Safety and risk assessment in Wind Energy: Analysis of Fire Accidents

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ABSTRACT

In recent years, the world has seen growing interest in energy transition from fossil fuels to a more diverse and less carbon intensity energy mix, with this trend towards more renewables expected to continue in the next decades. The Process Industries, as well as the Oil and Gas industry, have gone through a transformation in the past decades, leading to increased focus on management of risks and how safe operations increase productivity. The wind power industry could profit from these lessons. This work analyzed safety incidents involving the wind power industry from available literature and references. Among the accidents that can lead to a significant downtime, total loss of the infrastructure, and severe human consequences, fires are the second most common type of accidents, closely behind blade failure. According to the database research in this work, about forty percent of fires are caused by electrical hazards, while about twenty percent are due to mechanical causes, while an additional twenty percent of fires were caused by lightning strikes. Human injuries were found in 2.7% of the accidents, with 1.1% leading to fatalities. Risk of fatality due to a fire in a wind turbine was estimated at 1 to 16 cases per million, per annum. An important gap in the wind power industry encountered in this work was the lack of publicity and for compulsory report of accidents in wind farms. Looking at the level of risk that was estimated due to fire accidents alone, the wind power industry should not be considered as “low risk” and better hazard control practices may be required.

Keywords:

Fire; Wind Farm Accidents; Wind Energy Safety

1. INTRODUCTION

In recent years, the world has seen growing interest in energy transition from fossil fuels to a more diverse and less carbon intensity energy mix. According to the IPCC 2022 Report, intermittent renewable energy supply, like wind and solar power, can play an important role in mitigating the effects of climate change, especially if mixed with other initiatives to foster climate resilient development (1).

World wind power supply reached 4,872 TWh in 2021, which corresponds to around 2.95% of the world primary energy consumption. As it can be seen from Figure 0.1, the participation of wind in the overall primary power has been increasing significantly since the 1990’s, with Denmark arising as a world leader. In Brazil, the share of wind power surpassed 5% in 2021, despite the effects of the Covid-19 pandemic that affected the implementation of wind power projects in countries like the UK (2).

The increase in energy supply from renewables is expected to continue in the next decades. Currently, the installed capacity for solar and wind power worldwide is just over 800 GW for each of these two renewable sources. According to the scenarios drawn by bp in their 2022 energy outlook, in order to achieve a net zero emission goal by 2050, solar and wind energy supply will need to increase by about 600-750 GW per year (3).

This rapid increase has been accompanied with societal expectations regarding efficiency and safety. In order to maximize energy output and reduce downtime, the wind power industry must work towards guaranteeing safety of its operations, which will in turn have a positive effect on productivity, energy throughput and ultimately bring economic benefits. Letcher (2017) provides a comprehensive list of the current challenges of growing use of wind power; Safety is listed as one of these challenges that wind power industry must tackle (4).

