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Wind turbine inspection with drone: Advantages and disadvantages

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Abstract: The facilities on wind energy generation are increasingly finding usage areas in line with the ecologically friendly energy generation approach. One of the important activities of wind power generation facilities, which have high investment cost, low operating cost and low environmental impact is the maintenance and repair of wind turbines. A preventive maintenance approach is dominant to reduce maintenance times and eliminate lost time in wind turbines. Damage inspection of turbines has been evolved from tower crane access, rope access, camera viewing, and other applications to image with manual drones over the years. However, when these methods are evaluated within the framework of criteria such as cost, performance, occupational safety and data reliability, they are still insufficient and the need for inspection with autonomous drones arises. The advantages and disadvantages of autonomous drones used in the determination of damage in wind turbines are analyzed and the results are considered to contribute to the practitioners operating in the sector and academicians working in the field.

Keywords: *Drone, Inspection, Maintenance, Turbine, Wind energy*

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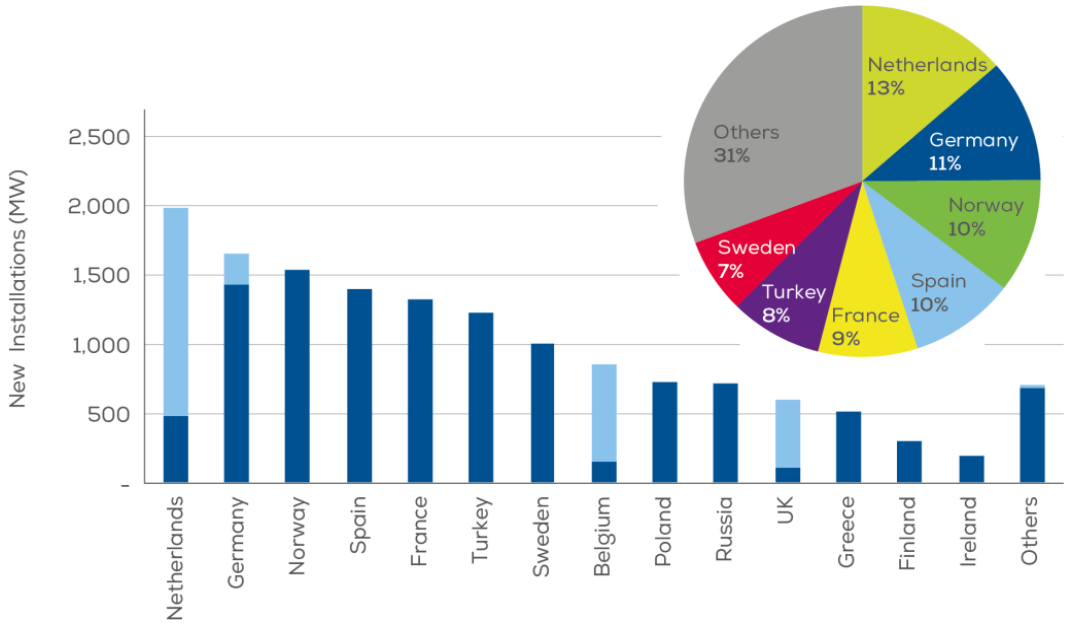
1. INTRODUCTION

In today's conditions, where the effects of climate change are being felt more and more, it is becoming more important to encourage the use of all types of renewable energy resources in order to steer the world away from the consumption of fossil fuels that trigger climate change. Widespread and effective use of clean and sustainable renewable energy sources, as they do not cause harmful emissions, is very important in order to minimize the negative effects of climate change [1]. Wind power plants (WPP), which have minimal harmful effects on the environment and become more efficient with technological developments, come into prominent as an important renewable energy source [2]. Wind power plants are becoming more common in both land and sea areas due to reasons such as wind energy being a clean, reliable and unlimited energy source [3]. European countries are realizing significant investments on returning to clean energy sources, and the data on the current situation in wind facilities in Europe are shown in Fig. 1.



