FIRE SAFETY IN OFFSHORE WIND TURBINES

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Abstract

Wind power is an important and growing source of renewable energy in Europe. Due to the wind conditions, offshore wind power is a promising option. Hence, optimization and reducing disruption to production of any kind is of interest. This report addresses one cause of generation interruption for wind power stations: the occurrence of fire within the wind turbine. It is estimated that 0.3–0.5 fire incidents of this nature occur per 1000 power stations (onshore and offshore) per year. The current report describes features of the general design of wind turbines, lists fire causes based on available data, as well as information about the presence of combustible material in wind turbines. The report also presents possible conceptual design solutions that lower the fire risk. The application of active fire protection systems, such as multi detectors and extinguishing measures, are effective options, as are the introduction of passive fire protection systems, such as systems that isolate hot surfaces (ignition sources) from combustible material. The primary objective of such fire protection systems is life safety, although a level of asset protection, business continuity, etc., is also possible with the proposed measures. However, decisions on investment in such measures would require a cost-benefit analysis so as to compare any financial impact with the cost of implementation. Finally, means of egress in the event of fire are discussed by applying emergency plans relating to technical installations used for access and fast egress in order to avoid exposure to the effects of fire. The major conclusion in the report is that fire safety engineering needs to be part of the design phase of offshore wind power projects.

Keywords

Wind power, offshore, fire, safety, egress.
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1. Introduction

There is a societal push to identify and optimize alternative sources of power generation. In 2013, wind power was the source for 1% of total energy consumption worldwide [1]. Offshore wind power represents about 2% of global installed capacity; a total of 8,759 MW. At present, more than 91% (8,045 MW) of all offshore wind installations can be found in European waters; mainly in the North Sea (5,094.2 MW: 63.3%), Atlantic Ocean (1,808.6 MW: 22.5%) and in the Baltic Sea (1,142.5 MW: 14.2%) [2].

Offshore wind power is a growing source of energy. In Sweden the general trend in recent years is that wind power stations have been built in increasing numbers (refer to Table 1). In 2011 about 200,000 wind turbines existed worldwide [3]. An increasing number are built offshore but also at increasing distances from the shoreline [4]. In 2013 the first turbines were built at a distance greater than 100 km from the coast [4]. At the beginning of 2013, 1,662 power stations were located offshore [5]. Wind energy has grown from a global generation capacity of 6.1 GW in 1996 to 369.6 GW in 2014 [2]. Global offshore wind power production has increased to 8.8 GW in 2014 [2]. To indicate the relativity of onshore wind installations, an increase to 23,322 TWh [6].

<table>
<thead>
<tr>
<th>Year</th>
<th>Total number</th>
<th>Yearly increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>1419</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>1723</td>
<td>304</td>
</tr>
<tr>
<td>2011</td>
<td>2039</td>
<td>316</td>
</tr>
<tr>
<td>2012</td>
<td>2403</td>
<td>364</td>
</tr>
<tr>
<td>2013</td>
<td>2665</td>
<td>262</td>
</tr>
<tr>
<td>2014</td>
<td>3048</td>
<td>383</td>
</tr>
</tbody>
</table>

Table 1: Number of wind power stations in Sweden [7].

There is a beneficial environmental impact from maximizing and optimizing this source of energy production and hence minimizing all significant sources of disruption to production. The occurrence of fire in wind turbines is one type of disruption, which is in focus of this paper in the context of offshore wind turbines. Currently there is only limited statistical information available in the public domain relating to wind power plants (both onshore and offshore) and their functionality. The current paper deals with five aspects of fires in offshore wind power stations. The first section deals with information on the incidence of fire and the causes for ignition. Thereafter, information on wind turbine design and fire protection systems are presented and discussed. Finally, a review of both current legislation and guidance documents is presented, relating to fire and evacuation.

2. Fire Incidents in Wind Power Stations

In this section statistics and a more detailed analysis of incidents of fire turbine fire is presented.

2.1 Statistics

In relation to both onshore and offshore wind turbines, between ten and thirty percent of all loss-of-power-generation incidents in wind power plants are due to fire [3]. According to Caithness Windfarm Information Forum data [8], the annual number of incidents during 2007-2012 has been steady at 120-160 worldwide. As discussed by Udalale et al., anecdotal evidence suggests that this represents only about 10% of the actual fire incidents. Unfortunately, the validity of the data is uncertain, as there is no formal process for recording incidents. Using the range of the Caithness data, there were between 12 and 48 fire incidents per annum between 2007 and 2012, or an average of two and a half fire accidents per month. Of course, if the anecdotal evidence is accurate, the true number of fire incidents could be ten times higher. Until 2013 Data from Germany and Austria indicate higher rates of fire incidents. There were 38 incidents reported during 2008-2015 in these countries of which 23 (60%) were fire incidents [9]-[31].