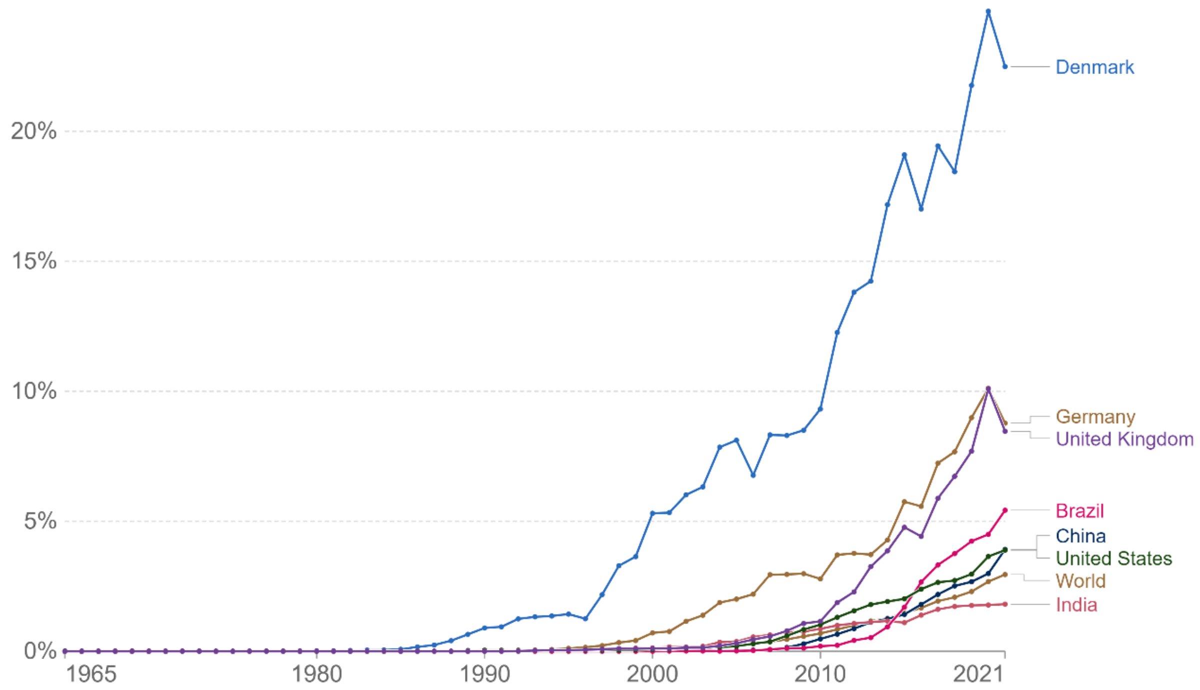

Figure 0.1 – Share of primary power from wind *(5)*.

The Process Industries, like Oil and Gas, have gone through a transformation in the past decades, leading to increased focus on management of risks and how safe operations increase productivity. The wind power industry could profit from the lessons learned in this transformation.

This work investigated available references and databases reporting accidents involving wind power generation. A detailed analysis of the fire accidents was conducted to determine possible causes of fires. Reports on fatalities in wind farms during fire events were also analyzed.

2. REVIEW OF THE HAZARDS AND RISK IN THE WIND POWER INDUSTRY

To appropriately manage and control the risks involved in Wind Power, it is first necessary to identify and understand those risks. While some industries, like Oil and Gas, are consolidated and have a long history of collecting data, emerging energy technologies like wind power do not have the same resources. There are some reasons for that:

- Novelty. While the use of wind power is not new, the technologies being used to harness this power are frequently evolving and being scaled-up. Developers are constantly trying to make wind turbines bigger, more efficient, and adaptable to new environments, like offshore (6);

- Incident data in wind industry is fragmented (7). In most countries, there is no specific requirement for reporting safety incidents in wind energy, and therefore reporting is done based only on general requirements, such as if an incident has impacts on occupational health (8).
- Poor quality of data that is available. Most databases available are managed by advocacy groups against the use of wind power, with limited quality of data (9).

The Transportation Research Board of the National Academy of Sciences, a US organization, compiled a comprehensive report on the risks that workers are exposed on Offshore wind power and how those risks compare to the risks to which offshore oil and gas workers are exposed (10). That comparison is reproduced in Table 0.1.

Table 0.1 – Risks from Typical Hazards for an Offshore Wind Farm Worker Compared with Those for an Offshore Oil and Gas Worker (10).