	Netherlands	Germany	Norway	Spain	France	Turkey	Sweden	Belgium	Poland	Russia	UK	Greece	Finland	Ireland	Others
Offshore	1,493	219	-	-	-	-	-	706	-	-	483	-	-	-	17
Onshore	486	1,431	1,532	1,400	1,318	1,224	1,007	152	731	713	115	517	302	196	688
Total	**1,979**	**1,650**	**1,532**	**1,400**	**1,318**	**1,224**	**1,007**	**858**	**731**	**713**	**598**	**517**	**302**	**196**	**705**

Figure 1. Onshore and offshore wind turbine installations in Europe (year: 2020) [3].

As shown in Fig. 1, although the investments made in wind turbines have reached a significant level, it is predicted that these investments will continue increasingly until 2025 in Europe [4]. Parallel to the cases in Europe, investments in clean energy resources tend to increase in Turkey. While the current installed power of wind turbines is 10,585.15 MW in Turkey, the share of wind energy in total electricity generation in Turkey is at the level of 9.2% [5]. Turkey has determined the year 2023, the 100th anniversary of its establishment, as a target year in terms of economic and energy indicators and plans to have 20 GW of wind energy installed power in 2023 [6]. The offshore wind energy potential, which has not yet been implemented in Turkey but is continuing rapidly, is estimated as 75 GW [5].

As well as all countries of the world, global climate change conditions and world-wide energy wars lead Turkey to wind energy, which is the most suitable renewable energy source. Wind turbines have an important potential for Turkey, whose electricity consumption increases by 8-9% on average every year and therefore imports energy to balance the consumption. In order to reduce Turkey's dependency on

other countries in energy, it is inevitable to invest in economical, sustainable and environmentally friendly wind turbines' production, transmission and distribution facilities in this manner [7].

While the wind turbines used in wind power plants have many positive features compared to other energy production methods, they also have various disadvantages. While the difficulty of installation (transportation, infrastructure preparations, assembly, etc.) and cost constitute a significant disadvantage, the repair and maintenance activities of turbines are also difficult to ignore. The relatively new of wind power plants will enable to understand their repair and maintenance needs over time. However, environmental factors such as lightning strikes, dust, sand, crop residues, rain, hail, etc., can cause damages to the turbines and that can sometimes cause planned maintenance activities to be done earlier.

The repair-maintenance activities of wind turbines are difficult and costly, but also contain many risks. In 2018, Gül classified the risks encountered in the maintenance processes of turbines as follows [8]:

1) Risks caused by weather conditions: While cold weather conditions pose a risk in winter, extreme heat in summer makes working conditions difficult and can lead to risks such as sunstroke.
2) Condition of wind power plant field: Since wind turbines are installed on high and rough terrain, land conditions can cause work accidents.
3) Working at height: The height of the turbines can lead to risks caused by falling if necessary security precautions are not taken.
4) Working in narrow and confined spaces: Since the internal structure of the wind turbine blades narrows towards the end point as shown as Fig. 2, working in a narrow and confined space during damage assessment or repair may cause the personnel be short of breath.
5) Icing: The icing occuring during the winter months can cause significant accident risks for inspection and maintenance.
6) Fire: There may be a risk of fire caused by electricity.
7) Difficulty in evacuation in emergency situations: There is a risk of evacuation in any emergency while working in difficult terrain conditions, at height, in confined and narrow areas.

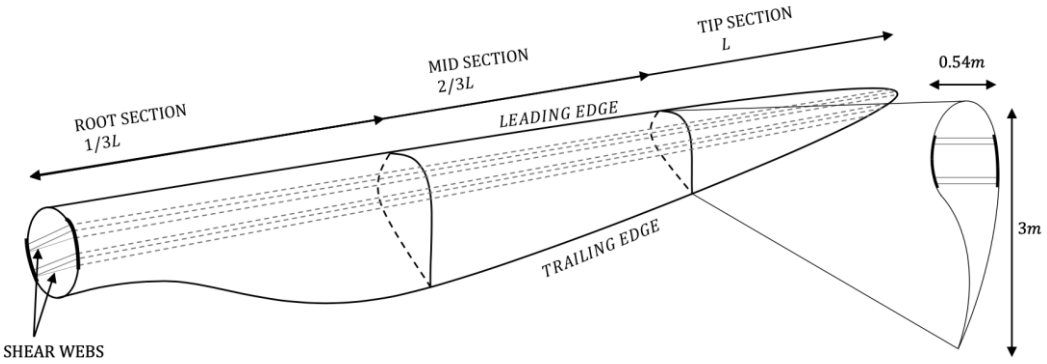


Figure 2. Dimensions of a sample 61.5 m Wind Turbine Blade from Ref. [9].

