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Review article

Fire risk assessments and fire protection measures for wind turbines: A review

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ABSTRACT

Wind turbine fires pose a significant global problem, leading to substantial financial losses. However, due to limited open discussions and lax regulations in the wind power industry, progress in addressing this issue has been hindered. This study aims to shed light on the fire risks associated with wind turbine nacelles and blades, while also exploring preventive measures and the latest fire detection and extinguishing technologies. The research conducted in this study involves a comprehensive investigation of various case studies, utilizing causal examination to identify common failure forms and their roles in fire incidents. Additionally, typical hazards, with a focus on fire incidents, in wind turbines are diagnosed. The primary causes of these fires were determined to be lightning strikes and hydraulic faults, often exacerbated by the presence of combustible materials. To conclude, the study includes a survey that encompasses education, knowledge analysis, and real-life accident experiences to assess fire risks and prevention measures in wind turbines. The participation of experts from wind farms, including those from the People's Republic of Bangladesh and other countries, adds valuable insights. The findings from this study serve as a crucial resource for enhancing safety standards and mitigating fire incidents within the wind power industry.

1. Introduction

Wind energy is one of the fastest-growing sectors among renewable energy sources. All nations actively support the development of new energy sources and low-carbon electricity in modern civilization to address the concerns of the more serious environmental pollutions levels for conventional energy sources and energy scarcity. Wind power energy has been produced and used worldwide as a new green energy source that is clean, renewable, and has little environmental impacts. This overview discusses the benefits of using wind power, the developments of wind power in China and abroad, the advancement of wind power technology, and the trajectory of wind power in the future. To provide individuals a resource so they may better grasp the state of the global wind power industry now

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and its projected course of development as can be seen in Fig. 1, the year 2022 already accounted for about 906 GW of installed wind power worldwide [1].

When viewing the data from the preceding years, the initial years before 2007 were quite low. Throughout the ascending years, for example, after 2011, the trend started to improve and gradually increased over time. When analyzing the last few years, 2019 showed 650 GW, 2020 showed 745 GW and 2021 led 830 GW. With this expressive growth, the wind sector already represents one of the most important energy sources for most developed countries. Given this, the security of supply for the wind sector becomes even more important to satisfy the electricity demand, which is also growing. We shall depend more and more on wind energy as a power source because of the wind energy industry's rapid expansion over the past few decades and global goals for using renewable energy [2]. Increased reliance on this energy production will put society at greater risk from the effects of fires at these plants. Therefore, research is required to understand better the fire behaviors of wind turbines' crucial nacelle components and blades. The role of the environment in developing the fire inside the nacelle for both suppression and detection needs. Passive methods, such as those used in the turbine's design or construction or the facility's administration, can increase fire safety inside the nacelle [3].

Wind turbine fires are a reality in wind farms worldwide and represent severe damages for the wind industry. Fire is the second most common accident caused in terms of incidents found. Fire can grow from a large number of sources, as well as some turbine types. These look more minded to fire than others. According to the insurance company Scotland Against Spin report of March 2023 [3], 459 wind turbines caught fire with total losses. Fig. 2 shows the fire numbers recorded by the Caithness Windfarm Information Forum (CWIF) [4].

As shown in Fig. 2, the numbers of fire incidents before 2000 are quite low due to lack of data. One of the great problems of counting the number of fires is the lack of an international organization which is mandatory to report all, and any case of fire produced. In the United States there is the National Fire Protection Association, NFPA, which is in charge of, among many other things, the statistical part of fires in American territory, but not globally. The reality is that many of the fires are not reported by the industry, since such fires are in isolated locations, they sometimes do not reach the media. In addition, some cases of fires are controlled before the entire wind turbine burns out, so it cannot be seen from the outside, in this sense, many times, the case is archived without reaching the public. Wind turbines are normally located in isolated areas, both for onshore and offshore applications, which makes fighting fires more difficult due to the time required for firefighters to travel to the incident sites.

Additionally, the wind turbines' heights make it difficult for firefighters to access, control and put out the burning parts that can detach while they burn. What happens mostly in wind turbine fires is simply isolating the environment of the turbine and watching it burn, without much to do. With the growing wind market and the sizes of wind turbines, the economic losses in case of fires are usually at high costs. Losses are represented not only by the purchase of a new wind turbine, which can reach 2 million euros per MW, but also by the electricity that would be produced, estimated at 4000 MWh per year, in the period necessary for the replacement, which it is usually 9–12 months. In a more common case for a 2 MW turbine fire, its loss can be as high as 4–5 million euros [5]. According to NFPA, fire cases in wind farms are mostly caused by lightning strikes. Wind turbines are equipped with protection systems, but it turns out that these are sometimes inefficient. Other causes of turbine fires are mechanical failures in windy situations, for example, short circuits in electrical and electronic devices or maintenance work inside the nacelle, where it involves a fire risk [6]. In addition to the economic part, fires in wind farms represent very negative publicity for the so-called green renewable energies. However, it has been verified by many experts that wind energy is one of the sources of energy with a low degree in cases of fires compared to other renewable energy sources or not.

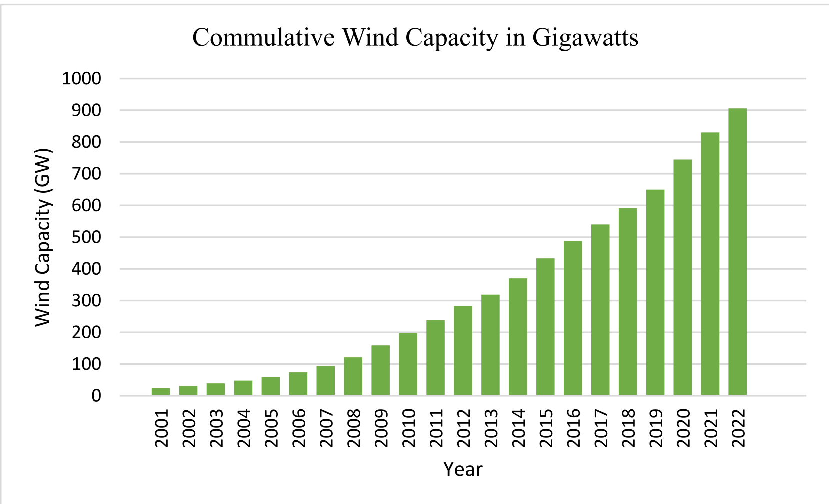

Fig. 1. Installed capacity of the wind sector in the world, in GW [1].

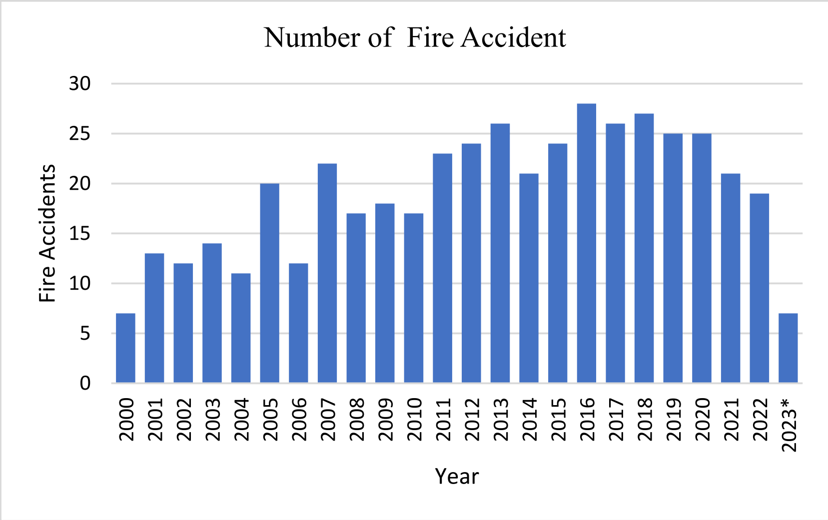

Fig. 2. Number of fire accidents from 2000 to March 31, 2023 in the world.

2. Wind turbine accidents statistics

CWIF identified 3287 reported Accidents between 2000 to March 2023, As can be seen from Fig. 3, an average of 143 accidents per year. Fire is the second most common cause of reported accidents in wind turbines. According to the study, the 3 most important reasons for accidents in wind turbines are [7].