Hazard	Relative Risk	Comment
Electrical Injury	Higher	Higher-voltage equipment and all activities related to this equipment.
Personnel transfers	Higher	More boat transfers expected for a worker on offshore wind turbines. Oil and gas platform boat landings/helipads larger than those for wind monopoles. Helicopters used more often for oil and gas.
Awkward postures	Higher	Generally, more room to perform tasks is available on oil and gas platforms.
Confined space entry	Similar	Wind turbines have more confined spaces and must be entered more frequently; regardless, confined space entry for both oil and gas and offshore wind carries inherent risk and can have serious consequences.
Falls into water	Similar	Activities in locations where falls int water are likely are similar.
Diving	Similar	Similar activities and frequencies.
Manual material handling	Similar	Similar needs for upgrades or maintenance requiring manual handling or equipment and materials.
Long-term physical wear and tear	Similar	Relatively little climbing is required for offshore oil and gas workers but shifts and work schedule may be longer.
Mechanical hazards (e.g., pinch points)	Similar	Both installations required work on machines that pose dangers to workers.
Slips and trips	Similar	Common hazards in all workplaces.
Exposure to heat and cold	Similar	Both wind and oil and gas facilities have limited climate-controlled spaces.
Fall from heights	Similar	More climbing and higher climbing is required for activities in wind turbines; however, a higher exposure rate for personnel on oil and gas platforms may exist.
Fire	Lower	Oil and gas facilities process flammable materials.
Explosion	Lower	Oil and gas facilities process flammable materials.
Crane lifts	Lower	Oil and gas facilities generally have permanent cranes that are used more frequently than those that may exist in wind turbines.

It has been suggested that there is a “benign perception” of the wind power industry, leading to a widespread belief that wind power is a low-risk industry (11). This is in part caused by the lack of data and the lack of publicity on safety incidents.

In Brazil, this scenario is also highlighted by Silva (2022). In this work, the author points out that data from the Brazilian Ministry of Labor and Employment (formerly Ministry of Social Security) shows accidents in the Energy Industry, without singling out different sectors like the Wind Power Industry (12). Nonetheless, the author cites at least three accidents leading to fatality in Brazil, sourced from newspaper articles.

The compilation presented in Table 0.1 show a classification based on the original authors' perception of risk but show that many hazards present in an oil and gas platform will also be present in an offshore wind installation. However, since wind power does not handle large amount of flammable material, when compared to oil and gas, the magnitude of major events like fires and explosions is smaller.

Furthermore, most oil and gas installations are permanently manned, whereas personnel will only be present in wind power installations during inspections and maintenance work, while the wind turbines are shut down. Workers are less exposed to risks in wind power than in oil and gas installations. That is possibly why wind power energy is perceived as low risk (11).

Boccard (2018) compiled fatality data per amount of energy generated across many energy sectors, including renewable energy such as wind power (13). This data is summarized in Table 0.2. According to this reference, the fatality rate of workers in wind power related accidents in the world was 0.29 fatalities per GWy, in the 1996-2016 period. While this figure is significantly lower than the fatality rate in Coal and in Oil and LPG industries, it is comparable to the fatality rate in the natural gas industry and higher than the nuclear power industry.

Table 0.2 – Number of fatalities and Fatality ratio, per technology in the Energy sector, 1996-2016. Adapted from (13).

Energy Sector	Fatalities	Fatality ratio (Fatalities / GWy)
Coal	2375	2.5
Oil + LPG	1047	0.79
Natural Gas	166	0.21
Hydro	782	3.2
Nuclear	103	0.55
Geothermal and Biogas	3	0.07
Power Network	227	0.17
Wind	7	0.29
Total Energy Sector	4711	1.1

According to this metric, wind power should not be considered low risk, especially when compared to the natural gas industry. In line with this conclusion, Wifa & Hunter (2022) argue that the wind energy should be subjected to similar goal-setting risk management regulation, in the form of the Safety Case regime, as the oil and gas industry (11).

Accidents in Wind Power

There is no readily available official database of accidents and investigation reports on Wind Power, as identified by several authors (9). The most famous source of accident statistics database is maintained by Scots Against Spin, who describe themselves as "an independent alliance campaigning for the reform of the Scottish Government's wind energy policy" (14). This database is often referred in literature by Caithness Windfarm Information Forum (CWIF), which was the organization that first started compiling wind power accident references.

This database collects data from sources from the internet and includes accidents ranging from total loss of the turbines to malpractices in implementation of windfarm projects such as bribery and legislation issues.

Some of the accidents listed in the database are from references that are not public, or that are no longer available on the internet. Despite these setbacks, it is used in several scientific research projects because of its good accessibility in the Scots Against Spin (SAS) website (14). Even Wind Power industrial associations have admitted the difficulty in sourcing accident data (15). There is reportedly data held by insurance companies, that are not available to the public (16).

