

SFPE EUROPE



Q3 2021 ISSUE 23



AN OFFICIAL PUBLICATION OF SFPE

Wind Turbines: Towering Inferno or False Alarm?

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The world is shifting to renewable energy and wind is one of its leaders. Wind turbines now account for over one third of the world's renewable power capacity. This article explores the impact of fire and the role of fire protection engineering on the wind industry. Fire is not a trivial hazard for the wind industry and it remains understudied.

1. Wind as leading renewable energy

The world is shifting to renewable energy because of the challenges of climate change and the finite supply for fossil energy generation. In this context, wind turbines are a leading energy generation type. A recent study [1] estimates that wind energy now accounts for one third of the global renewable power capacity. As shown in Figure 1, wind energy grew slowly at the beginning of the century, but in the last decade capacity has increased at an exponential rate. The future is bright, and wind attracts over one fifth of the world's financial investments in renewable energy, amounting to \$6 billion in 2018 [1].

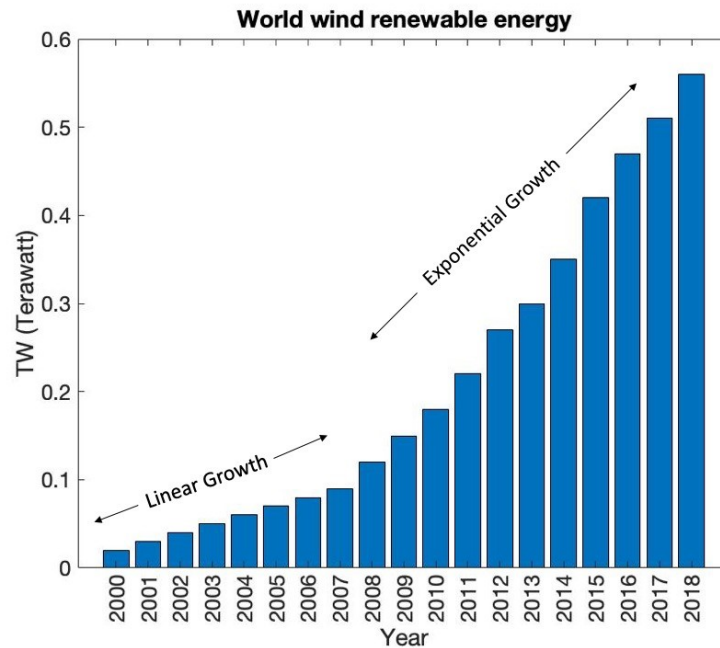


Figure 1. Growth of the global power capacity of wind energy since the year 2000. At the beginning, growth was linear but now it has taken off and wind energy capacity increases exponentially. Sources of data IRENA, BWE and GWEC.

To ensure that wind energy generation can remain competitive and keep pace with increasing demands in efficiency, there is a continuing trend on increasing the height of the turbines and the length of the blades. The historical evolution of turbine size is shown in Figure 2, whose average growth rate in height is 4 m per year. In 2015, turbines already could be as tall as 140 m, with blades up to 80 m long. In the foreseeable future, turbine size is expected to continue growing.