(i) Blade failure (19%)
(ii) Fire (15%)
(iii) Structural failure (9.7%)

2.1. *Blade failure*

Blade failure is the most common and highest number of incidents. 'Blade Failure' can grow an amount of likely origin as well as the results, such as the piece of the blade in either or the whole blade being cast from the turbine [8]. As can be seen from Fig. 4, A complete

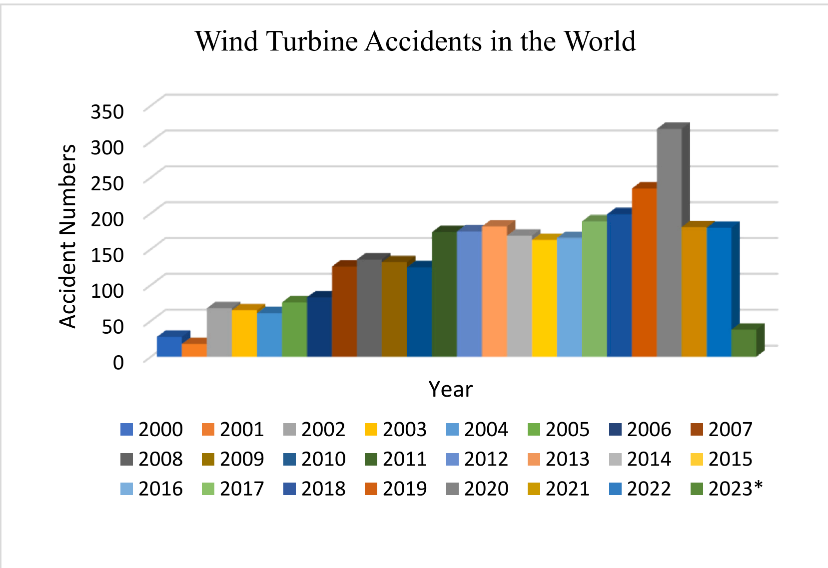

Fig. 3. Numbers of wind turbine accidents from 2000 to March 31, 2023 in the world.

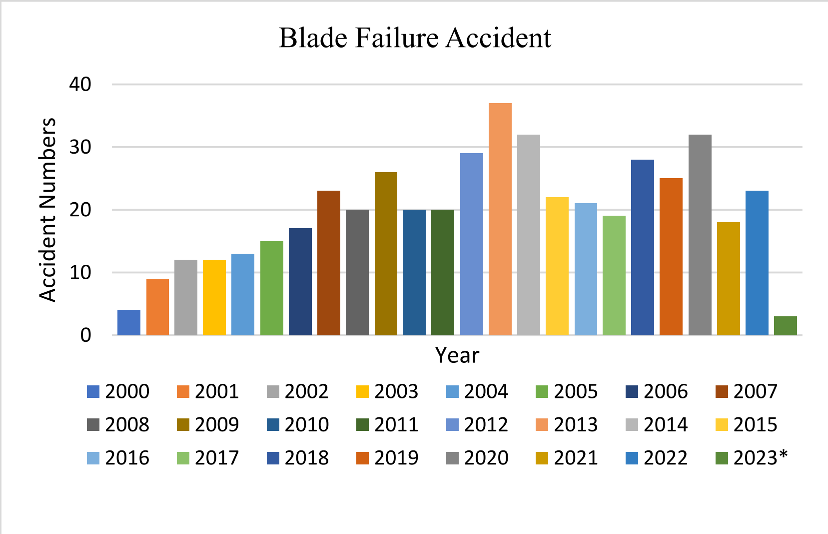

Fig. 4. Number of blade failure accidents from 2000 to March 31, 2023 worldwide.

of 481 individual incidences were initiated.

Traveling up to one-mile piece of the blade is recorded. Blade pieces have gone through the roofs and walls of close buildings in Germany. Hence, we suppose that there should be at lowest level distance of at least 2 km into turbines and workplaces or occupied housing. Apropos adequately addresses public security as well as other issues, including noise and shade glimmer.

2.2. Structural failure

Structural Failure is the third greatest common accident caused from the data obtained, with 243 cases found, as seen from Fig. 5. " Major component failure is assumed to be "Structural failure" under the provision, which components should be designed to inhibit. Storm damage to turbines as well as tower collapse raises multiple concerns. However, component failure, lack of maintenance, and poor-quality control can also be liable.

While blade failure is far less damaging and less expensive than structural failure, the risks and consequences and accidents to human health are likely lower from the turbine as risks are confined to within a relatively short distance. Therefore, as lesser turbines are now being installed on and almost several buildings with schools, the accident frequency is awaited to rise [9]. The pie chart in Fig. 6 evaluates the events and global wind turbine accidents from 2000 to March 31, 2023. The total number of accidents was

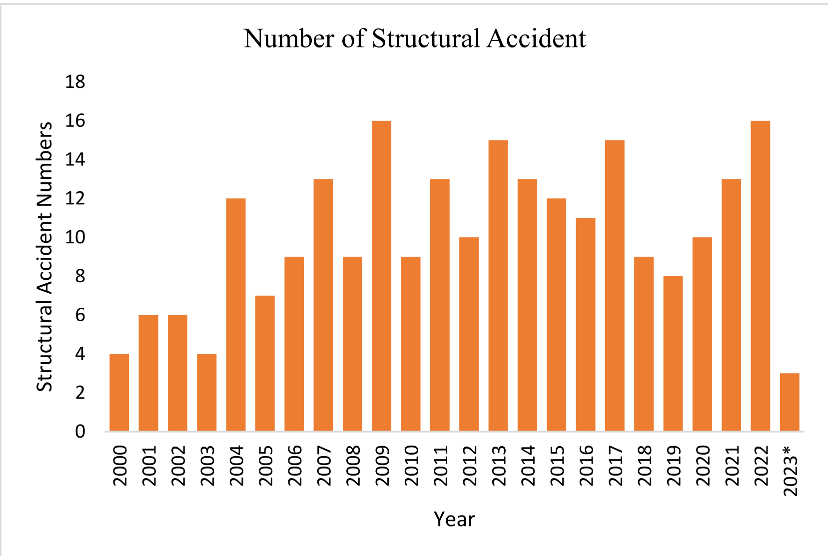

Fig. 5. Number of Structural failure accidents to March 31, 2023 in the world.

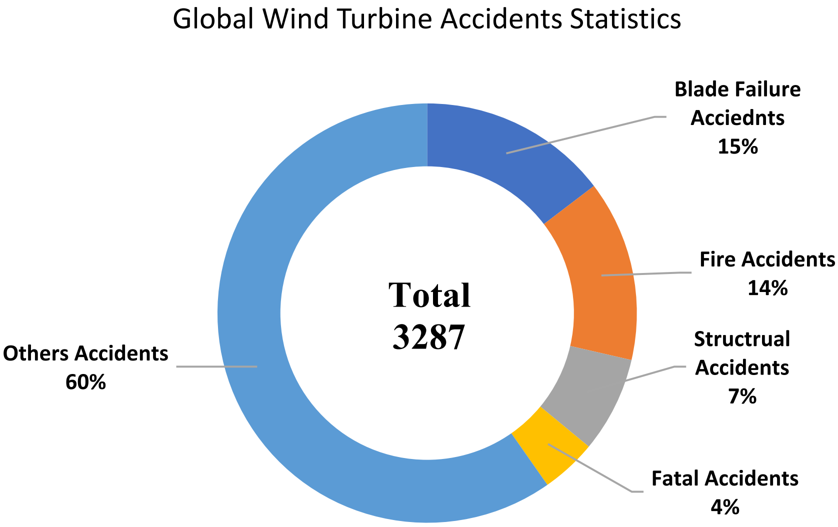

Fig. 6. Global wind turbine accidents statistics from 2000 to March 31, 2023.

recorded as 3287. Blade failure was the highest cause of accidents, which showed 15% of the total accidents. The second most common cause is fire accidents, which included 14% of the total number of global wind turbine accidents. The third most common cause of accidents was structural failure, which was 7% of the total accidents. Fatal accidents occurred as 4% of the total number of global wind turbine accidents, this was the minimum percentage seen amongst all the percentages divided in the pie chart. The majority of accidents were due to other causes, which showed that 60% were other accidents. Other accidents included environmental damage (including bird deaths), transport, ice throw, human injury, and human health (miscellaneous).

3. Literature review

Both domestically and internationally, scientific experts have conducted extensive investigations and a significant amount of process method research about wind turbine fires. The wind power industry, one of the market's largest segments today, provides a long-term, cost-effective energy source. One issue the wind industry faces, fire, can harm its reputation as being environmentally beneficial. The three elements of the fire triangle-fuel (oil and polymers), oxygen (wind), and ignition-are confined in the compact, enclosed turbine nacelle (electrical, mechanical, and lighting). Furthermore, it is highly improbable that the fire can be put out externally after it has started in a turbine due to the height of the nacelle and the wind farm's typically remote location. More accounts of wind farm fires have been discovered in the literature, but it is impossible to estimate their complete impact on the global energy market. Some information sources may include incomplete, erroneous, or secret information. The insufficient statistical information on wind turbine fires, a major cause of worry, hinders any research in this area. This is the gap between the current research on wind turbine fires and This report attempts to describe the present state of knowledge on this topic by offering a survey of the few sources that are now available to measure and understand the fire problem in wind energy. We have shown that fire is the second most frequent cause of catastrophic wind turbine accidents, accounting for 10%–30% of all known turbine incidents throughout the 1980s (after blade failure). 90% of the time, a fire leads a wind turbine to be destroyed or, at the very least, to be shut down for a period that results in accumulating financial losses. In descending order of significance, wind turbines main causes of fire ignition are lightning strikes, electrical malfunctions, mechanical malfunctions, and maintenance. Due to the numerous flammable materials used in wind turbines (such as fiberglass-reinforced polymers, foam insulation, and wires) and the massive oil storage required to lubricate mechanical components, the fuel load in a turbine nacelle is often very high. The study finishes by describing the active and passive protection choices and the economics (insurance) of wind turbines as alternatives to fire protection. With the aid of this paper, we hope to motivate the scientific community to strive toward a complete understanding of the problem and its extent, enabling the development of the greatest engineering solutions for fire prevention. The uniqueness of the fire problem the wind energy sector is facing, as well as the lack of information on such fires in the scientific or public realms, have been highlighted in this research. Numerous accidents have been reported in the media, all of which highlight the significant impact and ensuing downtime caused by fires.