3. METHODOLOGY

As a first step, a study was conducted using the accidents that were registered in the SAS database (14). An analysis of all the fire loss events was performed by verifying the original reports or internet sources to verify what causes and contributing factors led to the fire. These causes were cross-referenced with recognized publications on fire protection of wind turbines, such as (15), (16), (17), (18).

Causes of fire loss of wind turbines were ranked according to the number of references that were available in the database. Causes of fire were also classified according to during what stage of the wind turbine project, namely operation and maintenance, and whether a consequence to people resulted from the fire. These results were also compared to relevant publication found in literature discussing causes of wind turbine fires (9), (15).

4. ANALYSIS AND DISCUSSION ON THE FIRE ACCIDENTS IN WIND TURBINES

An analysis of the SAS database show that there are several types of events registered, not all related to process safety events. The database reports health complaints, allegations of bribery and animal fatalities, in addition to major accidents. Table 0.3 presents a subset of the data from the SAS compilation, considering only accidents that were catastrophic or had severe consequences to wind farms. The most common accidents related to total or partial loss of a wind turbines are blade failure, fire, and structural failure. Accidents during transportation of pieces of wind turbines prior to installation are also frequent.

Table 0.3 – Accident registered in Wind Farms in the 1980-2022 period, Adapted from (14).

Type of Accident	Number of registries	Percent of Registries
Blade failure	503	33%
Fire	434	28%
Damage during transport	276	18%
Structural Failure	248	16%
Ice Throw	46	3%
Others	38	2%
Total	1545	100%

Blade failure is the result of the detachment of an entire blade or of a piece of the blade. When this happens during operation of the wind turbine, or while it is in movement, the broken object may be propelled across a great distance and may impact members of the pubic, roadways, vehicles, neighboring facilities, among others. The wind turbine becomes inoperable, and the blade must be replaced, or, in a worst-case scenario, the turbine needs to be permanently shut down.

Fire can occur in a wind turbine due several causes, as it will be discussed in later sections. Fires in the wind turbine nacelle are of special interest, as the height of the turbine makes external firefighting virtually impossible in a timely manner. Fire can propagate from the turbine due to burning pieces being thrown or carried by the wind, leading to fires elsewhere.

Structural failure relates to the total or partial collapse of the tower, which may happen due to severe wind conditions, lightning, or collision. Faulty design, improver procedures during construction or operation, and maintenance issues have also been named as contributing factors for wind turbine tower collapse (19). Accident can escalate if the falling tower impacts neighboring structure. Structural failures lead to the complete loss of the turbine.

Other relevant accidents related to wind energy are accidents during transport of parts of a wind turbine, ice throw, and environmental damage. Due to the size of some of the components of the wind turbine, especially the blade, risks associated with the transport are significant. Ice throw relates to the detachment of ice blocks that form on the blades, with potential impact on neighboring installations or members of the public. Environmental damage can occur mainly due to impact between wildlife and the turbine blade.

Data from Table 0.3 suggests that the number of blade failure events is about the same as the number of fire events. In addition, the number of blade failure events is about twice the number of blade failure events.

Figure 0.2 presents an evolution of major accidents in wind farms, considering only major events that took place at wind turbine farms. As it can be observed from Figure 0.2, the number of accidents registered increased in the beginning of the 2010 decade but has been stable in the last few years. In addition, data from Table 0.3 and from Figure 0.2 suggest that recently the number of blade failure events and the number of fire events have similar magnitudes. While some authors have considered that blade failure events are the most common accidental events, the data from (14) point to blade failure and fires as having similar likelihood.