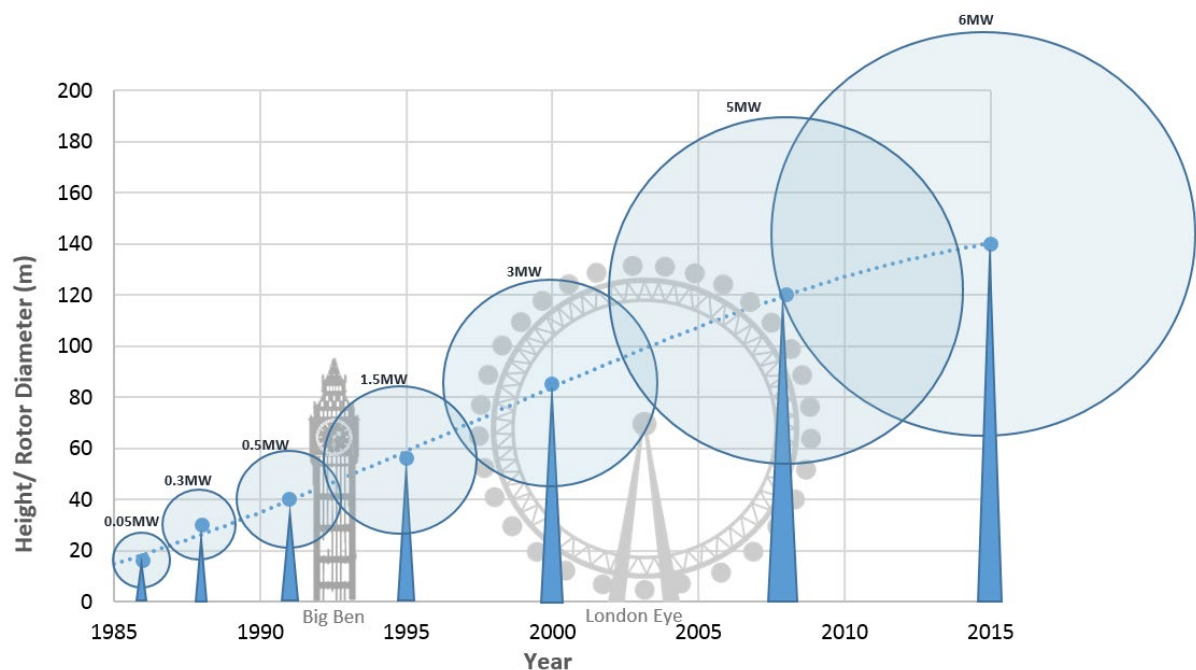


Figure 2: A London centric illustration of the growth of turbine size since 1985. The average growth rate in height is 4 m per year. Background compares sizes to the Elizabeth Tower (aka Big Ben) and the London Eye. Figure inspired after Prof Henry Seifert.

The reasons driving the increase in turbine size are power and return on investment, because every small gain in power capacity represents millions of dollars in revenue over the lifetime of a turbine. By increasing the size of the blades, the efficiency improves because the turbine captures per revolution more wind movement to convert into the torque driving the electric generator. Also, by increasing the height of the turbine, the blades are placed higher up where wind flows faster because there is less effect of ground friction and less flow disturbances by surrounding terrain, forest or structures.

Wind energy generation is a relatively new commercially viable technology, still maturing fast, which was made recently profitable thus attracting more investors. Therefore, future investments could be sensitive to costs and uncertainties. Fire accidents are a source of both costs and uncertainties. Each wind turbine costs in excess of \$2 million and generates an estimated income of more than \$0.5 m per year. Any loss or downtime of these valuable assets makes the industry less viable and productive. Moreover, the trend to install ever larger turbine means the cost per fire trends to increase as well. Also, any one wind turbine fire is very visible to neighbors and the media (both mass media and social media), and also the smoke emissions can cast a shadow over the industry's green credentials.

2. What are the key fire challenges posed on wind turbines?

The following are three case studies of actual wind turbine fires around the world that illustrate the variability of possible scenarios and the key challenges posed.



Figure 3: The nacelle and blade of this wind turbine in England were burning at height. Photo by Cambridgeshire Fire and Rescue Service, 2018.

In June 2012, a wind turbine in Riverside, California, caught fire due to arcing in the generator. According to the incident report by the fire brigade [3], the fire was detected by a resident. Despite the area cleared of vegetations around the base, firebrands (burning debris) from the nacelle fell on vegetation further away and caused a wildfire. The wildfire destroyed 4 km² of forest, burnt power lines and several other turbines. Residents were evacuated, and 100 firefighters attended. This case illustrates the challenge of secondary fires on nearby forest or urban sites. Owing to the significant height of wind turbines, firebrands can travel long distance aided by the wind, creating the need to protect against fire not just the wind farm but also a large area around it. In fact, our review of worldwide fires reported in the media between 2012 to 2016 shows that 12% of the turbine fires cause secondary fires in industrial or forested areas, whereas 73% are contained to the turbine alone and the rest (15%) are unknown containing cases.

In October 2013, a short circuit caused a fire inside the nacelle of a wind turbine in Netherlands [4]. At the time of the fire, four technicians were doing maintenance work inside the nacelle, and two of them were trapped by the flames and smoke. They could only evacuate to the roof of the nacelle where they waited to be rescued but sadly succumbed to the fire. These were the first recorded fire fatalities in a wind turbine. The difficult access to the nacelle housing highlights the issue for technicians performing work in wind turbines which increases the risk to life in case of fire.