In addition to the potential for secondary damage, such as road closures or the beginning of wildfires in rural areas, these flames cause property damage and electricity outages (particularly problematic in remote areas where wind turbines are a major source of electricity), which can be problematic. However, there isn't enough publicly accessible scientific data to draw from to objectively examine the problem because most of this information is proprietary. However, it is common knowledge and obvious that the nature of wind turbines makes fighting flames difficult. Since the nacelles are placed well above the ground, most firefighting tools cannot access them. The frequent installation of turbines in remote rural areas slows response times. However, the environment inside a wind turbine nacelle may increase the chance of ignition and make detection or suppression more challenging due to component selection or design in some circumstances, as the optimum environment requires a strong air flow through and around the nacelle. Firefighters are compelled to try to stop the fire from spreading to other areas when flames occur since, in most cases, the turbine construction is destroyed. Because of the wind energy industry's explosive growth over the past few decades and global targets for using renewable energy, we will concentrate more and more on wind energy as a power source. An increasing reliance on this method of generating energy will increase the danger that fires at these facilities pose to society. To better meet the objectives of both fire suppression and detection, research is needed to better understand the fire behavior of the essential nacelle components and the role of the environment in the development of the fire inside the nacelle. The fire safety inside the nacelle can be improved by passive techniques, such as those utilized in the turbine's design, construction, or administration. The fire risk associated with wind turbines is an issue that all parties are worried about. First, fire occurrences could make people wonder whether technology is environmentally friendly. Second, given the current and predicted increase in the usage of these facilities and reliance on them, a proactive approach to fixing the problem can significantly reduce societal hazards.

4. Case analysis

4.1. Case 1 (west union rexville, NY, USA, 2023)

A real case of fire due to a lightning strike occurred in 2023 [10]. One of the blades of a wind turbine was struck by lightning and it began to burn little by little until flaming pieces fell into the nacelle, causing a secondary fire, leading to the total loss of the wind turbine. In this case, the fire was started by a bolted connection of the lightning protection system. The arc formed between the arrester cable and the connection point resulted in the ignition of the cable terminal and ignited due to hydraulic oil residue on the rotor blades. It was found that the cause of the accident came from poor maintenance, as the bolted connection of the lightning protection system had not been properly fixed. Due to the fire, operations had to be interrupted for 150 days, resulting in a loss of approximately 2 million euros. Having started abroad, an extinguishing system would not cover the need in this accident. On the other hand, a passive protection system, such as fire protection coatings or barriers such as FRP, at the top of the nacelle could have prevented the second fire.

4.2. Case 2 - mechanical failure (senvion 3.2 M114, hohen Luckow wind farm, Germany, 2023)

A fire caused by mechanical failure in the generator of a 3.2 MW wind turbine that was completely burned [11]. The sparks produced by the impeller ignited the fan filter pad, igniting the insulation on the generator hood and spreading throughout the turbine. The cause of the accident may have been accidental, in this case, due to a mechanical failure of the generator fan slip ring. The generator is one of the components with a high fire risk due to producing sparks, working at high temperatures and having electrical circuits. In this fire, active extinguishing systems might have been the best solution. Aspirating smoke detectors would allow fire detection at an early stage and a gas or water extinguishing system would be adequate. In addition, the extinguishing system with heat-sensitive tubes and Senvion 3.2M114 would also be adequate. The incident ended with an estimated loss of 800,000 euros.

4.3. Case 3 – maintenance (vestas V112 3.0 MW, Lem kaer wind Park, Westrn Jutland, Denmark, 2023)

A circuit breaker inside the nacelle of a wind turbine caught fire due to overheating in a screwed connection, which was not properly tightened [12]. The source of the fire was identified as the circuit breaker itself. These screws could have been loose due to poor installation, poor maintenance, or vibrations. Failure of electrical circuits, as discussed in section 4.3, represents one of the most common sources of fire. Of the traditional adequate detection systems, in this case, they would be smoke detection and extinction with CO_2 (Carbon Dioxide) or inert gases under pressure. The detection and extinction system by thermosensitive tubes would be the most suitable since the tubes can reach these small areas without problems and efficiently. In this real case, the fire did not spread throughout the gondola but still generated losses of over € 500.

4.4. Case 4 – electrical failure (senvion MM82, Cullerin range wind farm, Southern Tablelands, Australia, 2023)

The incident occurred on January 5th, 2023, in the wind farm called Cullerin Range Wind Farm, located in Southern Tablelands, Australia, built by Infigen Energy. This project has a total of 112 turbines and an installed capacity of 278.5 MW [13]. During a heat wave, very characteristic of the Australian summer, with temperatures above $40^{\circ}C$, the automatic security systems of the wind turbines in the park had to deactivate them. The fire started while a maintenance team worked on one of the deactivated turbines. As a consequence, the entire wind farm had to be deactivated. The firefighters arrived at the accident scene, but little could be done, due to the height of this wind turbine, 67 m. It was found that the fire started inside the wind turbine's nacelle. The investigation concluded that the cause of the fire was due to an electrical failure inside the gondola, although it was not made public which part specifically [14]. Since the fire started while the maintenance team was working, it is possible that a lack of good fire training prevented the fire from being stopped. However, it is difficult to know the circumstances as these details were not publicized. The losses caused by this fire were of high magnitude due to the cost of the Vestas wind turbine, over 2.2 million euros, and also because of the time that dozens of wind turbines in the park had to be deactivated and without generating.

5. Typical fire risks of wind turbines

Fire risks can come from external factors, such as the weather, or a machine or human failure. Maintenance services play a crucial role in preventing fires since many fire cases are caused by the failure of old or weak devices that should be replaced, or repairs not so well done. Turbine aging is another factor that increases the risk of fires. According to the magazine Renewable Energy World [15], there are thousands of power turbines between 80 and 150 kW installed decades ago in the US and that do not have any or very vulnerable lightning rod system. With the large number of wind turbines installed since the 2000s, the number of fires in the next few decades may be a more serious problem than it is right now. The following sections will present the different possible risks reported by the industry as the most common in fire cases [16].

5.1. Lightning strike

Lightning strikes are natural phenomena normally generated in electrically charged regions of clouds and reach Earth in the form of electric discharges. The new turbines can reach 220 m and their height makes them even more conducive to attracting lightning. Although turbines are equipped with lightning arrester systems, according to the NFPA, lightning strikes are the most common source of fires in wind turbines [17]. The attraction of lightning will depend on the difference in electrical potential between the electrically charged clouds and the wind turbine, for example, since its metal parts can be easily charged, which makes them more likely to be hit at these points. Di-electricity is also important in attracting lightning [18]. The study of the aerodynamics of the blades in a wind turbine shows that when the turbine is running, the wind passage creates two zones of high and low pressure due to the Bernoulli principle.

According to Paschen's Law, air in high-pressure regions becomes more dielectric, making it difficult to conduct electrical current. However, the air becomes more conductive for -pressure regions until the breakdown voltage reaches [19]. The lowest point on the curve is called the breakdown stress, where the air is most conducive. This phenomenon explains why, in a wind turbine rotating, the rays sometimes reach the blade below, which is just passing near the tower, where the air in this space has less pressure and therefore is less dielectric. Some devices on the market can provide meteorological information and warn of lightning risks in real-time [20].

5.2. Mechanical and hydraulic faults

According to insurers, mechanical failure or machinery breakdown is another factor causing fires in wind turbines. Failures can occur in various parts of the turbine and for different reasons. Gear wear or damage, bearing overheating, fatigue, using the wrong oil or wrong oil temperature, vibrations, and overload are some of the most common causes of fires. Bearings, for example, must always be lubricated and if, for some reason, they start to run dry, the friction will cause them to overheat and produce enough sparks to start a fire. Another possible source of fires is the mechanical braking of the rotor. The new wind turbines are equipped with a control system for aerodynamic braking, but if this does not work properly or is not sufficient, mechanical braking is necessary. Due to the high inertia of the rotor, these brakes can reach very high temperatures, sufficient for the ignition of combustible fluids. In the case of emergency braking, this mechanical stress can be even greater and sparkling [21].