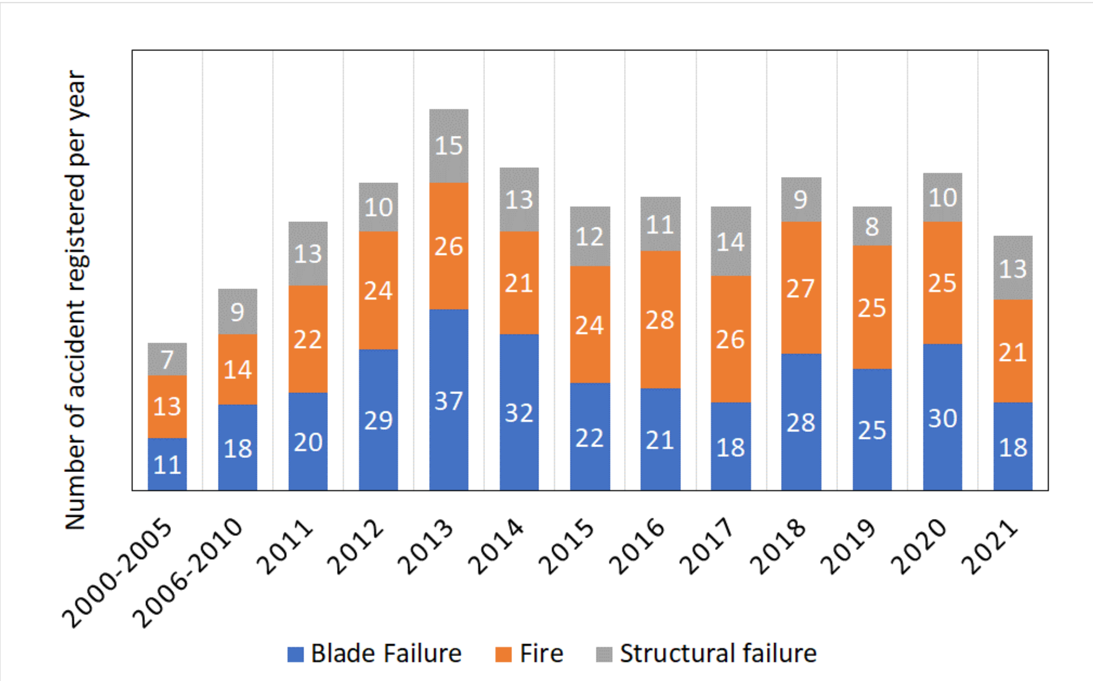

Figure 0.2 – Number of accidents in wind turbines categorized by type of failure. Adapted from (14)

Hetye & Nagy (20) use a metric by dividing the number of accidents by the installed capacity, on a yearly basis. This metric is not precise because it does not relate the accident to the date of installation of the wind farm where the accident took place. However, it does allow for some sensibility on the evolution of the frequency of accidents in wind farms. Figure 0.3 presents an updated version of this metric, considering that 2021 is the last full year of available data.