In January 2016, an electric arc resulted in a turbine fire in Germany and three technicians were injured with burns and smoke inhalation [5]. Firefighters attended but owing to the height of the turbine, they did not have an adequate mean to suppress it, relegating the response to preventing secondary fires.

The fire self-extinguished after 3.5 h of burning. This case highlights the challenge that the height of a turbine restricts firefighting. Our review of worldwide fires reported in the media between 2012 to 2016 shows that only 10% of the fires were suppressed by the Fire Service, whereas 72% were left to burn out and the rest (18%) were unknown suppression cases. This is a low number of successful suppression cases indeed.

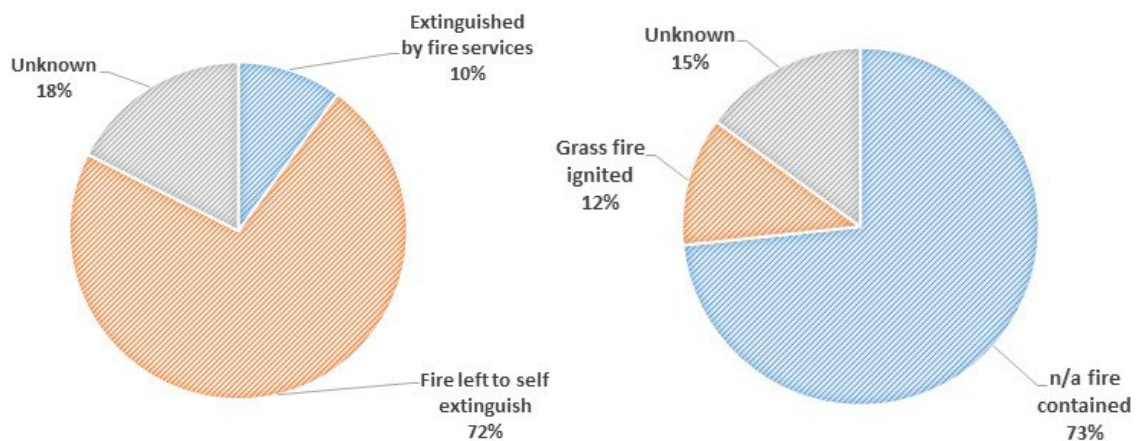


Figure 4. Results from a worldwide media search of turbine fires between 2012 to 2016. 120 fires were found. Left) Role of firefighting suppression. Right) Igniting of secondary fires.

3. How often do wind turbines catch fire?

With an appreciation of the key fire challenges to wind turbine, we turn to the questions: *is fire a cause of concern for the wind industry?* Are the three cases above just sporadic episodes amplified by the dramatic images in the media? How often do wind turbines catch fire?

The data in Figure 5 taken from [2] shows fire is the second leading cause of accidents in wind turbines (15% of the incident), after blade failure (19%). However, blade failures generally do not destroy the entire turbine while 90% of fires lead to total loss of the turbine.

A previous study [2] found 200 turbine fires worldwide from 1995 to 2012, this is 12 fires per year on average. We have extended this search from 2012 to 2016, and we found 120 fires, doubling the rate to 27 fires per year. The number of fire incidents seems to be accelerating. But this is a small number, just 1 fire per 10,000 turbines worldwide, which means the industry is safe by comparison with compared to other energy industries, like oil and gas that globally suffers thousands of fire accidents per year, some with devastating environment impacts. But a pressing question to consider is that in the context of all the challenges faced by the wind industry, is fire an important consideration?

