SAFETY MANAGEMENT AND FIRE PROTECTION IN WIND TURBINE NACELLE

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Abstract

Wind turbines play a major role in harnessing green power across 100+ countries with an installed capacity of 837 GW as of 2021 employing more than three lakh people worldwide. Through technology innovations and economies of scale, the global wind power market has nearly quadrupled in size over the past decade and established itself as one of the most cost-competitive and resilient power sources across the world. The size and generation capacity of each wind turbine has been increased in recent years. Higher the height, greater the rotor diameter helps to harness more power. Hence this becomes a need in the market and challenge to manufacture, construct and maintain components that could last for at least two decades involving high investments and operating costs per wind turbine. Any fire incident in these turbines could result in huge financial losses up to $6 million and the restoration period would be a minimum of 6 to 12 months. Studies show the normal firefighting methods and response time for the fire engine to reach the location is challenging and would not help much to save people nor assets. The objective of this study is to discuss the safety management considerations and active fire protection systems that are needed on the wind turbine nacelle to manage the fire risks during its lifetime using innovative technologies which are new and best in the industry.

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1. Introduction

Wind energy is widely regarded as the world's fastest - growing energy source, and it is frequently cited as a critical component in the fight against climate change. As renewable energy grows, wind energy will become the backbone of energy systems in many parts of the world. This will simply increase the wind energy capacity with new collaborations with stakeholders across the global energy system to uncover more powerful policies and unlock greater investments to fuel the Sustainable Energy. Harnessing of wind power is done at both onshore and offshore using horizontal axis turbine for many decades since invention. Currently, in the wind market, there are two different types of wind energy namely onshore wind farms and offshore wind farms. Now a days, wind power is becoming more financially viable because of technological advancements and global legislation addressing climate change. Many projects are also being funded by banks and private investors. The total installed capacity as on 2021 is 780 GW Onshore & 57 GW offshore [1].

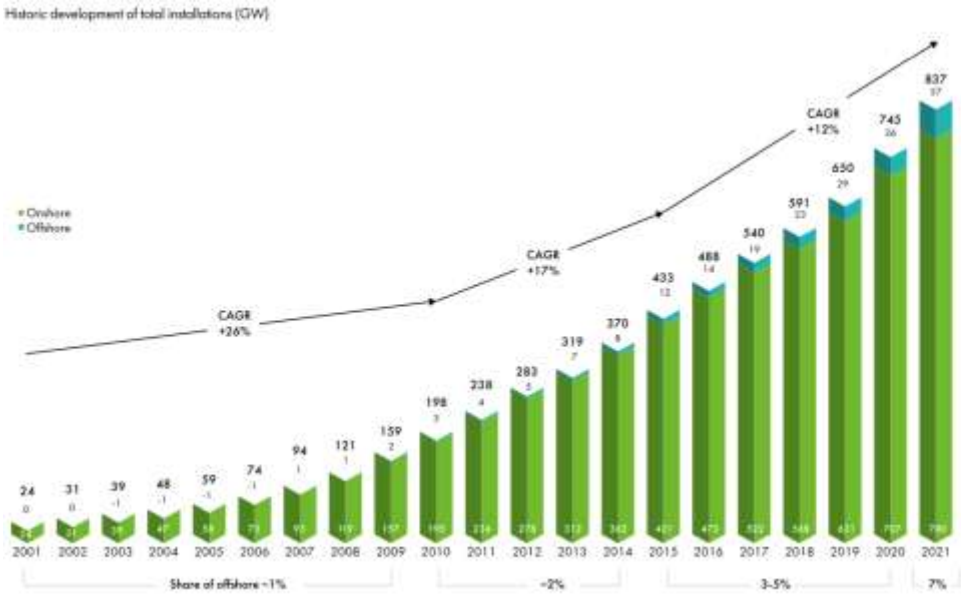

Figure 1: Historic development of total installations (GW) in Onshore & Offshore

2. Materials And Methods

Components of a wind turbine

A wind turbine generates electricity from the wind. It consists of a rotor (blades/hub) connected through the drivetrain (main shaft and gearbox) to a generator. When the blades capture the wind, the rotor start rotating and the generator produces electricity. The output from the turbine is converted by a converter and transformer to the desired current on the electrical grid. To control the rotation of the rotor, the blades can be pitch in or out of the wind. The pitch system is a hydraulic system and contains pressure vessels containing compressible fluid. Beside controlling the pitching of the blades, the hydraulic system also supply pressure to the brake on the highspeed shaft.