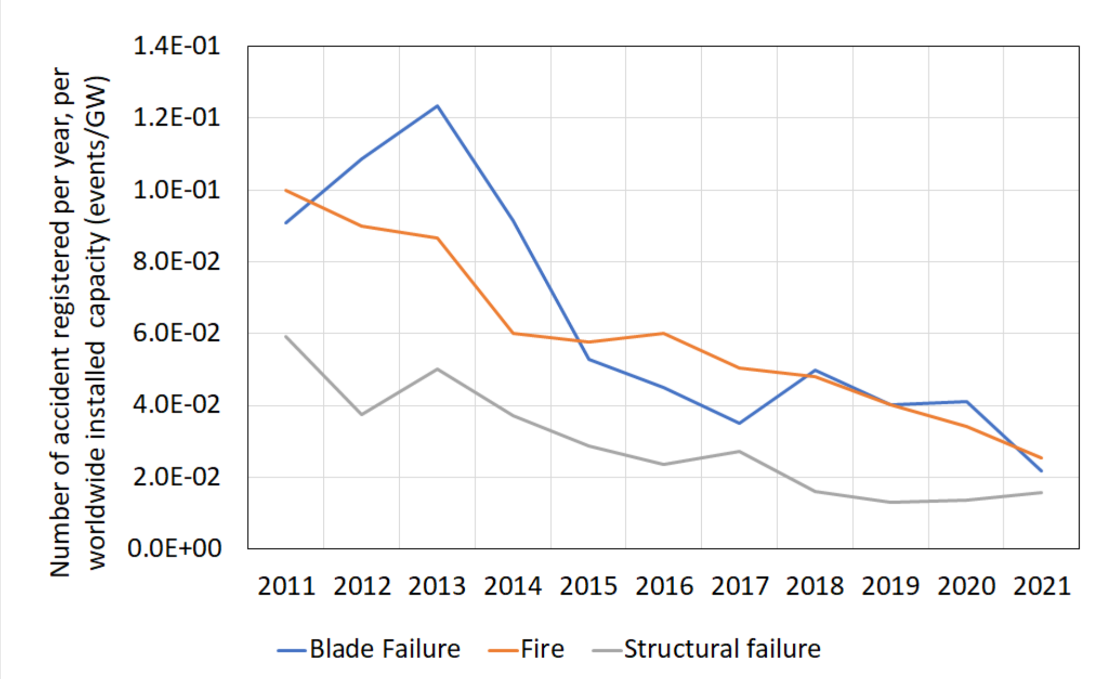

Figure 0.3 – Number of accidents in wind turbines, divided by worldwide installed capacity in GW, and categorized by type of failure. Adapted from (3) and from (14).

Figure 0.3 confirms that the frequencies of the three types of catastrophic events in wind farms have shown a decrease in the first half of the 2010 decade. This decreasing trend, however, seems to be waning off and are beginning to show a plateau.

In addition, Figure 0.3 makes it clear that in recent years, the frequency of fire events is about the same as the frequency of blade failure events. This could mean that the measures taken by designer and operators to tackle blade failures were effective in reducing the number of this type of accident, to the extent that nowadays fire events are taking over as the leading cause of a wind turbine loss.

For blade failure and structural collapse, there is a Dutch guideline on frequency of occurrence of these scenarios aimed to support hazard and risk analyses of wind farms, as reported by (21). These values are presented in Table 0.4 and indicate that frequency of a blade failure is about twice the frequency of a tower collapse. This observation is in line with the number of registries of these types of accidents presented in Table 0.3.

Table 0.4 – Frequency of occurrence of blade failure and tower collapse. (21)

Scenario	Expected value	Recommended value (1/yr)
Loss of entire blade	6.3×10^{-4}	8.4×10^{-4}
Loss at rated speed		4.2×10^{-4}
Loss at 1.25*rated speed		4.2×10^{-4}
Loss at 2* rated speed		5.0×10^{-4}
Loss of blade tip	1.2×10^{-4}	2.6×10^{-4}
Collapse of entire turbine at tower foot	2.0×10^{-4}	3.2×10^{-4}
Collapse of rotor and/or nacelle	5.8×10^{-5}	1.3×10^{-4}
Falling down of small parts from nacelle and hub	1.2×10^{-2}	1.7×10^{-3}

For fires in wind turbines, there is no equivalent guideline available. Dederichs et al. (16) compiled occurrences of fire in onshore and offshore wind turbines, using anonymous sources, data from selected countries, and insurance companies.

Meanwhile, a report by the SafetyOn Organization and the Energy Institute has investigated wind turbine fires on onshore installations from 2014 to 2018, using RIDDOR reports and self-reporting from its member companies (15). Data from Dederichs et al. (16), from SafetyOn (15), as well as some anecdotal references found elsewhere in literature are presented in Table 0.5.

Table 0.5 – References on the Frequency of occurrence of fire in wind farms

Frequency of Fires in wind turbines (1/yr)	Original source	Reference
5.0×10^{-5}	Anecdotal reference	(17)
2.0×10^{-4}	Reference form insurance company	(16)
2.0×10^{-4}	Compiled from Austrian, and German sources	(16)
5.0×10^{-4}	Swedish source	(16)
1.5×10^{-4}	Insurance company	(16)
5.0×10^{-4}	DNV GL	(16)
5.0×10^{-4}	Anecdotal reference	(22)
1.0×10^{-4} to 1.0×10^{-3}	RIDDOR reported incidents, compiled by British Wind Energy Association, from 2014 to 2018	(15)

Upon comparison of data from Table 0.4 and Table 0.5, the most common frequency values for fire events seem to align with values for tower collapse, while being about half of the frequency value of blade failures. This impression is stated expressly by Dederichs et al. (16) in their report.