5.3. Failure in electrical installations

Failures in electrical components in wind turbines are among the most common causes. External factors or defects can cause overloads that can subsequently subject these devices to overheating and starting a fire. Other factors that cause fires in electrical and electronic systems are ground faults, short circuits, and electrical arcs. Among the components that present the most risk in the nacelle are circuit breakers, inverters, capacitors, harmonic filters, control systems, batteries, and transformers. Batteries in wind turbines are present in some auxiliary systems, such as step control. They must be well maintained and operated with sufficient ventilation, especially lead-acid batteries. This type of battery can release hydrogen during charging and, in addition, overheating with hydrogen represents a risk of fire or explosion. High ambient temperature values contribute to reducing the batteries' useful life [22]. In 2003, a German 1.2 MW Venus's 62 wind turbine burned out completely due to a short circuit in the pitch control system batteries. Resonant systems made up of capacitive elements (capacitors, reactive power control, etc.) and inductive (generator, motors, etc.) can cause damage to the electrical installation. The resonance phenomenon can result from harmonics that generate high current values, which can damage, for example, capacitors. These, once damaged, can catch fire and thus start a fire [23]. Circuit breakers are devices where overheating can occur due to overloads. One of the many reasons these overloads can cause is, for example, bolted connections. In wind turbines, it is very common that there are vibrations due to the force of the wind that can loosen some screws in the electrical and mechanical system. In the electrical system, a loose screw can increase the electrical resistance and thereby cause overheating and, consequently a possible fire. An infrared camera's top wire connection has become hot due to a screw that came loose [24]. Transformers represent a risk of fire, especially if they are located inside the nacelle and are of the type that carries oil. In addition to the risk of oil leakage and spreading combustible material inside the gondola, these oils must undergo an expert review, at least every five years. If a defect occurs in a component of an oil transformer, an overcurrent can led to an explosion. Dry transformers present less risk but must also receive periodic maintenance [25].

6. International fire protection guidelines and certificate

There is currently no directive at the European level where fire prevention measures are marked explicitly for wind turbines. Available are either good practice guides, prepared by independent institutes and associations or private companies or directives that talk about machine parameters in general, such as Directive 2006/42/CE.

6.1. NFPA 850

The National Fire Protection Association, NFPA, is a global, non-profit US organization that eliminates death, injury, and economic loss due to fire, power failure, and related hazards. The organization is responsible for the publication of hundreds of codes and regulations as well as promoting education in the field of safety. The NFPA 850 [26], standard provides good practice recommendations for fire protection in electricity generation plants. Regarding wind energy, the regulations indicate important safety aspects for wind turbines that must be considered when preventing fires. In addition, being a guide, the recommendations may have to be adapted for each case since some of the hazards may not be present (transformer in the nacelle, for example). NFPA 850 makes safety recommendations for constructing new parks, but this work will focus on existing parks. In general aspects, in the event of a problem or accident, it is recommended that the wind turbines be equipped with automatic disconnection systems, total shutdown of the mechanical systems and electrical isolation of the tower. It is also recommended that there are different methods for stopping and that they should operate independently. The directive suggests a list of parameters that must be monitored remotely so that it is possible to initiate a shutdown process in case of abnormal operation of any of these parameters.

(i) Network disturbances.
(ii) Errors in the orientation or limits control system.
(iii) Brake problems.
(iv) Abnormal vibrations.
(v) Speeding (including wind conditions).
(vi) Temperatures.
(vii) Oil conditions (gearbox/lubrication and hydraulic system).
(viii) Engine protection.
(ix) Loss of communication between modules or with the control center.
(x) Blade angles and battery status.
(xi) Activation of smoke or heat detectors inside the nacelle.

In addition to these parameters, there are recommendations for lubricating oils and hydraulic systems. Oils and fluids that are fire resistant must be considered and, if possible, reduce their quantity in the turbine. Your pipes must be well maintained and marked, avoiding any possibility of leakage. Because they represent a risk to the installation, transformers must also follow some recommendations. These can be located inside the gondola, on the tower, or near the base of the tower. You must watch out if they are dry or contain any oil and, in this case, if there is a containment system for this oil in the event of a leak, in addition to using fire-resistant oils [27].

Some fire protection systems are recommended for wind turbines, but each case must follow even more specific safety recommendations. The systems mentioned in NFPA 850 include gas systems, water mist, compressed air foams, and aerosols. In the case of the gas system, there must be an automatic system for closing the ventilation system and doors, as well as turning off the fans during the fire, and special care when releasing gases that may contain toxic by-products of the combustion reaction. Systems with water must be dimensioned for each case since the space is limited. Due to the remoteness of most wind turbines and the lack of abundant water supplies in these areas, water suppression systems are not common. In offshore applications, fire water pumping and distribution systems can be very expensive and rarely used. For control cabinets and electrical systems inside the nacelle, it is recommended to install smoke detectors that can provide a quick alert in the event of a fire inside these cabinets [27].

6.2. NTP 1022, 1023 and 1024

At the Spanish level, the National Institute for Safety and Hygiene at Work, INSHT, has developed the Technical Prevention Standards (NTP), which guide good practices. Specifically for wind turbines, three standards were developed (NTP 1022, 1023 and 1024), which describe the main prevention and protection measures during wind turbine maintenance. The documents are aimed at the prevention of occupational risks and maintenance operations and, in addition, contemplate fire prevention since care can be one of the sources of ignition. The standards recommend using fire-retardant materials in areas of the machine with high fire risk. Suppose it is necessary to work inside the wind turbine, that may entail risks. In that case, using tools that do not generate sparks or fire blankets in operations, for example, welding and never storing flammable materials or smoking inside the wind turbine [28].

6.3. Directive 2006/42/EC

The European Parliament and the Council of the European Union have drawn up Directive 2006/42/CE, which defines the standards that machines, in general, must meet. Although it is not directly addressed to wind turbines, they are also included. The directive says regarding fire protection, "The machine must be designed and manufactured in such a way as to avoid any risk of fire or overheating caused by the machine itself or by gases, liquids, powders, vapors, and others. Substances produced or used by the machine in this fragment, although the directive emphasizes that fire risks must be avoided during the design and manufacture of the devices, it does not specifically clarify how that design should be and the appropriate measures for its protection. In addition, the directive specifies that in machines that cause displacements, the installation of easily accessible extinguishers must be allowed or be provided with extinguishing systems already integrated into the machine. Due to the difficulty of accessing the wind turbines in the event of a fire (due to their location, height, etc.), conventional fire extinguishers, although they have easy access, are practically unviable. However, extinguishing systems are the most appropriate option, although the directive does not specify how these systems should be. Wind turbine manufacturers can install their own detection and extinction systems or hire expert companies [29]. According to Jamie Scurlock of the RES group, risk assessment is one of the most important tasks for good fire protection design.

6.4. International certificate DNV GL SE0077

Quality Certificates are another way to ensure the firefighting system is robust and effective. Companies such as the Norwegian DNV GL, in its document SE0077 establishes the process and the requirements to receive this certificate, such as, for example, that the components of the detection and extinction system must pass different tests carried out by laboratories of a member of the European Fire Security Group (EFSG).

7. Wind turbine fire prevention method

7.1. Active fire protection systems

A large part of fire cases can be avoided if early fire detection devices are present in the wind turbines. In addition, these detectors must be connected to remote monitoring systems to inform the park manager and for firefighters to be activated [30]. Due to the remoteness of where these wind farms are usually located, even if the fire brigades are activated now, they can sometimes take hours to arrive, and then little could be done to avoid the loss of the wind turbine. Therefore, automatic extinguishing systems should be installed inside the nacelle and control the fire in an initial state.

7.1.1. Infrared flame detector

Infrared flame detectors among the types of detectors are the simplest, although they have a good response. It is normally equipped with 3 sensors and its operation is based on detecting the CO_2 (Carbon Dioxide) produced by the combustion reaction through specific wavelengths. Once the information has been processed, it activates the alarm if it is the case [31]. According to the Vertrauen Durch Sicherheit (VDS), these detectors are uncommon for wind turbine applications.

7.1.2. Linear smoke detector

Linear smoke detectors operate on the principle of reflection. Infrared rays are sent to a receiver that sends you back. It has algorithms to avoid false alarms and can monitor 5–100 m. As seen from their wide operating range, these detectors are more suitable for warehouses and places where the ceiling is too high and normal infrared sensors are unreliable [28,32].

7.1.3. Aspirating smoke detector

Aspirating Smoke Detectors work with an aspiration system that works continuously, sucking in ambient air and evaluating the presence of smoke. They can work in two different wavelengths, infrared and blue, and in this way, they can detect airborne particles generated by the initial phases of a fire. They can differentiate smoke, dust and vapor particles, ensuring reliability [29].

7.1.4. Multi-sensor flame detector

Multi-sensor detectors are more advanced solutions for places where a slightly higher investment is justified [33]. They are equipped with infrared sensors that will be processed and have a dynamic system that adjusts the algorithms to the conditions of each environment, becoming more efficient. They also have a temperature and carbon monoxide detector, CO (Carbon monoxide), produced in partial combustion. The CO (Carbon monoxide) detector can prevent slow fires from going unnoticed for long periods.

7.1.5. Extinguishing with gases

Extinguishing systems are mandatory in wind turbines. However, in this work, we are trying to demonstrate that there are several different types of cost-effective extinguishing systems on the market. Still, not all of them are suitable for application in wind turbines. Among the most common types are those for gas systems, water, and other chemicals such as powders or aerosols. Gas extinguishing systems typically use gases such as carbon dioxide, CO_2, Ar (Argon) or N (Nitrogen) that are appropriate for handling fires in electrical systems. These reliable systems act by displacing the oxygen in the air inside the nacelle. In this way, they disappear because one of the elements of the fire tetrahedron interrupts the combustion. According to VDS, extinguishing systems in gondolas must contain at least 6 kg CO_2 [34,35].

