse weather conditions such as storms, lightning, heavy rainfall, freezing cold, or metal fatigue in turbine components can lead to malfunctions, reduced efficiency, interruptions in energy production, or shortened turbine lifespan. Repairs due to wear-related malfunction in turbines can be prolonged or the malfunctions can be permanent. Depending on the severity of the malfunction, solutions involve either part replacement or repair. If energy production is halted for an extended period during the solution process, then the cost becomes significantly higher. Rapid detection of malfunctions and immediate part replacement when necessary prevents the failure of other turbine components. Short-term, temporary faults due to sensor or grid issues can be resolved by temporarily shutting down and restarting the system and they cause only energy production losses. Figure 2 shows a wind turbine blade damaged by lightning.

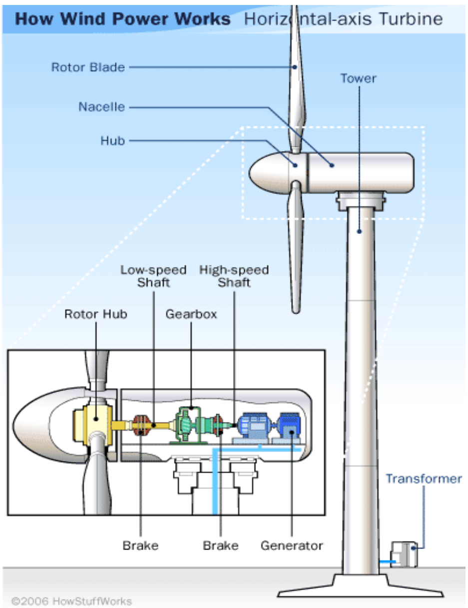

Figure 1. Basic Components of a Wind Turbine (URL-4)

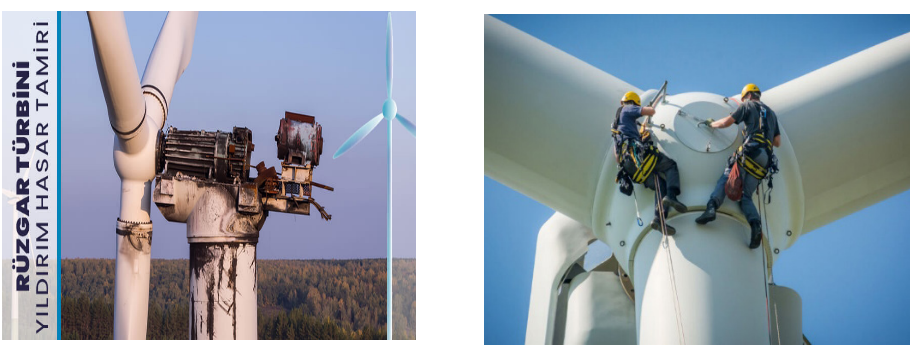

Figure 2. Wind Turbine Lightning Damage & Maintenance (URL-5)

Adverse weather conditions such as storms, lightning, heavy rainfall, freezing cold, or metal fatigue in turbine components can lead to malfunctions, reduced efficiency, interruptions in energy production, or shortened turbine lifespan. Repairs due to wear-related malfunction in turbines can be prolonged or the malfunctions can be permanent. Depending on the severity of the malfunction, solutions involve either part replacement or repair. If energy production is halted for an extended period during the solution process, then the cost becomes significantly higher. Rapid detection of malfunctions and immediate part replacement when necessary prevents the failure of other turbine components. Short-term, temporary faults due to sensor or grid issues can be resolved by temporarily shutting down and restarting the system and they cause only energy production losses. Figure 2 shows a wind turbine blade damaged by lightning.