The major components of wind turbine are:

- Foundation – Entire wind turbine is mounted on it
- Towers – Used to mount nacelle
- Blades – Usually 1 One -3 three
- Hub – Blade interface
- Nacelles – Consists of drive train and generator

2.1 Study of Incidences of Fire in Wind farm

The threat of fire is rarely present, and the industry takes it extremely serious. While most fires start in the nacelle, they can also start in other micro-environments such as control cabinets, braking systems, and hydraulic systems. Because of their inaccessibility, the chances of emergency personnel being able to put out a fire before the turbine is destroyed are practically negligible. As a result, it's critical to try to put out a fire right where and when it starts.

2.2 Fire Incident Statistics

The statistics [2] shows fire incidents are possible under poor management of assets or wind turbine which incur huge financial loss if the turbine catch fire. Few people have also lost their life by getting entrapped in smoke or blocking the normal access during maintained task in these unmanned turbines. A total of 414 fire incidents [7] were found The data is presented in the Table 1. Five fire accidents have badly burned wind industry workers.

Figure 2: Picture of burnt turbine

Table 1. Data of the number of fire incidents

Year	**Before 2000**	**2000-2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
No.	7	77	12	21	17	18	16	22	23
Year	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
No.	26	19	20	28	25	27	23	22	9

2.3 Challenges to Emergency Response

These turbines are normally built after identifying sites / locations through micro sitting. Those are normally in remote locations such as hills, plain lands, desert, offshore etc., so that they are away from residential or industrial areas which bring challenges to respond on time for rescue and support in case of fire. Other challenges are access ways or poor mud roads for fire vehicles in plain land or hills, location access not possible through GPS coordinates, non-availability of helicopter access and basic version of fire truck / fire engine in local districts close to wind farm. Many developing countries or under developing countries does not have even built their infrastructure to fight fire or rescue a person from even 65 meters height as they are limited with basic version of fire truck / fire engine only. The cost of restoration is high including the timeline on an average minimum six months which involves insurance surveyor visit, assessment of damaged components, arrangement of spares, cleanup of site, health and safety assessment to de-erect and erect wind turbine followed by special procedures and considerations. Fires are not a common occurrence for wind turbines – but when they do strike, they can be very costly. The costs of establishing the wind turbine as well as reestablishing costs are proportional with the installed effect. Hence Prevention and protection are therefore essential to save life and property. Thus, it becomes a necessity for a proper safety management to prevent and protect wind turbine from fires to for successful and safe operation.

2.4 Nacelle

It is well known that nacelle is one of the important parts of the wind turbine. In this research, the nacelle is taken for the fire risk assessment because of the chances of fire are more prone in many of the nacelle components. The approximate weight of the nacelle ranges between 30 and 300 tones. Nacelle[3] is located at the top of wind turbine ranging from 30m to 200m. It consists of rotating elements [7] such as low - and high -speed shafts, brake disc, gearbox which are possible source of heat energy and mechanical energy, chemical substances such as hydraulic oils for pressure applications, gear oils, lubricants, coolants electrical components such as cabinets, busbar, convertor, controller, generator, power cable, so on and other substance such as solid glass fibber or plastics. Cost of wind turbine nacelle is comparatively high when compared to other components of wind turbine [8]. The various components present in the Nacelle is illustrated in the Figure 3.

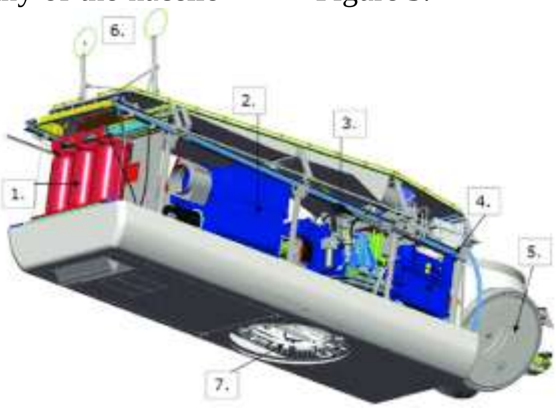

Figure 3: Parts of the nacelle: 1, transformer; 2, alternator; 3, gearbox; 4, hydraulic equipment: 5, blade pitch regulation system; 6, weather sensors; 7, yaw system.