7.1.6. Extinguishing with water

Water systems are also suitable for fires originating from mechanical or hydraulic parts. The water can be used as a shower, sprayed, misted, or combined to form foams. These systems can cool the fire area and control the flames. Depending on the park's area, the effect of freezing water must be considered. For gondola systems, at least 9 L of extinguishing foam are recommended [36].

7.1.7. Extinguishing with dust and aerosols

Other extinguishing systems, such as powders and aerosols, are also used in fires. According to VDS these elements are not suitable in fire systems for wind turbines. Extinguishing systems must be well maintained regularly, at least every 2 years. When environmental conditions put them under stress, maintenance should be performed in periods more frequently [37].

7.1.8. Extinguishing with heat-sensitive tubes and fluid under pressure

Despite being widely used in this industry, the traditional extinguishing systems mentioned above have many drawbacks. Traditional suppression systems, for example, are handicapped by the multiple openings to allow air circulation that the nacelles have. In addition, the reliability of detection in these environments is quite compromised due to the accumulation of dust and dirt, which can result in false alarms, false suppressions, or disabling the system. Vibrations can also seriously inconvenience these systems due to the risk of loosening connections and rendering the system unusable. A new solution to extinction that is beginning to have force in this sector is the extinguishing system utilizing pressure tubes with fluid. Unlike the systems above, this is a simple system, which does not depend on electricity for detection, is quite robust, requires little or no maintenance, and is not affected by temperature variation, vibrations, or other pollutants. Another advantage of this system is that it can act from small spaces such as control cabinets, or on the wind turbine brakes or transformer. The system consists of a cylinder where a special fluid is stored, thermos-sensitive tubes are connected to it and installed in all risk areas of the wind turbine. Inside these tubes, the special fluid mixed with nitrogen is kept at a pressure of 195 PSI until a fire breaks out. The tube walls are specially designed to break at 350 °C, when something is surely catching fire. The fire opens a hole in the pressurized tube, and the released fluid immediately displaces the heat and extinguishes the fire.

The fluid in question is 3 M Noves 1230, listed in NFPA-2001 and evaluated and approved for use in occupied areas as a total flooding agent. It is a colorless liquid fluid with a low odor, low toxicity, electrically non-conductive, leaves no residue and is an extremely effective fire extinguishing agent. In addition, it does not affect electronic systems and is not dangerous for the ozone layer with its ozone depletion potential of 0.00, and atmospheric life of 5 days (other halocarbons have an atmospheric life of 33 years) [38]. Despite the rupture temperature of the tube walls is $350^{\circ}C$, the manufacturer recommends that they not be placed in places where the ambient temperature exceeds 80 °C to not compromise their performance. In addition, for very low temperatures above $-40^{\circ}C$, the manufacturer recommends that the system be disconnected by closing the cylinder due to the pressure changes caused by these extreme temperatures.

7.1.9. Installation monitoring

Detection systems must be connected to a monitoring system that is remotely controlled. If a fire is detected, it is important to automatically activate the complete shutdown of the wind turbine and disconnect the electrical systems, in addition to contacting the fire brigade. Leading companies such as Siemens have complete fire-fighting systems that can be installed in third-party wind turbines. These monitoring systems can communicate through a Virtual Private Network (VPN) internet connection, and the park operator can know the cause of the fire from the control station and thus be able to direct the next steps. Communication systems are normally installed in the gondola and at the foot of the tower that is connected but operate autonomously, increasing safety [39]. Another monitoring option is through a SCADA (Supervisory Control and Data Acquisition) control system. This is connected to the control station via Ethernet, fibre optic cables, or radio waves.

7.1.10. Deactivation of facilities

In the event of a fire, the wind turbine all mechanical, electrical, and hydraulic systems must be switched off and the wind turbine disconnected from the distribution network automatically. Except for emergency information systems and lights that must have an autonomous power source, if people are inside the turbine, they can find their way out. An additional system that ensures that the electrical, mechanical, or hydraulic component is completely isolated can be considered. For example, the switches must be equipped with a safety device, which can prevent the turbine from being reconnected before the maintenance work is finished. Furthermore, these switches must not depend on a control logic, which can, for some reason, reconnect the system [40].

7.2. Passive fire protection system

7.2.1. Lightning protections

Most new wind turbines are already equipped with lightning protection systems. These systems are focused on conducting electrical discharge, or lightning, to the ground, avoiding damage to the components. Table 1 and Table 2 show some of the parameters and probability levels for positively and negatively charged cloud rays to the ground.

According to the International Energy Agency (IEA), positive discharges represent 10% and negative discharges 90% of total discharges but may vary with geographic area [41]. The range of peak current that lightning can have can vary considerably, and as can be seen in Table-1 and Table-2, these values can vary from 5 to 250 kA (Kilo-Amperes) but, in most cases, when they are spoken,

Table 1
Parameters and probability levels of lightning originating from negatively charged clouds.

Parameters		Probability Level		
		95%	50%	5%
Peak Current	kA	14	30	90
Long Duration Charge Transfer	C	15	7	40
Specific Energy	J/Ω	6×10^3	6×10^4	6×10^5
Maximum di/dt	kA/s	40	20	100

Table 2
Parameters and probability levels of lightning originating from positively charged clouds.

Parameters		Probability Level		
		I (98%)	II (95%)	III-IV (90%)
Peak Current	*kA*	5	35	250
Long Duration Charge Transfer	*C*	20	80	350
Specific Energy	*J/Ω*		8×10^5	13×10^6
Maximum *di/dt*	*kA/s*		3	32

lightning strikes, the values are usually between 5 and 14 kA. However, protection systems must be prepared to cover a high discharge current range, although this is reflected in the price of the device Wind turbines are divided into classes from I to IV, depending on the maximum and minimum current limits that it can withstand, by IEC 62305. In Table 3, it is possible to appreciate these limits and how they are divided into the lessons. The range of current peak value that lightning can have can vary considerably, and as can be seen in Table-3, these values can vary from 100 to 200 kA (Kilo-Amperes) but, in most cases, when they are spoken, lightning strikes, the values are usually 200 kA. The design basis for Vestas lightning protection is protection level I, following the standard IEC61024-1, which means that the system must be able to handle lightning strokes with high specific energy [42].

Systems classified as classes I and II are the ones that offer the most protection to wind turbines. In this work, it is chosen to study in detail a model of the protection system of the company Vestas, applied to the model of its 3 MW V90 wind turbine, class I [43]. It is possible to see the protection systems installed on the wind turbine blades. The lightning receptors are located on the blades in total. There are 7 individual receivers located at R44.7 m (near the tip), R42 m, R39 m, R35 m, R30 m, R25 m, and R20 m measured from the center of the rotor shaft. Inside the blade, a 50 mm^2 copper conductor passes that connects the receivers to the steel band, located at the base of the blade.

The lightning current will be conducted from the steel strip to the chassis of the nacelle utilizing a Lightning Current Transfer Unit (UTCR). This device prevents these current peaks from penetrating the rotor shaft and the transmission system (gearbox). From the gondola chassis, the current peak passes to the tower structure through brass conductors, which also protect the orientation system [44]. In addition to the wind turbine blades, another favorable point to be reached by electric discharges is the back of the nacelle where the anemometers and aviation lights are normally installed. To protect the anemometers, a steel ring is installed that is connected to the chassis of the nacelle, as well as the grill above the cooling system. To protect the aviation lamp, a lightning rod is installed, also connected to the chassis of the nacelle. The grounding systems in a wind turbine have the tower's foundation as its ground reference. This reference is also used for the entire electrical, control and protection system against over voltages. Even if the safety devices are installed, it is not so unusual that the rays end up reaching the blades outside the area of the receivers. When the discharge reaches the blade outside the receiver, it penetrates it and creates an arc within. The pressure and temperature at this point are quite high, which results in considerable damage, and high costs for the replacement of the blade [45].

7.2.2. *Minimize risks in electrical systems*

Protective equipment for electrical systems, such as fuses and circuit breakers, must be able to selectively detect a faulty part of the circuit, or equipment such as the generator, transformer or cables and disconnect them. When disconnecting the defective part or equipment, the system must automatically notify the park operator so that a maintenance group can be sent to the site. Furthermore, they must also be able to shut down the turbine and disconnect it from the distribution network. Implementing new devices can be a cost-effective measure to increase security levels. Compact circuit breakers can be an option for protecting auxiliary systems from overloads that can lead to overheating and be integrated into alarms in case of failure. Semiconductor protection fuses can protect fires caused by failures in equipment such as an insulated gate bipolar transistor (IGBT) and sophisticated parts such as thyristors in a converter or motor starters. Differential current monitoring devices can detect faults in the ground system by detecting differential currents. Once these differential currents are detected, the device must send an alert signal so that a maintenance team is sent to the site to repair it before a fire breaks out. Generated power monitoring devices can measure the quality of the power injected into the network and the parameters of the electrical circuit, allowing the early detection of overloads and failures in the installation. Insulation defects can represent a danger for fire and maintenance personnel who can receive a strong electric shock [46]. Residual current measurement devices must be installed in such a way as to disconnect the affected circuit and prevent fires. Another protection measure for wind turbines [47] is the replacement of cables by bus bars. Unlike PVC-insulated cables, busbars have a low fire potential.