It is useful to normalize the data so that the figures are linked to the number of wind turbines. In Germany and Austria, 23,000 wind turbines were constructed up until 2013. With the total number of fire incidents reported over the period 2008-2015 results in on average 0.02% fire incidents per turbine per year.

Table 2 presents a comparison of estimates of wind power stations fires from various sources. The average rate is 0.3 fires per 1000 turbines per year. To put this figure into context with building fires, by comparison in Sweden there are typically approximately 20 fires per 1000 buildings per year. It is estimated that between 0.3 [34] and 0.5 [33] fire incidents occur per 1000 offshore wind power stations per year. Hence, the number of offshore fires is of the same order of magnitude as onshore.

<table>
<thead>
<tr>
<th>Number of fires per 1000 turbines per year onshore and offshore</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>[3]</td>
</tr>
<tr>
<td>0.2</td>
<td>[32]</td>
</tr>
<tr>
<td>0.2</td>
<td>[10]-[34]</td>
</tr>
<tr>
<td>0.5</td>
<td>[36]</td>
</tr>
<tr>
<td>0.15</td>
<td>[38] reference to the insurance underwriter Gcube</td>
</tr>
<tr>
<td>0.5</td>
<td>[38] reference to DNV GL</td>
</tr>
</tbody>
</table>

Table 2: Number of fires per 1000 turbines per year onshore and offshore.

Table 2 presents a comparison of estimates of wind power stations fires from various sources. The average rate is 0.3 fires per 1000 turbines per year. To put this figure into context with building fires, by comparison in Sweden there are typically approximately 20 fires per 1000 buildings per year. It is estimated that between 0.3 [34] and 0.5 [33] fire incidents occur per 1000 offshore wind power stations per year. Hence, the number of offshore fires is of the same order of magnitude as onshore.

2.2 Incidents details

With respect to the frequency of occurrence, the problem with respect to fire may appear minor compared to general problems with quality and mechanical failures in offshore wind power stations [32]. However, wind turbine fires tend to cause substantial losses (equal to or above the original cost of the wind power plant), especially offshore. Offshore wind power stations are more difficult to access in case of fire. Furthermore, offshore turbines are bigger and more costly to install and repair and will incur much higher costs in the event of a fire incident. Causes of fire incidents in onshore and offshore installations appear to be alike. Hence, the frequency for on- and offshore wind turbines may be assumed to be comparable. However, the consequence is assumed to be larger offshore due to accessibility and possibilities to intervene in case of fire. This leads to a higher assessed risk [33].
Fire causes are only registered by insurance companies when the loss exceeds the deductible, i.e., when the insurer actually has to make a payout. Various sources of information [3], [32]-[35] indicate the following fire incidents:
- After maintenance (the highest frequency)
- Lighting strike (has been reduced with design changes)
- Electrical failure
- Hot surface ignition
- Hot work maintenance
- Cooking

The Swedish Civil Contingencies Agency, MSB, records all incidents where the fire service intervened. In the period 2009-2014, nine incidents were recorded which matched the search in the MSB database on fire for ‘vindkraftverk’ (wind turbines) and ‘vindkraft’ (wind energy) [36].

Table 3: Fire causes in wind turbines, Sweden[36].

<table>
<thead>
<tr>
<th>Year</th>
<th>Initial fire location</th>
<th>Cause</th>
<th>Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>Elevator engine and cables 50 up in the tower</td>
<td>Technical error in the elevator</td>
<td>Smoke filled the tower and nacelle</td>
</tr>
<tr>
<td>2014</td>
<td>Turbine</td>
<td>Unknown, technical error plausible</td>
<td>The nacelle had reached flashover when the fire service arrived. They extinguished fires on the ground due to objects falling down</td>
</tr>
<tr>
<td>2014</td>
<td>Electrical cabinet inside the tower</td>
<td>Capacitor started to burn</td>
<td>Fire was extinguished by a portable fire extinguisher (powder)</td>
</tr>
<tr>
<td>2011</td>
<td>Tower</td>
<td>Unknown</td>
<td>Fire spreads to include tower, nacelle and rotor blades. Falling objects,</td>
</tr>
<tr>
<td>2011</td>
<td>Electrical cabinet inside control room</td>
<td>Unknown</td>
<td>Fire self-extinguished</td>
</tr>
<tr>
<td>2011</td>
<td>Cooker inside the nacelle</td>
<td>Cooker left on. Shortcut</td>
<td>2 persons were trapped above the fire. They rescued themselves</td>
</tr>
<tr>
<td>2010</td>
<td>Nacelle</td>
<td>Unknown</td>
<td>Fully developed fire inside the nacelle. Falling objects on fire.</td>
</tr>
<tr>
<td>2009</td>
<td>Electrical cabinet</td>
<td>Shortcut in electrical cabinet made it impossible to stop the wind power plant</td>
<td>Fire was extinguished by a portable fire extinguisher (powder)</td>
</tr>
<tr>
<td>2009</td>
<td>Battery on ground</td>
<td>Overloading due to strong winds</td>
<td>Fire service extinguished the battery on fire. Smoke-filled structure.</td>
</tr>
</tbody>
</table>

As can be seen in the Table 2 some were minor fires that were extinguished with a portable fire extinguisher and not all were located in the tower or nacelle.