The following are the common causes of fire from Nacelle

- Exploding capacitors igniting
- Nacelle Insufficient/repair/in breaker/bus bar/HV sect
- Re-energizing an arc error - insufficient check
- Defect HV transformer
- Generator cable connections
- Hot brake - high wind - no grid Hot generator bearing
- Defect and hot main bearing
- Poor Maintenance -Inspection, Repair & Replacement Program
- Failure to assess /mitigate risks for hot works in nacelle

2.4.2 Common Ignition sources in wind turbine nacelle

The most relevant ignition sources in the turbine as a machine have an electrical, thermal, or mechanical origin. Lightning strikes [4], rotating and moving parts leading to hot surfaces and sparks due to friction, HV and LV components which can generate arc flashes, arc blast, overheating or short-circuits, batteries, chemical materials such as oils, grease, etc., Other ignition sources have a human interaction such as large corrective involving hot woks during maintenance replacement and repair activities, smoking and cooking.

2.4.3 Combustible materials in wind turbine

To determine the fire risks, a proper fire risk assessment [3, 4] is performed on the wind turbine, components and interfaces. Those are assessed and the adequate reduction measures are put in place. Risk management of serious accidents has identified five critical ignition areas with highest occurrence of ignitions. Many of the critical sources of ignition are present in the Nacelle. Hence the prevention, detection and extinguishing efforts will therefore be focused on these areas of the Nacelle. The primary transformer compartment where the

Combustible materials do exist in different forms, from solid glass fibre or plastics to oils. Changes of the material state may occur under certain circumstances depending on the failure mode, e.g., vaporized oil.

2.4.4 Fire Risk Assessment

transformers act as a link between wind turbines and distribution grid. It steps up the low output voltage from the generator to higher distribution voltage level. The following are the five critical areas which are the sources of ignition.

- Auxiliary transformer
- Generator and slip ring area
- High speed shaft area / Mechanical parking brake area
- Heat blowers
- Electrical control cabinet especially those containing Capacitors

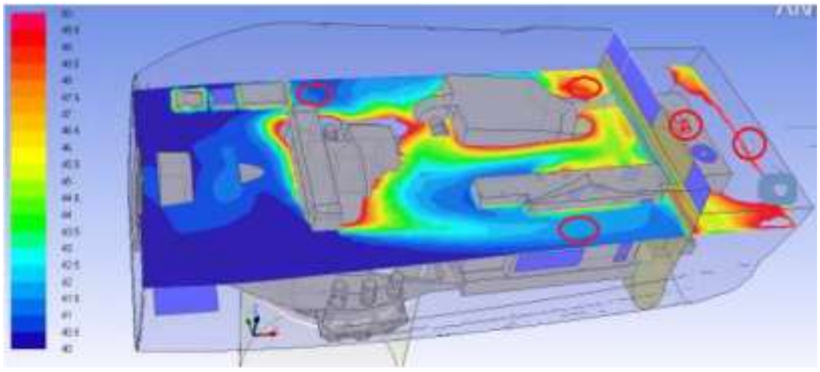

Figure 4: Thermal imaging

Ignition sources and combustible materials are the basis to determine foreseeable events and errors that might lead to a fire. In the Figure 4, it is seen that the various high temperature zones at normal operating conditions.

2.4.5 Bowtie methodology

This risk management tool used to identify and assess the potential consequences of a hazardous event and the measures in place to prevent or mitigate those consequences. The Bowtie model is illustrated by the Figure 5. To use the Bowtie methodology for fire risk assessment, the following steps can be followed:

1. Identify the hazard: Define the fire risk and what could cause it.
2. Define the top events: Determine the most severe potential outcomes of the fire risk.
3. Identify barriers: Identify the measures in place to prevent or mitigate the fire risk.
4. Assess the likelihood of the top events: Evaluate the likelihood of the fire risk occurring.