However, as discussed previously, the number of event registries in the SAS database (Figure 0.2) suggest that fires may be as frequent as blade failures. The data collected from a smaller sample of wind farms by (15) also suggests this conclusion. If that is the case, a more accurate estimation of the frequency of fire in wind turbines is in the $5x10^{-4}$ to $1x10^{-3}$ range.

Fire Accidents

The most common causes of fire events in wind turbines ranked per the number of incidents reported in the SAS database are presented in Table 0.6. It should be noted that there was a total of 302 incidents that had no obvious cause reported in the database or that could be found doing internet research. These cases with no cause disclosed represent about two-thirds of the total number of fire registries.

Seventeen registries are somewhat vague in the description and attribute the cause of a fire to a “Technical defect”. This can mean any fault in a system that can lead to fire, including electrical faults, or mechanical faults leading to overheat. These events not listed in Table 0.6 because the actual cause of the fire could not be ascertained. However, these fires started due to technical defects would most likely not be caused by lightning strikes or events outside of the nacelle. There is a likelihood that the number of events due to electrical faults or overheat could be even more frequent than what is shown in Table 0.6.

Some of the fire events listed in the SAS database were excluded because they were related to activities not exclusively to a wind turbine. For instance, several cases of brush fire were reported during blasting to clear terrain for installation of a turbine. Another event that was excluded took place when a crane collided with a power transmission line.

From Table 0.6, it is clear that the main cause of fire in wind turbines are faults in the electrical systems contained in the nacelles. They represent over a third of the fire events with reported causes from the SAS database. This observation is in line with the statements from (23) that name the capacitor and converter cabinets in the nacelle as the one of the three major fire risk systems in a wind turbine. Fires started by lightning strikes of by overheat due to a mechanical failure are tied for the second leading causes of fire in wind turbines.

Table 0.6 – Fire incidents in Wind Farms. Adapted from (14).

Cause of fire in wind farm	Number of incidents	Percentage of incidents
Electrical fault in the nacelle		
During operation	34	29.6%
During Maintenance	13	11.3%
Total Electrical Fault in the nacelle	47	40.9%
Lightning	24	20.9%
Overheat	24	20.9%
External fire	8	7.0%
Electrical fault off-nacelle		
Transformer fault	4	3.5%
Battery fault	5	4.3%
Substation fault	2	1.7%
Total Electrical Fault off-nacelle	11	9.6%
Fire after the collapse due to high winds	1	0.9%
Total number of incidents	105	100%

Maintenance vs. Operation

Maintenance works often require the use of fire hazards, such as welding, abrasive cutting, soldering, flame cutting, or the use of electrical equipment not designed for use in the power turbine. One reported fire started due to an electrical fault in a coffee maker brought by maintenance workers to the nacelle of the wind turbine (16).

In addition, there are several recorded instances of fires that occurred upon the electrical systems in the turbine being restarted. From the SAS database, it was possible to classify the fire events due to electrical faults that occurred when the turbine was in operation, and those event that started when the turbine was being serviced by a maintenance crew. The results of this classification are also presented in Table 0.6.

About 72% of the fires due to electrical faults started during regular operation of the turbine, while 28% started while some sort of maintenance work was being done to the turbine. The expected amount of time a turbine undergoes maintenance has been reported to be in the 1% to 2% range (23), leading to the conclusion that there is a disproportionate number of events that took place during maintenance activities.

Fatalities and Human Injury in wind turbine fires

Among the 434 accidents registered and reviewed from the SAS database, there are seven fatalities, resulting from four different fire events in wind turbines (14):

- In 2003, a worker was performing a switching operation at the base of a wind turbine tower in California, when an explosion followed by fire took place. The worker did not resist the injuries.
- In 2005, a worker fell during escape from a fire in Southern Minnesota, while the other two workers present were able to safely evacuate. Workers were replacing a bolt on the Wind turbine generator.