Sudden changes that might occur in atmospheric weather conditions can create mechanical imbalances in the turbine blades and lead to vibration issues (Eric and Bayrak, 2015; Bayrak, Eric and Küçüker 2016). Therefore, it is very important to ensure that turbines operate within the specified wind speed limits. Operating outside these limits reduces efficiency, remarkably affects turbine lifespan, or may cause much larger failures. Monitoring systems help mitigate potential losses by early detection of mechanical imbalances (Herbert-Acero, Probst, Réthoré, Larsen and Castillo-Villar 2014; Hansen, 2008; Gong and Qiao, 2010). The most common failures in wind turbines are mechanical failures; however, periodic maintenance and data tracked by monitoring systems reduce efficiency loss, energy interruptions, and potential financial losses (Ramlau and Niebsch, 2009).

2.3 Failure Costs in Wind Turbines

The annual operation and maintenance cost of wind turbines corresponds to approximately 3%-5% of the installation cost (Milborrow, 2010). When compared to the installation cost, malfunctions that can be resolved at a much lower cost consist of four primary cost components. Equation (2) expresses the failure cost(CF) in a wind turbine, which consists of four main costs:

$$C_F = C_M + C_S + C_0 + C_L \tag{2}$$

C_M : The cost of parts that need to be replaced due to failure

C_S : The service cost related to the facilities and equipment required due to failure

C_0 : The cost of revenue loss in electricity generation due to the failure

C_L : The total labour cost required for the repair

The performance of a wind turbine's energy production is expressed by the capacity factor (Boccard, 2009). The capacity factor provides information on how many hours in a year (8760 hours) the energy production systems operate at full capacity. In Türkiye, a wind power plant operates with an average capacity factor of 35%, although this can vary according to region. Considering a 1 MW wind power plant operating at a 35% capacity factor, the annual energy produced can be calculated as follows:

$$E_{\frac{Produced}{year}} = 1\,MW \times 8760\,hour \times 0.35 = 3066\,MWh/year \quad (3)$$

The daily energy production can be calculated as:

$$E_{Produced/day} = 3066\,\frac{MWh}{year} \div 365\,Days = 8.4\,MWh/day \quad (4)$$

The financial loss that would occur in case of a malfunction at a wind power plant and a one-day halt in energy production, based on the unit energy production pricing of 73 $/MWh as listed in the Electricity Market YEKDEM (Renewable Energy Resources Support Mechanism) List and according to Law No. 3453 of the Renewable Energy Law (URL-6) can be calculated as follows:

$$E_{Loss\ cost} = 73\ \$/\mathrm{MWh} \times 8.4\ \mathrm{MWh/day} = 613.2\ \$/\mathrm{day} \quad (5)$$

Preventative maintenance and inspections can prevent such malfunctions before they occur, thus prevent potential production losses and associated financial damages.

2.4 Malfunctions in Wind Turbines: Causes, Detection Methods

A malfunction occurs when a device no longer operates as intended. Various types of malfunctions may occur in wind turbines, which can cause partial or complete halts in energy production. Primarily, malfunctions that lead to a total loss of electricity generation occur when the main components of the turbine, as listed in Table 1.1, fail or are damaged. Minor malfunctions such as surface damage and cracks, oil leaks, or loose connections are less significant as they do not stop energy production, but if ignored and not addressed, they can lead to major malfunctions.

Table 1. Wind Turbine Subcomponents and Main Components (Kahrobaee and Asgarpoor, 2011)

Subcomponent	Main Components
Structure	Nacelle, Tower, Foundation Structure
Rotor	Blades, Hub, Brake
Mechanical Brake	Brake Disc, Spring, Motor Mechanical Brake
Main Shaft	Shaft, Bearing, Couplings
Gearbox	Gears, Pump, Oil Heater/Cooler, Hoses
Generator	Shaft, Bearings, Rotor, Stator, Coil
Yaw System	Yaw Drive, Yaw Motor
Converter	Power Electronics Switch, Cable, DC Bus
Hydraulic Pistons	Cylinders, Hoses
Electrical System	Starter, Capacitor, Transformer, Cable, Switchgear
Pitch System	Pitch Motor, Gears
Control System	Sensors, Anemometer, Communication System, Processor, Relays