5. Evaluate the efficacy of the barriers: Identify and or Assess the effectiveness of the measures in place to prevent or mitigate the fire risk.
6. Analyze the risk: Determine the overall risk level and prioritize risk reduction measures.
7. Apply complementary measures to deal with fire if any that could arise to limit he consequence
8. Review and revise: Regularly review and update the risk assessment to reflect changes in the fire risk and risk reduction measures.

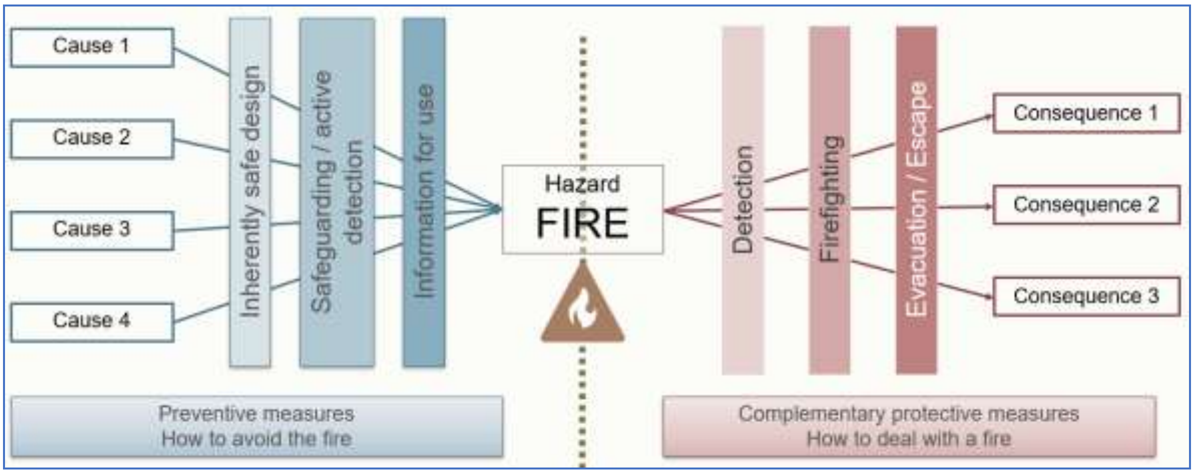

Fig. 5. BowTie model for fire risk assessment

This methodology is adopted for the fire risk assessment. Three events are identified in three different zones and

Zone	Event	Preventive		Protective	Residual risk	Information for use (ISO 19353, clause 7)
		Inherently safe design	Safeguarding			
Drive train	Sparks and heat in the mechanical brake due to different failure modes	Selection of pads material: The parts are selected in organic material, not producing sparks when worn out. Brake designed according to expected thermal	Thermistor monitoring some of the pads, threshold 120 degrees. Above this temperature, an alarm is sent. Safety system in turbine will ensure the brake only is activated under defined preconditions	None	Low, enclosure, reduced combustible materials and controlled ignition source	1. Acoustic signal and notification y control system (break heats up). Operation, alarms, and warning. Ref. Operating manual, OEM tool kit 2. Scheduled inspections. Ref. Service manual 3. Repair activities. Ref. Service

		loads. Brake enclosure				manual 4. Evacuation Instructions 5. Safety Manual
Nacelle	Lightning strike hits blade, Spinner or Nacelle.	Design of the LPS system according to the IEC 61400-24 standard.	None	None	Lightning strike occurs in a very short time span only side flashes would hit the Nacelle covers, and these carry a much less current than a direct lightning strike thus unlikely to ignite the covers.	1. Scheduled inspections of lightening conductor cable. Ref. Service manual 2. Lightening protection system conductivity test, Service manual 3. Safety Manual 4. Evacuation Instructions (Marine / weather forecast)
Human factor	Hot works	Turbine designed to reduce hot works, e.g., assemblies by bolted joints	Smoke detection and alarm	hot work permit Manual firefighting equipment	Medium. Implementation of hot work permit required	1. Repair activities, hot work permit. Ref. Service manual 2. Evacuation Instructions 3. Safety Manual
	Foreseeable misuse, personnel smoking, cooking, or using heat elements or open flames	NA	1. Smoke detection and alarm	Manual firefighting equipment	Medium. Not possible to control what people will do	1. Safety warning signs 2. Evacuation Instructions 3. Safety Manual

Figure 6: Fire Risk assessment Study

Fire protection concept

The fire protection concept consists of a series of active and passive fire prevention measures. Some of them are targeting personal safety whereas others are targeting asset protection or both. The following classification divide the measures between passive [9] and active, by the hierarchy of prevention first and protection after.