Table 3
Parameters of electric shock and protection levels.

Lightning Parameters		Probability Level		
		I (98%)	II (95%)	III-IV (90%)
Current Peak Value	I_{max} *[kA]*	200	150	100
Total Charge	Q_{total} *[C]*	300	225	150
Impulse charge	$Q_{impulse}$ *[C)]*	100	75	50
Specific Energy	*W/R kJ/Ohm]*	10,000	5600	2500
Average Steepness	$di/dt_{30/90\%}$ *[kA/s]*	200	150	100

In addition, the busbars can have an epoxy coating that makes them more resistant to aging and can increase the protection for the conductors. Also, busbars offer a greater resistance to thermal effects caused by lightning than conventional cables. As discussed in Section 4.3, transformers represent a significant risk for the wind turbine.

Graduated protection concepts for transformers can achieve the best possible fire protection. For example, in the case of an arc in a switch on the voltage of the transformer that results in a circuit breaker failure, a specific arc detection system must detect the fault and open the circuit breaker on the high-voltage side of the transformer, thereby disconnecting the faulty part of the system. For oil transformers, Buchholz Relays can detect various types of faults. In the event of a transformer overload, a chemical breakdown of the oil can produce small amounts of gases that will accumulate on top of the relay and cause the oil level to drop. When the oil level gets too low, a switch activates an alarm. In the event of an arc in the transformer, a quantity of gas can be generated suddenly, which activates a switch in the path of the expansion tank. This switch disconnects the transformer before other damage is produced [48].

7.2.3. Fire protection coatings

Fire retardant coatings, or fire-retardant resins, widely used in the civil construction sector, can have great potential as a protective measure in the wind power sector. Much of the structure of wind turbines is composed of fiberglass and carbon fiber, which are relatively flammable materials, and their fire is difficult to put out due to the epoxy resins used to melt the fiberglass. The coatings available in the market can reach up to 120 min of fire resistance, this time can be the key factor to avoid a greater damage since, during this time, it is possible that the firefighters arrive or else that the fire ends due to lack of combustible material, for example. The most common is wind turbines have anti-erosion coatings since with the wind speeds to which they are subjected, even small dust particles can cause structural damage, especially in the blades. As it is not regulated, wind turbines are not required to apply any fire-resistant coating. However, some companies, such as the Dutch Akzo Nobel, have specific solutions for wind turbines [49].

7.2.4. Maintenance

Wind turbine maintenance must be carried out periodically with a certain level of quality. Many reported fires are due to improperly performed maintenance services. What Minimum maintenance of crucial parts such as the transmission system, generator windings, transformer, hydraulic systems, and bearings must be performed frequently, although it has been seen in this work that many other devices can be responsible for causing fires and should also be checked. The maintenance of the wind turbine blades can be complicated due to the conditions in which the responsible technician must be subjected, who must know about canyoning. A new alternative for this type of maintenance [50]. It is good practice to have registered all the specific modifications that have been made to the wind turbine as well as all the diagrams of each component and its specifications. In addition, all security and fire systems are inspected and if any part is defective, its respective replacement. The British Standards (BSI) also describes in EN50308:2004 a series of protection measures, requirements for the operation and maintenance of wind turbines. Regarding maintenance, among many of the recommendations, some are pointed out in this work. Insurers actively encourage their clients to use risk reduction methods and put them in place to reduce the chances of fires. Insurers in the renewable sector such as Windproof, have about 20% of their claims for fire accidents and spend about € 4 million annually on these claims. Should they be installed, many insurers encourage their clients to install fire prevention and extinguishing systems by offering discounts on premiums. Experts assure us that the investment can be recovered in 5–7 years and taking into account that the useful life of a turbine is 20 years, it would be worth it [51].

7.2.5. Training

Staff training is a very important measure, as human error is still one of the leading causes of fire accidents. Even if the wind turbine is equipped with protective equipment that gives it acceptable safety, a human error can be enough to start a fire, especially if it puts your life and others at risk. The training must guide the personnel about the danger of carrying out maintenance work inside the turbine. On all repairs carried out that may generate sparks, arcs or other ignition sources. If it is impossible to prevent the work from being carried out, safety measures must be taken before, during and after the operation so that ignition sources are avoided or that an initial state of the fire can be detected and combat it in an effective way. In addition, the training must clarify to all those who enter the turbine how the extinguishing systems work, and how to proceed in the event of a fire. Exit breaks, and how to behave in an emergency are critical steps that can save more than one life. Officials should conduct regular nacelle evacuation training and, if possible, conduct training with the local fire department. It is important always to avoid carrying possible sources of ignition or combustible material inside the nacelle. Pieces of clothing soiled with oil or solvents, common in maintenance personnel, can represent a spontaneous ignition hazard. Also, in all turbine areas, no-smoking notices must be signposted and respected.

7.2.6. Insurance

As mentioned in previous sections, economic losses due to accidents can reach millions of euros and, for this reason, wind farm owners usually look for insurers that can cover these expenses in exchange for monthly premiums. It has been seen that there are two types of insurance for the wind sector: property insurance and guarantee insurance. However, that alone does not guarantee complete protection and will depend on the contract conditions in each case. Among the many types of property insurance, we will focus on the all-risk modality in which the insured is covered in the event of machinery breakdown, short circuits, storms, and fires. In the event of a fire, insurers normally cover all the costs necessary to replace a turbine destroyed by a fire. However, even if the wind turbine has a warranty, normally given for 5 years by the manufacturer, even if it is verified by the insurer or by the park operator that a failure of a specific part caused the fire, the warranty of this would normally only cover the costs of the defective part and not of the entire turbine, for what is recommended to always have fire insurance. Insurers actively encourage their clients to use risk reduction methods and put them in place to reduce the chances of fires. Insurers in the renewable sector such as WindPro, have about 20% of their claims for fire accidents and spend about € 4 million annually on these claims. Should they be installed, many insurers encourage their clients to install fire prevention and extinguishing systems by offering discounts on premiums. Experts assure that the investment can be recovered in 5–7 years, and considering that a turbine's useful life is 20 years, it would be worth it [7].

7.3. Objectives of the survey

This study aims to diagnose the fire risks and related prevention measures associated with wind turbines. Those people who have worked in or around wind farms are preferred and chosen as first choices (subjects). The main aims of this survey are.

- To find out the main cause of fires occurring in wind turbines.
- What are the risks that lead to fires in wind turbines?
- What are the protective measures to avoid fires in wind turbines?

7.4. Target design of the survey

Notable targets of the survey are mentioned below.

- The duration of the survey will be approximately 15 min.
- Four wind farms were selected to accommodate this survey.
- Out of these participants, 100 people were randomly selected.
- This survey was conducted with real-life accident experiences from the participants.
- The wind turbines and wind farms in Bangladesh or other countries are generally addressed.
- Answers were taken from the questionnaire according to practical careers, experiences, or impressions.
- Asked questions about experiences at wind farms.
- Asked questions about fire hazards, fire prevention measures, and other related questions in or around wind turbines and wind farms.

7.5. Findings from the survey

The Wind Turbine Accidents Questionnaire shown in Appendix I demonstrated that most people were in their early thirties to fifty. Males made up the bulk of those surveyed and were almost all employed. 40% of all those questioned met the preponderance of qualifications and had a master's degree. 77% of respondents knew something about wind turbines. Most folks have observed how wind turbine's function. 40% of those surveyed had some degree of education and were familiar with wind turbines. However, 40% of them had over five years of experience. The fact that 61% of those surveyed had seen a fire near a wind turbine suggests that fires are common. Fires don't happen frequently, according to those questioned. Almost all of the fires that were observed were caused by maintenance failures. Most people questioned had incidents involving fire when it came to other accidents they had seen. Many people believed that wind farms were normally safe. They believe that, compared to earlier, wind energy generation has improved. Compared to the previous ten years, wind turbine safety has improved. The top-rated comments showed this. Most participants also believed that wind farms currently have adequate fire safety measures in place, negating the need for more protection. The usage of multi-sensor flame detectors as well as infrared flame detectors was the most popular choice for active fire protection, according to the number of respondents. 29% of those surveyed believe that lightning for passive fire prevention could be improved. 10% of employees also mentioned that sometimes there are accidents or injuries. Above is an assessment of participants who have worked in or around wind farms. We have completed a survey regarding analyzing knowledge and experience in wind farms. Most people interviewed are mature; therefore, their responses are quite reliable. Most are employees or have a lot of experience working on wind farms. Many of them have witnessed a fire. Most of them see fires occur sometimes. The accidents that were witnessed were fire related. These fires were mostly due to maintenance failures. There are two types of protection in fire safety protection: active and passive. Most people suggest that active fire protection should be utilized. A positive factor is that to wind turbine fires, casualties or injuries seldom occur.

8. Conclusion and discussion

Many factors must be considered to achieve high fire protection for wind turbines. In this work, the most common causes of fire have been diagnosed, as have the prevention measures, active and passive, that can be implemented to reduce the risks. In addition, the importance of maintenance work has been pointed out, as has the importance of the staff knowing the risks and protection systems. A lot of experimental research and testing has been performed, with the following aspects mostly completed.