According to the data of CWIF (The Caithness Wind Farm Information Forum), which provides data about work accidents in the wind energy sector, work accidents continue to increase every year, and totally 3033 work accidents with death and injury occurred between 2000 and June 2021. The causes of these accidents are classified as 1. Those caused by turbine blades, 2. Those caused by fire, 3. Those caused by structural faults, 4. Those that occur during transportation, 5. Those caused by the turbine blades throwing ice, and 6. Miscellaneous causes. Wind turbine blades have the most important role with a share of 24% among these causes, and the most effective way to prevent these accidents is preventive maintenance [10,11].

Preventive maintenance activity is very important both to reduce occupational safety risks by considering the importance of human life and to reduce costs and energy losses. These requirements, along with the developing technology, also revealed the necessity to reduce the need for periodic inspections and fault maintenance of wind turbines, and studies were done to perform inspections using autonomous drones. It is seen that various studies are practiced drone inspection in the international literature and practice. Activities in different sectors (control of fields, photography, etc.) are carried out with drones in Turkey and the use of drones for the detection of damage in wind turbines and the software development work in this context was carried out for the first time with the study.

In this study, unlike the traditional damage detection methods, it is aimed to imaging the data of the damaged areas that occur in the turbine blade surface with an autonomous drone, and then to record them in the system and to facilitate the detection of damaged components by using artificial intelligence technologies. In this context, we seek an answer to the question "What are the advantages and disadvantages of autonomous drones used in damage detection of wind turbines?".

2. LITERATURE

Inspection and preventive maintenance detection is an important requirement in large-volume and hard-to-reach facilities which operate in difficult terrain conditions such as power generation plant, transmission and distribution lines, wind turbines, solar power plants. For this reason, it is important to perform periodic checks and to eliminate the faults quickly in order to eliminate the losses. Especially in hard-to-reach places, inspection with unmanned aerial vehicles offers very important advantages for cost reduction and efficient imaging [12].

Maintenance activity in wind turbines is among the most important operating activities. Gül stated that the maintenance activity is the riskiest stage and determined some risks that may occur an electric shock, fire, emergency evacuation problem, falling down from height, etc., during the maintenance [8]. While it is not possible to fulfill all kinds of maintenance needs with robots due to the fact that they require different business processes, it is possible to use unmanned aerial vehicles for the determination of maintenance needs and in some of the inspection and repair activities [13].

In the wind energy industry, wind turbine blades are the most important component, the failure of which can lead to significant cost losses. Currently, larger turbine blades have been used in the wind industry with a focus on reducing energy conversion costs and meeting higher energy demands; therefore, the requirement for periodic damage estimation and condition-based viewing for the blades is also increasing [14]. The detection of surface damage in time on wind turbine blades is a must to minimize downtime and avoid potentially catastrophic structural failures [15].

Wind turbines are complex and complicated structures, which have hundreds of moving parts. The inspection is based on periodic inspection through telescopic imaging, drone imaging, and/or human control with rope access. Each of these approaches require turbine downtime, which can require work intensive tasks, such as collecting large amount of data and making blade assessments [16], take a lot of time and occur safety risks [17]. For these reasons, the development of remote monitoring systems has significant potential to provide practical, efficient and reliable solutions [14].