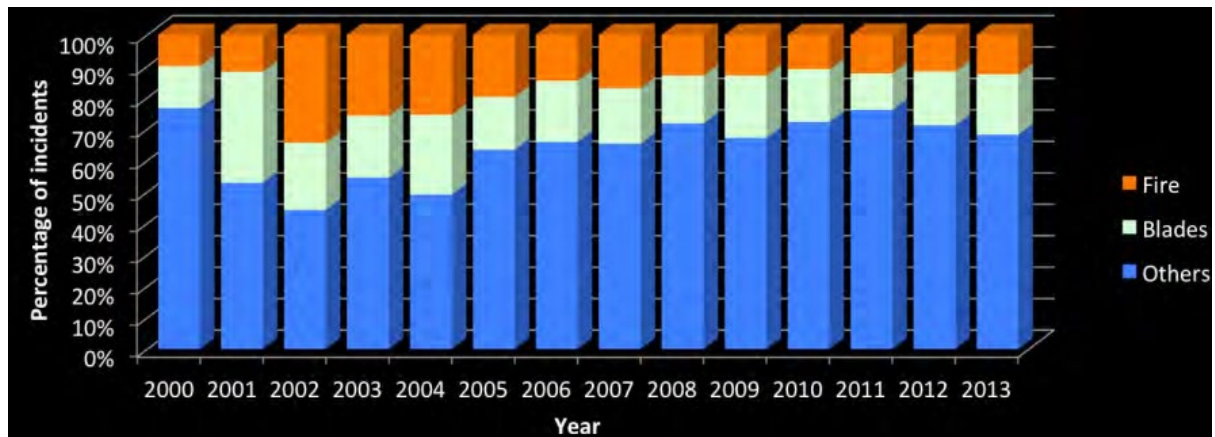


Figure 5. Cause of wind turbine incidents including fires, blade failures and others. Data taken from [2] which source is CWIF.

In trying to answer these questions, we faced a first hurdle in that there is little data publicly available. The best source existing right now is ad-hoc reporting by mainstream media and social media, which brings a bias towards countries with international online journalism like USA, UK and Germany (63% of the fires are reported there), and completely misses Asia which account for 1/3 of installed power. Other databases are Bundesverband WindEnergie, CWIC and Bulldog. CWIF (Caithness Windfarm Information Forum, UK) is the biggest and most accessible database (curated from media reports) but they run a self-confessed anti-wind turbine agenda which can be perceived as a conflict of interest. We have independently confirmed many of the fires reported by CWIF, and therefore we know these fires did occur. Two key databases used in the 2012 landmark study [2] are no longer accessible: AREPA and Bundersverband landschaftsschutz. The question remains: are we just seeing the tip of an iceberg? We know of pro-wind associations who have confirmed they hold large databases on turbine fires, but unfortunately, we have not been granted access to the data despite our requests. Therefore, any analysis is restricted to what is publicly available. This is our best endeavor at this point in time.

4. Anatomy of a wind turbine fire

The three elements of the fire triangle (fuel, air and ignition) are all present inside the turbine nacelle, near each other. Air is plentiful around and inside a turbine, so the focus is on the fuel and the ignition as illustrated in Figure 6.

The fuel consists of various flammable components like oils in the transformer, hydraulic or lubricant. For example, a study [6] of flammability hazards of oils in a turbine nacelle indicates that the transformer oil is the easiest to ignite while lubricating grease is the most difficult. In addition, there are hundreds of meters of cables (a flammable component) for power and communications. Other fuel sources include the insulation for sounds and heat, and the composites of the nacelle housing and the blades.

For the other element of the fire triangle, there are four known ignition sources in nacelles [2] which in order of importance are lightning strike (despite turbines having lightning protection), electrical malfunction (short-circuit or arcing), mechanical malfunction

(hotspots or motor failure), and hot maintenance work (low safety during maintenance like welding).