(i) As discussed in the case analysis section, fire accidents are largely costly and dangerous to human life. However, for the number of wind turbines currently existing, the number of burned turbines is relatively low. However, the number of fires may increase due to the aging of large turbines, which are the type that attract the most lightning, for example. With the trend of offshore wind farms, the losses are even more significant, and the access and arrival of the fire brigade can be limited. This sometimes takes too long, and the fire cannot be fought.

(ii) This paper identified various types of case studies discussed in the section dedicated to case analysis. Fire incidents are generally expensive and pose a significant risk to human life. As large turbines age, they become more susceptible to lightning strikes, leading to an increased occurrence of fires. The consequences of such fires are particularly severe as we move towards offshore wind farms, where access for the fire brigade can be challenging and sometimes delayed.
(iii) According to different types of data analyzed earlier,a total of 3287 incidents recorded, 15% caught fire.There are numerous examples of accidents reported in the popular press in this study, all of which highlight the significant impact and ensuing downtime due to fires. These fires result in financial loss, power loss, and secondary damage, for example, through road closures or the ignition of wildfires in rural areas.
(iv) The study finishes with a description of the active and passive fire protection systems, as well as the economic costs and insurance of wind turbines, to compare the value of a lost turbine to the cost and alternatives of fire protection.
(v) A study has been thoroughly coordinated to understand different types of analysis of employees and employers currently working in wind farms or having experience with wind farms. A detailed and intricate wind farm survey has been completed. Most of the people surveyed are responsible adults; therefore, their opinions may be trusted. Many engage at wind farms as workers or have extensive experience there. Countless of them have seen a fire or dealt with a fire. They entailed mishaps involving fires. Maintenance errors were the major cause of these fires. Two variable forms of fire protection are utilized in fire safety: active fire protection and passive fire protection. Most individuals advocate the use of active fire defense. The fact that deaths or injuries are rare in connection with wind turbine fires is meritorious.

9. Limitation of the work

The research has several limitations that must be acknowledged.

- As the questionnaire was condensed, certain factors could not be studied.
- The conclusions are drawn after conducting an opinion survey with a random sample of 100 employees out of 120 working in the organization.
- More studies need to be done to determine if fire affects wind turbines.
- Studies need to be done on multiple wind turbine farms.
- The time period for research was short.
- It is also difficult to persuade people to conduct a proper interviewing process.

10. Future research work

This article has conducted a more in-depth study on risk diagnoses and protection measures for wind turbine fires, but many shortcomings still need to be improved [42]. Therefore, it is believed that future research work can focus on the following aspects.

(i) Extinguishing systems are present in many new models of turbines. Although it is mandatory to have them installed, it is not defined what types of systems or technology were used or, specifically, how the design of their installation should be. The installation of these systems could be of interest to the owner of the park, who has invested the money, and to the insurers. These companies must bear the costs; although that will depend on the conditions of the type of insurance signed, it could be considered to reduce the premiums paid by the owners in the case of an improvement in their protection systems.
(ii) There isn't a bunch of publicly accessible scientific data to draw from to objectively examine the problem because most of this information is proprietary. It is common knowledge and obvious that the nature of wind turbines makes fighting flames difficult. Since the nacelles are placed well above the ground, most firefighting tools cannot access them. The frequent installation of turbines in remote rural areas slows response times.
(iii) However, the environment inside a wind turbine nacelle may increase the chance of ignition and make detection or suppression more challenging due to component selection or design in some circumstances, as the optimum environment requires a strong air flow through and around the nacelle. Firefighters are compelled to try to stop the fire from spreading to other areas when flames occur since, in most cases, the turbine construction is destroyed.
(iv) To better meet the objectives of fire suppression and detection, research is needed to understand better the fire behavior of the essential nacelle components and the role of the environment in the development of the fire inside the nacelle. The fire safety inside the nacelle can be improved by passive techniques, such as those utilized in the turbine's design, construction, or administration.

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Additional information

No additional information is available for this paper.

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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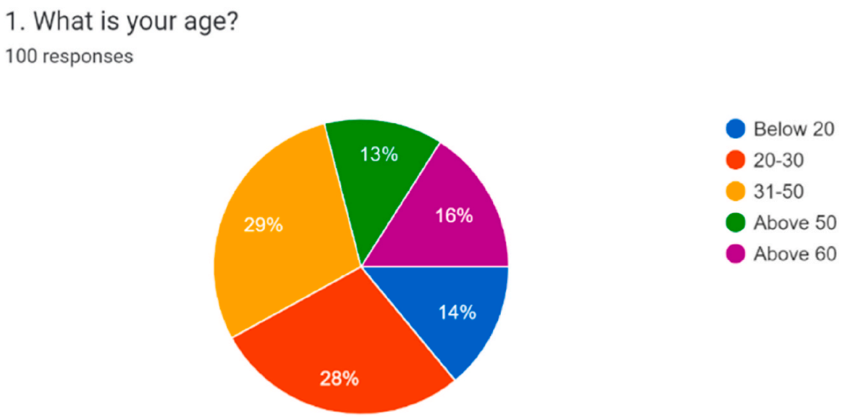
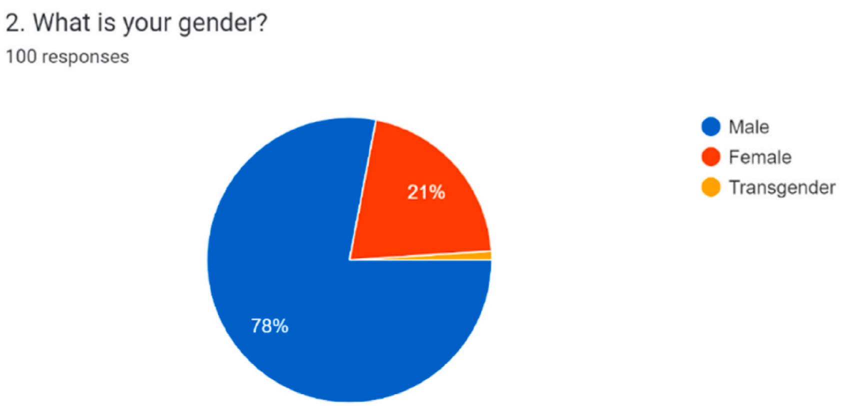
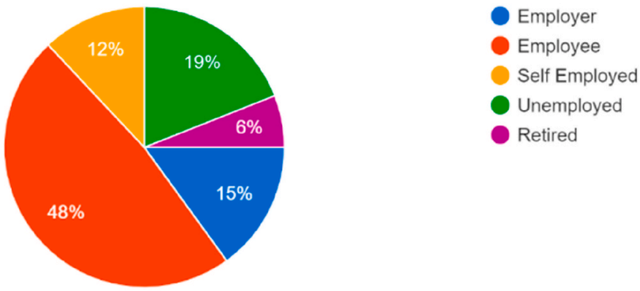
Appendix I

Wind Turbine Accidents Questionnaire: Assessment of participants who have worked in or around Wind Farms.

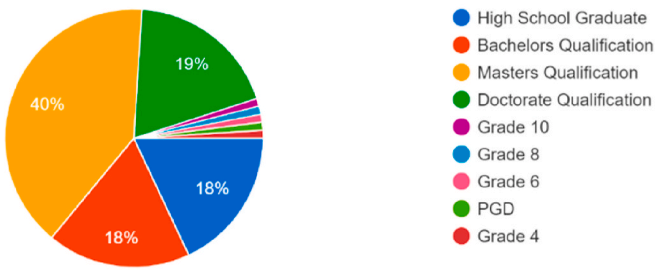




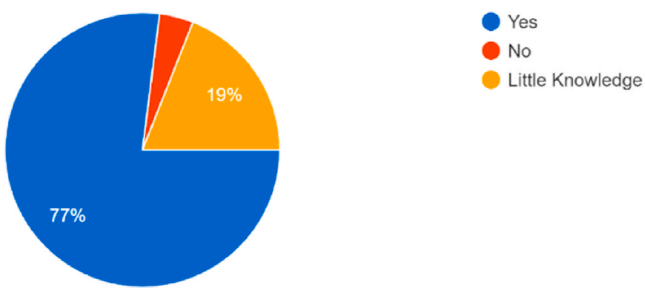
3. Are you currently employed, if so as which occupation?
100 responses



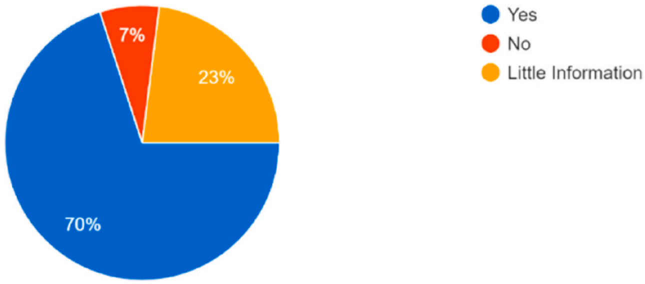
4. What are your qualifications?
100 responses