In order to reduce the operating and maintenance costs of wind power plants, studies are performed to reduce human intervention and increase efficiency by using emerging technologies such as automation, data analytics, smart sensors and artificial intelligence. However, it is still challenging to have technology that can be used for on-site wing inspection for wind turbines both on land and at sea in unpredictable weather conditions and can obtain high-quality data efficiently. A possible solution is to use an unmanned aerial vehicle-based inspection of wind turbine blades [18]. In this respect, Morgenthal

and Hallermann [12] listed the advantages of inspection with unmanned aerial vehicles in wind turbines as follows:

1) Unmanned aerial vehicles require an operator working only on the ground to control the flight and camera during the inspection. Therefore, they offer the opportunity to work in high-risk situations without endangering human life.
2) Thanks to fast, real-time data collection and storage, lower costs can be achieved compared to large and staff intensive examinations.
3) Examination of real blade conditions and determination of blade life by photographing with a drone not only provides an advantage in terms of cost and maintenance investments, but also contributes to providing cheap and clean energy for the world.

In addition to the advantages listed above, the limitations of the inspection of wind turbines with unmanned aerial vehicles are reported by Martinez and co-workers as follows [16]:

1) While many flight systems have low-cost technologies, they can achieve a high level of complexity for professional applications.
2) The system is only suitable for use with lightweight and small cameras due to its small carrying capacity.
3) Due to the low weight, the flight system is very sensitive to changes in weather conditions, especially in critical wind conditions.
4) Usually, a permit to fly is required by civil aviation authorities.

There are many studies on wind turbines in the literature. In the studies conducted, the high cost of care and the importance of preventive examination were mentioned. Doğan, Kurt and Emeksiz [3] emphasized the importance of the subject in their study on fault detection in wind turbines. They stated that failure predictions will provide both minimum hardware damage and low cost results for the wind turbine and the entire system it is connected to, and it is important in terms of energy continuity. In 2020, Öztürk [19] stated that deterioration and/or corrosion on the wing surfaces causes a decrease in electricity production, and that the vibration that will occur due to malfunctions in bearings or moving parts will cause both a decrease in energy production and turbine downtime. In the study, it was also emphasized that maintenance activity in wind turbines has a direct effect on the electricity production value and the issue of preventive maintenance has become increasingly important.

However there are limited academic studies on the use of unmanned aerial vehicles in the inspection of wind turbines. Shihavuddin et al., [15] conducted a study on the development of a deep learning-based automated damage recommendation system with the analysis of drone images. As a result of the experimental studies, they stated that the proposed approach can reach almost expert level sensitivity for the proposed damage location and types on wind turbine blades.

In their study, Khadka, and co-workers [14] proposed an approach that can perform a non-destructive evaluation of wind turbine structures using contactless, three-dimensional full-field optical digital image correlation (DIC) technique. Wang et al., [20] presented a method for detecting anomalies in the images on the turbine blades. They stated that blade inspection by an autonomous drone requires less labor and the inspection time can be significantly reduced compared to manual access in works at height. Recorded images are also useful in the long run for a variety of purposes. However, the decision whether an image shows evidence of damage depends on the visual examination of the images by trained experts and the skill and experience of the relevant expert. The lack of such specialists for maintenance is also a serious problem [20].

Martinez et al., [16] presented an approach for using turbine past fatigue metrics and machine learning to estimate the remaining life of turbine blades and stated that this method can be used in many predictive maintenance applications. They emphasized that a blade inspection with an autonomous drone can reduce human error and provide more consistent results. Finally, Kaycı et al., performed a study within

the scope of collecting thermal images from solar panels with the use of unmanned aerial vehicles and fault detection with deep learning and stated that the faults were successfully detected in the tests [21]. These studies above reveal the requirements for the improvement of maintenance works, which is an important activity in wind power plants, which are increasingly used, and constitute the starting point of this study.

3. APPLICATION

This study was developed as an idea in line with the requirements specified in the literature section. The most innovative part of current application is that it is the first study that has been implemented in the wind turbine inspection within the scope of use of drones, development mobile application that provides flight path optimization for all different types of turbines, analysis with machine learning in Turkey.