Passive

Separation

One of the most effective methods to prevent fire is the separation between ignition sources and combustible materials. However, it is not always possible to achieve due to the nature of components, their location, and their functionality in many cases.

Enclosure

Enclosure of elements such as gearbox, generator brakes, oils and electrical elements avoids the conjunction of ignition sources and combustible materials and/or the energy released by mechanical, electrical, or thermal events into an open environment with a higher number of flammable materials.

Cabinets have been tested in compliance with IEC-60439-1 standards in order that all safety guidelines covering insulation distance and lines of fire with working voltages are observed.

Selection of materials

Oils and other hazardous materials are selected with high flash points and low flammability, reducing the autoignition and the ability of catching fire.

Fire retardant capability of some components such as HV cables, reduce the propagation of the fire between components and areas in the turbine.

The cover is designed with fire retardant properties on those areas where personal safety cannot be guaranteed in terms of separation or enclosure.

Lightning protection system

The lightning protection system is designed to receive the lightning strikes and safely conduct the current down the tower to the transition piece in a controlled manner.

Tests

Factory and commissioning tests ensure that assemblies are done in a correct manner, reducing the risk of failures when the turbine is energized and put in operation. Some components are designed, and type tested according to specific standards might be type tested, e.g., switchgear.

Maintenance

Maintenance of critical components is scheduled to assure that components are in an appropriate state, reducing the risks of malfunction leading to electrical, mechanical, or thermal events.

Active

Cooling and Conditioning

A cooling and conditioning system is provided to reduce the fire hazards caused by mechanical or thermal events on those components where temperature is expected to raise during operation of the wind turbine such as gearbox, the generator, the transformers, and the converters.

Fire Protection Controller

A fire extinguishing controller handles all inputs and outputs and all processing for warnings and alarms. The fire protection controller is also the point of the system that communicates with the SCADA system.

Figure 7: Fire protection controller based on industrial PLC

An industrial controller will be used for the fire protection controller. This controller will be shared with the switch gear controller for new platforms and will be added for fire protection in retrofit solutions. Thus, a single solution with consistent interfaces will be used for both new and retrofit applications.

The fire protection controller interfaces with

- the extinguishing trip valves
- alarms, sounders, and any possible human-machine interface
- the arc-detection system
- the addressable detector bus for all point and aspiration detectors
- the turbine controller for shutdown, warning, error, and shutdown handshake signals as well as Ethernet communication
- the switch gears

Monitoring

Critical components are monitored to ensure that the turbine is stopped before mechanical or thermal events leads into a fire, e.g., temperature monitoring.

Fire detection system in wind turbine

System that ensures that all components such as arc and smoke detection, protections relays and safety system are in good conditions and active prior to energization.

- An arc detector will immediately disconnect the switchgear from the grid and shut down the turbine.
- A smoke detector will make a controlled shut down the turbine.
- The switchgear protection relays opens when an overload or short-circuit is detected on the high voltage system.
- The safety system controls the trip functions and monitors that the switchgear is ready to trip.

Arc detection

Arc detection sensors are placed in specific areas and cabinets to detect arc flashes in the electrical systems and disconnect the source of power.

Advance smoke detection (ASD)

The function of the ASD is to detect smoke, disconnect the power source, activate the alarm sounders and report via SCADA. Its primary function is preventive, although it has the alarm feature as a protective function.

Timely inspection & maintenance recommendations of supplier / OEM become crucial to prevent or limit fire under unforeseen situations. Otherwise, no point in having them

Detection of fire-in-the-making

The smoke detection system forms the second line of defense by removing power sources earlier then the smoke level and the certainty required for extinguishing.