Malfunctions in wind turbines can arise from a variety of causes, as detailed in Table 2, including weather conditions, mechanical failures, electrical issues, or wear and tear. The performance and lifespan of wind turbines can be significantly influenced by various factors such as weather conditions, mechanical failures, electrical issues, and wear and tear. Weather conditions including high wind speeds, lightning strikes, and ice accumulation can reduce the turbine's efficiency and cause mechanical damage. Extreme winds may cause the turbine to automatically shut down, while lightning strikes can result in short circuits in electrical components, and ice buildup can impair aerodynamic performance. Mechanical failures often arise from the wear of turbine components. For instance, cracks and erosion in the blades reduce efficiency, while failures in the gearbox and bearings can cause the turbine to stop functioning. Electrical issues such as generator malfunctions and control system failures can lead to power generation interruptions and complete turbine shutdowns. Wear and tear from continuous operation results in component degradation over time, leading to efficiency loss and increased maintenance needs. All of these factors can disrupt turbine operations, causing production losses, higher maintenance costs, and reduced turbine lifespan. As a result, these issues can lead to financial losses. Regular maintenance and monitoring are essential for ensuring that turbines operate efficiently and have a long service life.

Table 2. Causes of Turbine Malfunctions

Weather Conditions	Mechanical	Electrical	Wear and Tear
High wind speed	Production and material defects	Grid faults	Aging
Icing	Human error	Overload	Corrosion
Lighting	External damages	Human error Software error	

Different methods can be employed to detect malfunctions in wind turbines, as outlined in Table 3. Detecting malfunctions in wind turbines is crucial for maintaining their efficiency and minimizing downtime. Modern detection methods, such as vibration monitoring, temperature sensors, condition monitoring systems, and predictive analytics, offer significant advantages in identifying issues early. These technologies help operators take preventive action, reduce repair costs, and extend the operational lifespan of turbines. Regular monitoring, combined with advanced diagnostic tools, is essential for ensuring the reliability and performance of wind turbine assets.

Table 3. Malfunction Detection Methods

Control / Inspection	Visual Auditory
Condition Monitoring	Vibration analysis Oil analysis Infrared thermography Ultrasonic
Maintenance	Time-based Condition-based

Among the malfunction detection methods, the most commonly used ones are visual/auditory inspections or those conducted during the general maintenance of the turbine. However, the fastest and most reliable method is online condition monitoring. Vibration analysis, oil analysis, infrared thermography, and ultrasonic monitoring are among the fastest malfunction detection analyses within online condition monitoring methods (Wu, Lang, Zargari and Kouro., 2011).

In developing countries, malfunction detection and maintenance practices for wind turbines differ significantly from those in developed countries due to factors such as infrastructure, technology access, workforce expertise, economic resources, and local conditions.

Infrastructure and technology in developing countries often lack advanced tools like Condition Monitoring Systems (CMS) and predictive maintenance software, which are commonly used in developed nations for real-time data analysis and early fault detection. As a result, maintenance in developing countries relies more on manual methods and basic diagnostic equipment, leading to delayed fault detection and higher costs.

2.5 The Importance of Maintenance in Wind Turbines

Maintenance of wind turbines plays a very important role in efficiency, safety, durability, cost reduction, and minimizing environmental impact.

- Regular maintenance of wind turbines ensures that they operate at maximum efficiency.
- Conducting maintenance regularly ensures safe operation of turbines and safety of operational personnel.
- Routine maintenance extends the durability and lifespan of wind turbines.
- Preventive maintenance helps reduce operational costs by preventing unexpected malfunctions and downtimes.
- Regular maintenance enhances the sustainability of wind energy and contributes to reduced carbon dioxide emissions and environmental impact.