3.1. Requirement of the Study

Wind turbine blades are the most unprotected parts of wind turbines due to their exposure to atmospheric environment, and in these parts; ice, paint damage, lightning damage, bird strike damage types are frequently seen. The periodic and preventive maintenance needs of the turbine blades are high and regular blade inspections are critical to avoid more significant costs. In addition, it is expected that blade inspection with drone will gain much more importance with the offshore wind turbines planned to be installed in Turkey. Offshore wind turbines, which have much larger blade lengths than onshore wind turbines, are also difficult to reach and control due to their environmental environment. Therefore, examination with autonomous drone is of great importance in offshore wind turbines.

Wind turbine blade inspections performed with traditional methods are performed by rope access technicians. As an alternative to rope access, there is the use of ground-based photography, crane or mobile platform. However, these methods offer both very slow and costly solutions, and the basic needs that guide the examination with the drone are listed as follows:

1) *In the inspection made using rope access or mobile machines, the wind turbine must be stopped for approximately 12-18 hours, during this period, electricity production losses occur and significant costs occur.*
2) *The risk of occupational safety is high in inspection performed using rope access or mobile machines.*
3) *The cost of access and imaging with the tower crane is very high.*
4) *In the ground-based photography method, high operational and field costs occur in order to display the same area within the same time period. In addition, while the photographs are taken with a drone at an angle of 90° directly opposite the blade, they are taken with different angles that are not standard in the ground photography method. This does not give accurate results in determining the damage location and damage size on the blade.*
5) *Due to the same flight route in different types of wind turbine blades, standardization cannot be achieved in the images.*
6) *The UAV pilot is depended on the inspection process.*
7) *The flight route cannot be optimized because turbine dimensions vary for each brand and model.*
8) *While only the damages on the surface can be visualized with the existing solutions, the capillary damages advancing towards the inner surface cannot be clearly visualized.*
9) *While existing damages can be detected with current methods, it is not possible to provide predictions about future damages that will improve the preventive approach.*

3.2. Goals of the Study

The drone inspection technology is a technology that continues to be used and developed around the world. The drone must be equipped with autonomous flight capability in order to collect the desired images in the inspection method with the drone. Thus, the autonomous drone can fly over the desired object and collect the desired images. In line with the determined requirements, the objectives of this study were determined as follows:

1) *Increasing the number of inspections per day from 2 to 8,*
2) *Reducing turbine downtime by 75% and production losses are reduced at the same rate,*
3) *Reducing inspection costs,*
4) *Obtaining detailed images with 1 pixel/mm accuracy using a high-resolution camera,*
5) *Obtaining the same standard images from different brands/models of turbines through autonomous flight,*
6) *Detecting distance of damage to the blade root with the sensitivity of cm,*
7) *Determining the length of the damage on the blade with precision.*

Within the scope of the study, software and research and development (R&D) studies were carried out for the wind turbine inspection method with drone, which is still very new in Turkey. As a result of these studies, it was aimed to reduce the operation and maintenance costs thanks to the work efficiently of the wind turbine blades, which are of critical importance and need to be controlled continuously, the early detection of damages. The activities described below were implemented.

Activities carried out within the scope of the study: Within the scope of the study t, software and R&D studies were performed for the wind turbine inspection method with drone, which is still very new in Turkey. As a result of these studies, it was aimed to reduce the operation and maintenance costs thanks to the work efficiently of the wind turbine blades, which are of critical importance and need to be controlled continuously, the early detection of damages. The activities described below were implemented.

Mobile Flight Software Development: The drone to be used in the study is controlled manually with standard flight software. However, the wind turbines currently worked on are varied with different blade lengths, different tower heights and different blade types for each brand/model. For this reason, it is aimed to create a suitable flight route for drone with the mobile flight software and to collect the same standard image from each turbine. Thus, in line with customer demands, maintenance and repair processes will be implemented quickly and easily by presenting distance of damage to the blade root and dimension the damage is on the blade.