Fire Suppression systems

Wind turbine fire protection can take a variety of forms. Wind turbines can be outfitted with smoke, heat, and flame detectors, as well as fire suppression systems. These varied detectors can detect fires in their early stages and transmit information to a central alarm system, which will cause the turbines' components to shut down completely and turn on a fire suppression system [11].

Automatic Fire Suppression Systems

Figure 8: Automatic Fire Suppression system in Electrical cabinets

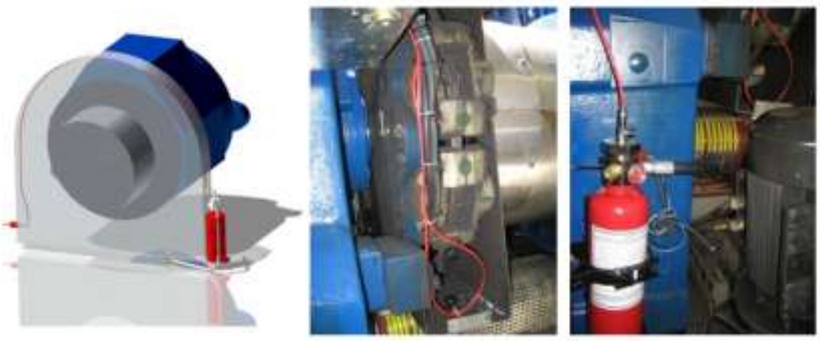

Figure 9: Fire Suppression system with flame and heat detection with 1 nozzle discharge.

Manual firefighting equipment

Manual firefighting equipment is provided to support the evacuation and escape in case of fire at identified locations. It is not intended to extinguish the fire rather to fight fire in incipient stage. Fire escape gears, a fire blankets are installed in prominent locations.

Emergency lighting

In case of a fire detection where the grid input is interrupted to the system, the UPS will automatically take over the power supply. The electrical switching will disconnect the work light and only power the emergency light in the WTG. Whenever the grid is lost, an internal timer is started to ensure sufficient time for evacuation or escape.

Evacuation and escape

An evacuation and escape strategy [9, 10] are defined to ensure that at least one route is always available while persons are in the turbine.

Evacuation in case of fire

1. If a fire breaks out inside the wind turbine, consider the possibility of fighting it as long as the safety of people is not compromised. The portable extinguishers in the wind turbine or in the transportation vehicle are only effective in the initial stage of a fire. Once the fire has taken on considerable dimensions, they should no longer be used.
2. The wind turbine should be evacuated will depend on the relative position of the people in relation to the fire. Whenever possible, evacuation should take place using the habitual access

routes (tower ladder). Do not use the lift in the event of a fire, it could delay and complicate the evacuation.

3. Zero level fire in the wind turbine and staff on the same level. Evacuation should be carried out through the door of the wind turbine tower.
4. Fire in the base of the wind turbine and staff at a higher level (tower or nacelle). The evacuation should be carried out by accessing the nacelle as quickly as possible and using the emergency descent system.
5. Fire in the nacelle and staff at a lower level. Evacuation should be carried out using the habitual access routes to the wind turbine.
6. Fire in the nacelle and staff in the nacelle. Exit the nacelle using the habitual access routes to the wind turbine. The use of emergency descent equipment is forbidden.
7. In the event of a fire, the wind turbine affected must be isolated from the mains power grid as soon as possible. That is, Disconnecting the wind turbine from the mains power directly from its cell, from the substation or from the cell of the previous wind turbine on the same line.

3. CONCLUSION

Harnessing of wind power is presently an important source of renewable energy in many parts of the world. Fire can be a serious threat to the operation of wind turbine and its location possesses many challenges to reach and support. Since these are normally unmanned turbines, the risk to workforce arises once during maintenance which is extremely low but still exits. If the turbines are maintained by the original equipment manufacturer or by the third-party service provider, compromises should not be made to keep the equipment and it's system in perfect condition including timely replacement and repair of components.

Design considerations and fire risk assessment plays a vital role in determining the hazards to establish appropriate risk reduction measures in the wind turbine. The impact of fires on wind turbines can be mitigated by using active and passive fire protection measures. Potential ignition sources should be avoided by appropriate design.