- In 2012, two workers were performing maintenance in the nacelle of a wind turbine in Inner Mongolia, China, when a fire started. The workers were not able to escape and perished.
- In 2013, four workers were performing routine maintenance in a wind turbine in The Netherlands when fire broke out. Two workers were able to safely escape, one worker was trapped inside the nacelle and perished while the other worker was found dead at the base of the turbine, having fallen during the escape.
- In 2017, a fire broke out in the substation platform of the offshore SPIC North Binhai Wind Farm, in Jiangsu, China. Eighteen workers were able to escape by jumping into the sea, while one worker has not been found. Fire broke out during construction of the wind farm.

Likewise, there are seven registries for human injuries due to a fire event in wind turbines from the SAS database (14). In one instance, two firefighters were injured during firefighting activities on the ground. The remaining six registries are related to maintenance/construction activities. Considering the total number of fire accidents registered, 1.1% of them led to fatalities and 1.6% of them led to human injury, totalling 2.7% of the registries indicating consequence to people.

It is worthy to note that all but one of these fire events leading to fatalities and human injuries took place during maintenance/construction activities. There is no expectation of human presence during regular operation of a wind turbine, so that this should be always the case. This finding is in line with the conclusion by Asian et al. (9).

Considering the frequency of occurrence of fire in wind turbines from Table 0.5 and the data the percentage of fires that result in fatalities, the annual risk to a wind farm worker can be estimated between 8×10^{-7} and 1.6×10^{-5} event per annum, or an annual risk of fatality between 1 and 16 per million. This annual risk is of the same order of magnitude as a general risk to employees in the UK, reported to be 8 fatalities per million per annum (24). It should be noted that these figures cover the risk due to fire only, but they do not cover the overall risk to people in a wind farm. That figure can only be estimated considering the other undesirable events that can have severe human consequences.

It should be noted that the HSE UK stated limit between “broadly acceptable and tolerable regions for risk entailing fatalities” is one in a million per annum for workers and the general public (24). The actual risk to wind farm workers depends on each operator’s approach to risk management and may vary greatly from the average values estimated in this work. This figure is, however, a warning to wind farm operators that the medium risk of fatalities in the past decades is not broadly acceptable – meaning that operators should take a proactive approach to managing risk in each facility.

5. CONCLUSION AND RECOMMENDATIONS

The main objective of this work was to investigate the approaches used in the Wind Power Industry to hazard identification and to risk assessment. Several references that advocate using similar risk management techniques were found in literature, even though there seems to exist a misconception that the wind power industry is low risk.

The main reason for this perception is the lack of publicity of safety incidents in wind farms. Except for a few selected countries, there is no national or international requirements for accident reporting and analysis. The accidents that do gain exposure are the ones that lead to severe consequences or that are easily identified by the community living on the areas surrounding wind farms. The accident registries that are readily available are maintained by advocacy groups, but they are often incomplete and do not adhere to the same standards of quality that the accident reporting required by legislation in other industrial sectors.

The frequency of accidents in wind farms from the available database were found to be decreasing or stabilizing, which is often attributed to improvements in technology, and lessons learned as the wind power industry grow. The overall number of accidents in 2021, however, is still at the same level as they were in 2015.

Among the accidents in wind farms that can lead to a significant downtime, total loss of the infrastructure, and severe human consequences, fires are the second most common type of accidents, closely behind blade failure. According to the database research in this work, about forty percent of fires are caused by electrical hazards, while about twenty percent are due to mechanical causes. An additional twenty percent of fires were caused by lightning strikes. About 72% of the fires due to electrical faults started during regular operation of the turbine, while 28% started while some sort of maintenance work was being done to the turbine, which means there is a disproportionate number of events that took place during maintenance activities while workers are present in the power generation and transmission installations.

In addition, human causes were found in 2.7% of the accidents, with 1.1% leading to fatalities. Risk of fatality due to a fire in a wind turbine was estimated at 1 to 16 cases per million, per annum. Considering fire accidents alone, this figure is enough to contradict the argument that wind power is low risk.

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