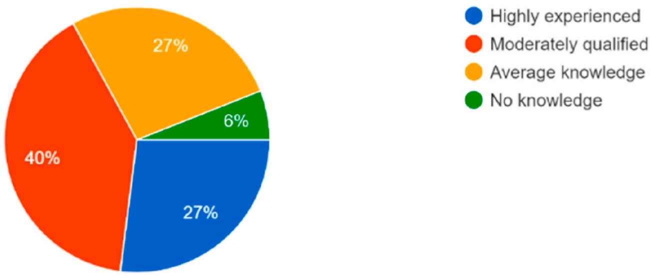
5. Do you know about wind turbines?
100 responses



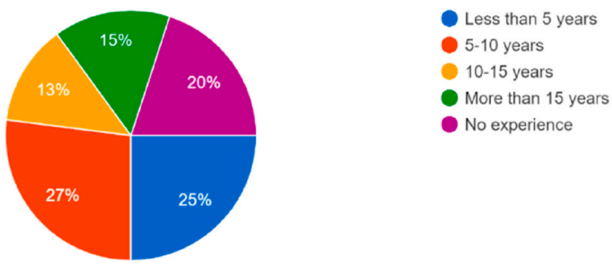
6. Have you seen how wind turbines work?
100 responses



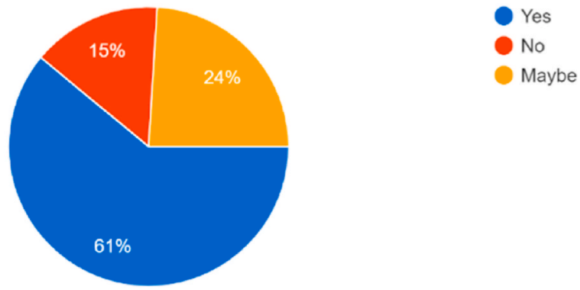
7. How much do you know about wind turbines?
100 responses



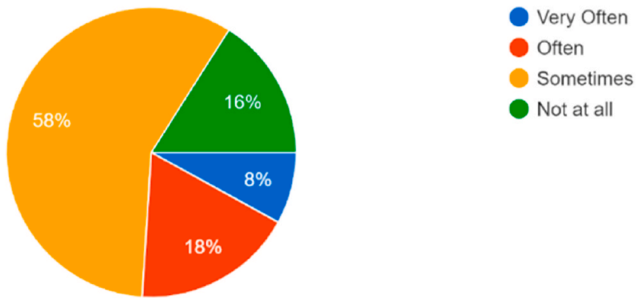
8. How many years have you been working in the field of wind farms of wind energy?
100 responses



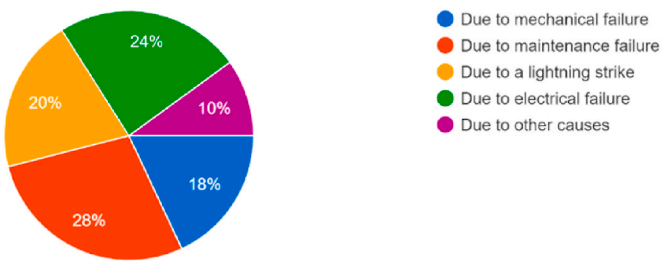
9. Have you experienced a fire occurring around or involving a wind turbine?
100 responses



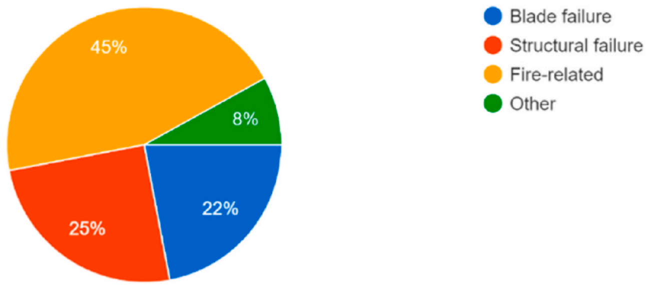
10. Do you think fires occur often in wind turbines?
100 responses



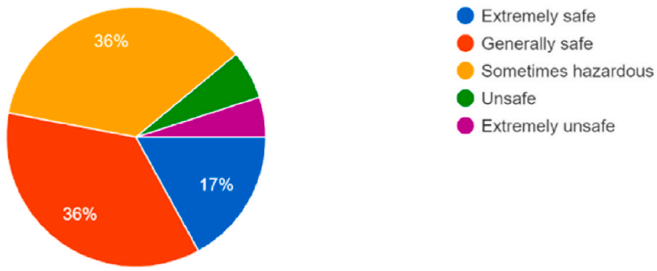
11. If you did experience a fire, what type of fire did you see?
100 responses



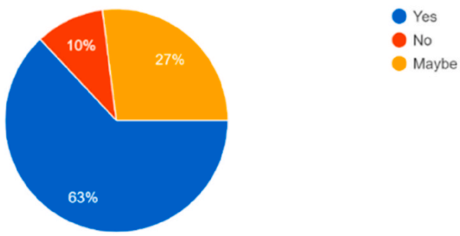
12. Did you experience any other accidents?
100 responses



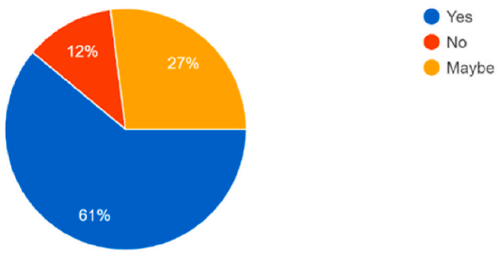
13. In your opinion, are wind turbines safe?
100 responses



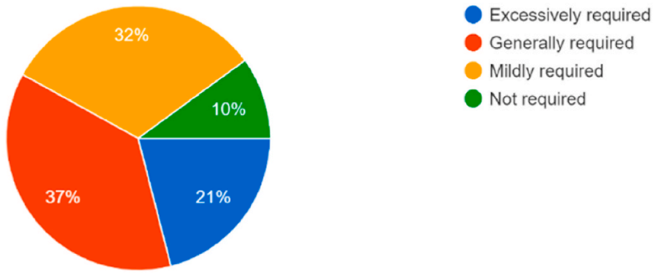
14. In the last decade, do you feel wind energy production has improved compared to the past?
100 responses



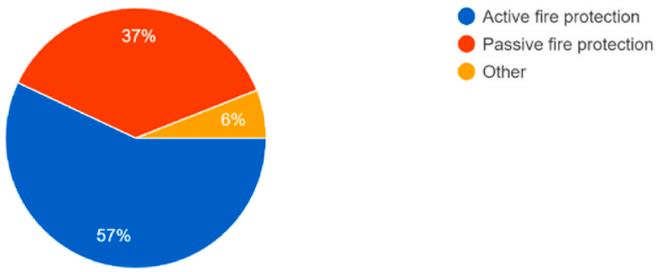
15. Do you feel wind turbines are now more safe compared to safety in the last decade?
100 responses



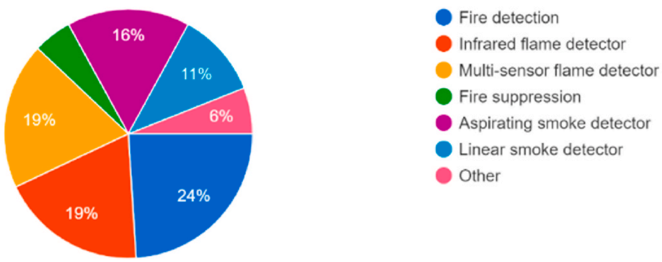
16. In your opinion, for a wind farm, how much fire safety is required?
100 responses



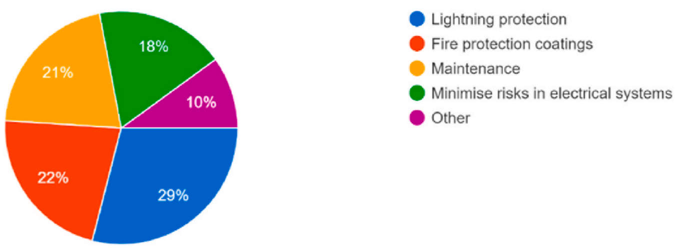
17. Which method should be used to ensure fire safety protection?
100 responses

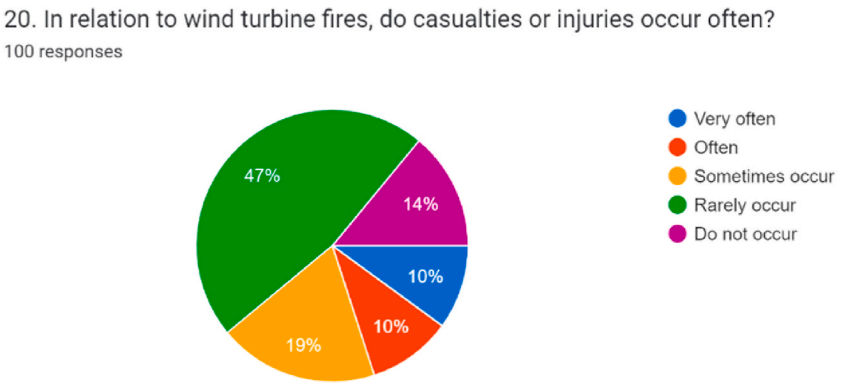


18. In active fire protection, which method is used often?
100 responses



19. In passive fire protection, which method is used often?
100 responses





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