National regulations on fire specifically for wind farms still do not exist in many countries. Hence wind turbine manufacturer must put health & safety requirements at the highest level through international guidelines and standards.

It is also further recommended that the operator or service provider establishes and tests the Fire Safety Plan along with the relevant rescue services. Furthermore, it is recommended to carry out the required trainings to all personnel who work in wind turbine established by Global Wind Energy Organization which gives benefit to the entire industry.

Thus, wind turbine manufacturers need to have separate focus & have a structured approach on fire risk management to improve the safety through design. This should happen during the initial stage of "**Product Design& Development Process**". BowTie methodology or similar tools to perform fire risk assessment can be opted to identify potential consequences, and prioritize risk reduction measures to ensure the safety of the people & Wind turbine

4. REFERENCES

1. GWEC | GLOBAL WIND REPORT 2022, Global Wind Energy Council, Rue de Commerce 31 1000 Brussels, Belgium. Lead Authors Joyce Lee, Feng Zhao. Published 4 April 2022
2. Caithness Windfarm Information Forum, "Summary of Wind

Turbine Accident data" Source http://www.caithnesswindfarms.co.uk/AccidentStatistics.htm

3. The Manufacturing Engineering Society International Conference, MESIC 2015 New wind turbine manufacturing techniques J. A. Sainza,* a Jose Antonio Gonzalez Sainz. Department of Manufacturing Engineering, National Distance University of Spain (UNED), C/ Juan del Rosal 12, 28040-Madrid, Spain
4. Frank Markert (2016), "International workshop on Fire Safety of Wind Turbines"
5. ISO 19353:2019 Safety of machinery — Fire prevention and fire protection
6. NPFA 550 (2007) Guide to the fire safety concepts. National Fire Protection Association, Quincy, MA
7. Overview of Problems and Solutions in Fire Protection Engineering of Wind Turbines, SOLOMON UADIALE1, ÉVI URBÁN1, RICKY CARVEL1, DAVID LANGE2, and GUILLERMO REIN3, Department of Mechanical Engineering, Imperial College London, UK
8. L. Fingersh, M. Hand and A. Laxson, "Wind Turbine Design Cost and Scaling Model," National Renewable Energy Laboratory, 2006
9. Anne S. Dederichs, Greg Baker, David Lange, Benjamin Krause, David Winberg, Jonatan Gehandler (2016), "Fire Safety in Offshore Wind Turbines", *SP Technical Research Institute of Sweden Box*, 857
10. Onshore Wind Health & Safety Guidelines from Renewable UK by Sgurr Energy Ltd
11. R. Dudley, "Automatic Fire Detection and Alarm Systems - An introductory guide to components and systems," BRE, 2010
12. Confederation of Fire Protection Associations in Europe (CFPA E), Wind Turbines Fire Protection Guideline, No 22:2010 F, 2010.
13. BBC News, "Wind turbine fire at Ardrossan wind farm," 8 December 2011. [Online]. Available: http://www.bbc.co.uk/news/uk-16115139.
14. International Renewable Energy Agency (IRENA), "Wind Power," Renewable Energy Technologies: Cost Analysis Series, vol. Power Sector, no. 5/5, June 2012.
15. Avionex/USA Corporation, "Main Components of a Wind Turbine"
16. J.L. Bryan, "Fire Suppression and Detection Systems," Glencoe Pres,, 1974
17. The European Wind Energy Association, "Wind in Power, 2012 European Statistics," 2013.
18. M. Ragheb, "Safety of Wind Systems," 26 February 2011. [Online]. http://www.windfarmaction.files.wordpress.com/2011/10/safety-of-wind-systems.pdf.
19. "Wind Power and Wind Farms in Australia," [Online].

http://ramblingsdc.net/Australia/WindPower.html

20. VdS Verlag, "Wind turbines - Fire protection guideline," German Insurance Association (Gesamtverband der Deutschen Versicherungswirtschaft e.V. - GDV, VdS 3523en: 2008-07 (01).
21. D. Lesinski, "Synthetics to Protect the Wind Turbine and the Environment. Fire prevention and biodegradability are important factors to consider in selecting gearbox lubricants," 2013.