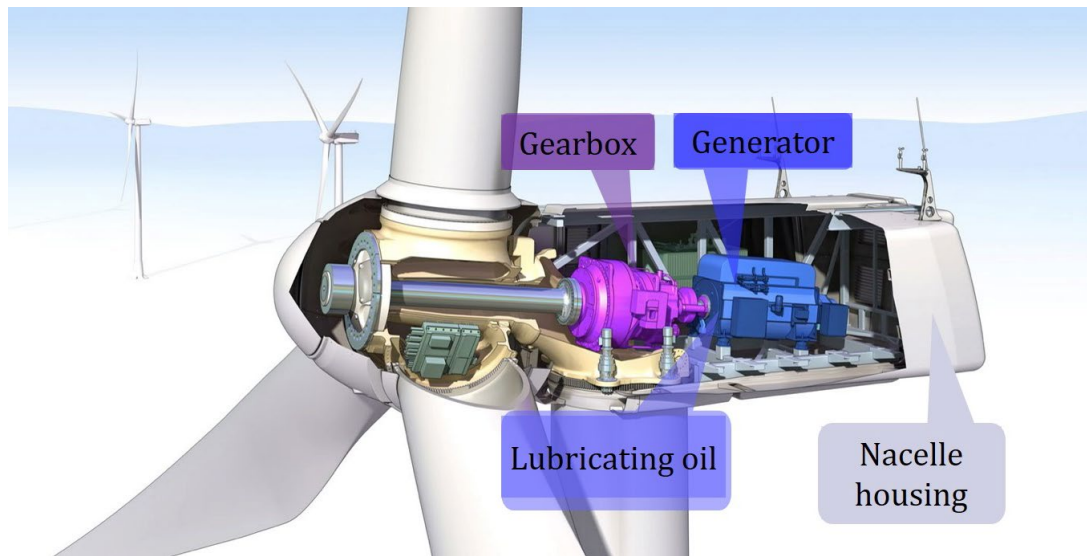


Figure 6. Schematic of a wind turbine highlining its four most important elements in term of fire hazards, based on a similar figure in [2].

5. Solutions? Disrupt the fire triangle and Smart systems

The rough analysis of a wind turbine fire as done above provides a better understanding of the problem. This helps in developing effective solutions. For the complex situation of a wind turbine, we advocate the philosophy of system safety made up of a series of layers of protection including prevention, detection, evacuation, compartmentation and suppression and stability.

For prevention, the risk of a fire can be reduced during the engineering design stage by disrupting the fire triangle and separating ignition sources and fuels. For example, by reducing the failure points, e.g. increase machine maintenance to avoid hotspots due to excessive friction, minimizing cable junctions that could fail electrically, or advancing the use of direct drive turbine which do not require a gear box (no lubrication oil and no hotspots there). The fuel size can be controlled by reducing the presence of flammables, e.g. by replacing mineral oil with synthetic oil, and considering the use of composite materials with low flammability.

The evacuation layer requires a reliable and fast detection to begin with so that technicians are immediately aware of the peril, and egress can be supported by providing additional routes for a quick egress, like foldable ladders or ropes (already existing in some turbine designs) [7]. Compartmentation would require major re-designing for fire and smoke resisting walls separating the major parts of a nacelle (gear box from generator?). The structural stability layer would be to design additional resistance in the nacelle, the blades and the tower to minimize chances of collapse during a fire or shortly after it.

For the suppression layer, water mist systems or gas flooding systems could be considered as a compromise between size and fire suppression efficiency in the close compartment of

the nacelle. We appreciate the substantial weight associated with the gas-based suppression system, plus these systems are also very costly and requires a significant space. A localized fire suppression system focused on the most flammable element could also be considered to put out a small fire before it grows to damage the turbine. A localized system is likely to provide a balance between cost, space, weight and effectiveness compared to a full system for the whole of the nacelle interior.

But above all, a systems design approach to fire protection can take advantage of the fact modern wind turbines are already equipped with myriads of smart sensors that monitor its performance in real time. However, none of these sensors are used for fire safety. For example, a good detection layer calls for smart devices that avoid very costly false alarms by combining heat and gas composition signals in multiple points. Or using temperatures sensor to detect overheating ahead of an ignition event.

These sensors can be utilized as a first line of defense whereby if an anomaly is detected, an alert signal can be dispatched, or a shutdown can be initiated. Further when sensors and data collected are paired with a smart algorithm, an automated predictive maintenance monitoring regime can be implemented where the smart system can attempt to predict the potential point of failure and provides an early warning to the operators that a specific wind turbine should be checked.

6. Conclusions

Fire is a cost, an extra liability and a negative public image for wind energy. Fire is the 2nd most frequent incident in wind turbines, and often leads to the total loss of a turbine. Media reports about 1 turbine fire per day worldwide and this is just the tip of iceberg. The true extent of the fire impact on wind energy remains unknown.

Wind turbine fires are an investment risk but also a life safety risk due to the difficult evacuation of technicians, and that the fire cannot be suppressed from the exterior due to their height thus often leading to a total loss of the turbine. Further, a fire creates an additional hazard zone where secondary fires could be possible.

Our experience underlines the fact that wind energy needs to have a complete and open approach to data on fire incidents. The availability of such statistics will enable risk professionals to carry out a probabilistic cost benefit analysis to examine the pros and cons of each option, weighing it against the implementation cost, consequences cost and the level of risks expected. We want to emphasize that engineering solutions exist, but we need to first understand the phenomena, causes and the extent of the challenges.

We hope this work encourages others to pursue this problem, and to make the data available so the fire community can contribute to fire-proof wind turbines, thus better secure this key element in our world's energy future.

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