Maintenance is divided into two categories: planned and unplanned. Unplanned maintenance is performed when machinery and equipment fail or malfunction. In planned maintenance, maintenance is conducted according to a schedule (Öztürk, 2020). Li, Jia, Ren and Li.(2024) conducted a study by scientifically formulating a maintenance strategy that can optimize the cost-effectiveness of wind energy generation systems per unit time and address the challenges of developing a reasonable maintenance strategy for wind turbine components, as well as the issues of high operation and maintenance costs.

Planned Maintenance methods can be implemented in three different ways:

- Preventive Maintenance : Preventing failures at the initial stage before they occur. Small adjustments in lubrication systems or operating conditions can eliminate the causes of failures.
- Predictive Maintenance: By analyzing measurement results taken at specific intervals from certain points, potential failures in machinery and equipment

are detected in advance. Predictive Maintenance prevents untimely production stoppages and unnecessary part replacements.

Unplanned Maintenance methods can also be classified into four groups:

- Routine Maintenance
- Corrective Maintenance
- Emergency Maintenance
- Opportunistic Maintenance

Unplanned Maintenance is conducted when failures occur. Neglecting failures can lead to more significant breakdowns or severe damage.

This study complied with research and publication ethics.

Findings and Analyses

Neglecting regular maintenance on wind turbines can lead to efficiency losses and high repair costs, resulting in financial losses. A wind turbine, if not properly maintained, can lose 5-10% of its annual efficiency. This translates into a revenue loss of $5,000-10,000 annually, depending on the energy sales price. In the event of a major malfunction due to a lack of maintenance, repair costs can increase significantly. A small maintenance issue can evolve into a major breakdown over time, causing the turbine to be out of operation, leading to both revenue loss and higher repair expenses. As a result, the financial impact of maintenance neglect extends beyond just efficiency loss and can be compounded by high repair costs and prolonged production downtime.

Conclusions

It is possible to mitigate the impacts of global warming caused by fossil fuels by using renewable and clean energy. Among renewable energy sources, wind energy investments have been increasingly common in recent years, as the initial investment costs continue to decrease with technological advancements. Wind turbines are long-lasting and uncomplicated energy production systems. Regular maintenance of wind turbines is of great importance in terms of efficiency, safety, durability, cost-effectiveness, and environmental sustainability. It reduces energy production losses, minimizes the risk of accidents and failures, and enhances the lifespan and efficiency of the equipment.

It has been determined that if the necessary maintenance/controls are not carried out on time, a financial loss of 613.2 $ / per day will occur for 1 MW wind power plant operating with %35 capacity factor, based on the unit energy production pricing of 73 $/MWh as listed in the Electricity Market YEKDEM and according to Law No. 3453.

Not performing the necessary maintenance operations at specific intervals on wind turbines can shorten their lifespan and, in some cases, cause the turbines to become completely inoperative. Compared to the cost of the turbine itself, addressing faults through planned or unplanned maintenance can be managed at significantly lower costs. Preventing failures that may arise from adverse weather conditions, mechanical and electrical faults, or corrosion-induced wear requires various fault detection methods such as online condition monitoring, vibration analysis, oil analysis, infrared thermography, or ultrasonic monitoring. These methods help to identify issues and prevent sudden turbine shutdowns, thereby avoiding energy production losses. The role of technological innovations and predictive approaches in this field is increasing, contributing to the sustainability of wind energy. In the future, the development of more intelligent and integrated maintenance systems will enable us to benefit more from wind energy.

Energy, money, and time are crucial factors. Therefore, the maintenance of wind turbines, which require significant investment, is vital. Neglecting maintenance can lead to decreased energy production, higher repair costs, and prolonged downtime. Regular maintenance of critical components such as rotors, generators, and gearboxes is essential to prevent costly failures. Without it, small issues can snowball into major problems, resulting in substantial financial losses and operational disruptions. In short, maintaining wind turbines is key to maximizing energy efficiency, controlling costs, and ensuring long-term profitability.

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