The mobile flight software, which has been developed with the studies, can identify the blades edges with computer vision, and create autonomous flight route via the mobile application. By controlling drone with the mobile application, fully autonomous drone can be controlled instantly for different types of turbines. With computer vision support, the distance of the drone to the blade can be determined and so that the images are always collected from the same distance and at the same standard. Thus, the distance of the drone to the blade can be adjusted with the software instead of a LIDAR sensor (imported and highly cost product) that can detect sensitive distances. Thanks to the mobile application, pilot-made errors are eliminated and the images are captured at the same standard.

Internal Blade Inspection: It is determined that the detection of the damage in the blade is an important need in discussions with the most important wind turbine blade manufacturers of the sector. In this study, while controlling the outer surfaces of blade with the drone, inspection was carried out inside the blade by the developing mobile flight application and the design studies necessary for the drone to fly inside the blade. In this way, it is possible to detect the damages in the wind turbine blade.

Machine Learning: A software has been developed using Python/C# programming language and open-source machine learning algorithms for predictive damage estimation. By using this software, values such as the size and degree of damage can be estimated within 3-6 months periods by considering the existing damaged images and the environmental factors of the turbine location. By transferring the analyzed images and data to the system, damaged blades can be detected quickly and the operation & maintenance processes can be managed faster by reporting them in the desired report template. Thanks to information such as damage distance from blade root and how many cm the damage is, necessary preparations for operation and maintenance activities can be made, turbine downtimes can be shortened, and thus, losses in electricity generation can be reduced.

4. RESULTS AND DISCUSSION

Within the scope, three main activities were implemented, and the validity of the findings was tested by field studies. The findings regarding the advantages of the system used in line with the turbine inspections and analyzes are presented below:

1) *With the embedded system integrated on the drone, the images taken from the drone are processed instantly and a route is created instantly for each turbine via the mobile application.*
2) *With the use of autonomous drones, the dependency on the UAV Pilot has been reduced and the flight safety of the drone has been increased. When the same autonomous flight path is applied for each turbine, a blind spot emerges, while images are collected so that there are no blind spots from the turbine, thanks to the instantaneous flight routes.*
3) *With the existing solutions, only the damages on the surface could be displayed, while the capillary damages advancing towards the inner surface could not be displayed clearly. Within the scope of the study, the capillary cracks in the wind turbine blades were also visualized by using a thermal camera during the inspection, making use of the temperature differences.*
4) *With the developed mobile application, the drone can fly on the inner surface. This has contributed to more reliable results in damage assessment.*
5) *Software development has been made for future damage estimation by using machine learning, considering the environmental factors at the location of the turbine and the material structure of the blade. In this way, turbine companies are able to make more effective maintenance plans for blades and contributed to the prevention of unforeseen breakdown and maintenance costs.*

The determinations regarding the advantages of the system overlap with the literature. Shihavuddin et al., [16], as stated in their study, the deep learning-based automatic damage suggestion system can reach almost human-level precision in terms of suggested damage locations and types in wind turbine blades. With regular, cost-effective and accurate drone inspection, the planned maintenance frequency of wind turbines can be reduced, contributing to the reduction of energy costs by reducing general maintenance costs. In line with the study, the disadvantages of wind turbine inspection with drone have also been determined. As stated in the study of Morgenthal and Hallermann [12], flight systems are exposed to environmental effects and the most important factor affecting the picture quality is the constant movement of the vehicle due to fluctuations in wind speed and direction. This affects the image quality and may cause problems in the analysis. Other disadvantages identified are:

1) *Transportation difficulties may be experienced in cases where wind turbine sites are located in bad weather conditions and rough terrain,*
2) *In case of an accident caused by a drone, significant damage can also be caused to the turbine,*

3) *Unauthorized flights are prohibited in accordance with civil aviation rules and the flight permit process takes a long time for wind farms located in the region close to military areas,*
4) *Inability to fly in rainy weather,*
5) *Battery life is a significant constraint in drone flights.*

CONCLUSIONS

Within the scope of the study, the steps were performed as planned and the testing of the system studies continues in field. The most important limitation of the study is that sufficient field studies could not have been carried out yet, so the advantages and disadvantages of the system have not been clarified. In future studies, it is recommended to test the reliability of the data provided from the system by obtaining more data on the outputs, and to define the advantages and disadvantages.

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