3. Wind Turbine Systems

The components of a wind turbine can be grouped into three categories: the structure, the primary system, where power is generated, and the control system. The structural components comprise large passive elements, and include the turbine blades, the nacelle, and the tower and associated supporting structure. Primary components include the mechanical and electrical components within the wind turbine which convert the movement of the blades into a rotation and convert this rotation into electricity and associated transmission. Control systems are those secondary systems which are required for either optimisation of the position of the nacelle and angle of attack of the blades, based on wind speed or direction, for maximum utilisation of the turbine; or systems required to ‘turn off’ or stop the rotation of the blades to prevent damage in for example high winds, or during maintenance.

Figure 1 illustrates schematically the components of an offshore wind turbine. The different groupings of components are denoted by colour. Included in the schematic is also the off turbine components required for transmission of the power to an onshore grid.

3.1 Structural components

The wind turbine blades capture the wind energy and convert it into mechanical energy. They typically either comprise a structural shell with shear webs (Figure 2), or a box spar with shell fairings [36]-[40]. The shell of the blades is typically a composite “sandwich”, i.e., a lightweight core material with a high-strength skin. Core materials of the composite include Balsa, Foam cores (such as PVC, SAN, Urethane, PET), and engineered core materials [47], while the “skin” consists of a fibre-resin matrix. The fibres include glass, carbon, aramids [47]; and resins include epoxies, Vinyl or Polyester, toughened resins and thermoplastics [47]. The most common material of choice for turbine blades is a glass fibre reinforced polymer, with low cost and high reliability being the driving factors in material choice [47].
Once the energy has been converted from kinetic energy to electrical energy the transformer steps up the voltage, from less than 1kV to between 10 and 36 kV, for transmission. For weight saving, in modern turbines, the transformer is normally located at the base of the tower. The inner cable array then transmits the power from one turbine in the farm to the next on its way to the offshore substation. The export cable then transfers the energy from the offshore substation to the grid [50].

3.3 Control system

The blade pitch change mechanism adjusts the angle of attack of the turbine blades to reduce the lift if the wind speeds are too high or to increase the lift if the speeds are too low. The mechanisms are installed in the hub or rotor assembly, and one is installed for each blade. Both electrical and hydraulic systems can be used, however in offshore applications hydraulic control is more common [51]. Control of the angle of attack is based on the input from external sensors.

The yaw system, similar to the blade pitch change mechanism, adjusts the turbine for optimum power generation. It is located between the nacelle and the tower. It is typically hydraulically actuated [36].

There are two types of mechanisms for addressing overspeed in wind turbines in addition to control of the blade angle of attack; these are either mechanical devices or aerodynamic devices. The mechanical brake acts on the low speed shaft to lock the wind turbine when needed [36]. On the ends of the turbine blades the rotating tip / rotating vane are two of the most common methods for aerodynamic overspeed control [36].

3.4 Ignition sources and combustibility of components

In order for a fire to start a source of ignition and combustible material is needed. Possible sources of ignition are identified and listed in Table 4. Combustible materials inside a wind turbine are also identified and listed in Table 5. The presence of ignitions sources and combustible material create the possibility of ignition and fire development. However, details of the design will influence the particular outcome in the event of a fire occurring.

Table 4: Possible sources of ignition.

<table>
<thead>
<tr>
<th>Component</th>
<th>Ignition mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blades</td>
<td>Lightning strikes</td>
</tr>
<tr>
<td>Gearbox</td>
<td>Overheating / hot surface ignition</td>
</tr>
<tr>
<td>Generator</td>
<td>Electrical fault</td>
</tr>
<tr>
<td>Electrical system</td>
<td>Electrical fault</td>
</tr>
<tr>
<td>Mechanical brake</td>
<td>Overheating or damage to the brake causing sparks</td>
</tr>
<tr>
<td>Hydraulic system</td>
<td>Overheating of the pump</td>
</tr>
<tr>
<td>Oil pumps</td>
<td>Overheating / hot surface ignition</td>
</tr>
<tr>
<td>Transformer</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Combustible material inside of a wind turbine.

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blades</td>
<td>FRP / composite</td>
</tr>
<tr>
<td>Low speed shaft</td>
<td>Future turbines are likely to use CFRP for the low speed shaft</td>
</tr>
<tr>
<td>Gearbox</td>
<td>Gear box oil, in relatively small quantities, is likely to contribute to the fuel load inside of a wind turbine</td>
</tr>
<tr>
<td>Nacelle</td>
<td>Varies, but FRP composites are used</td>
</tr>
<tr>
<td>Yaw system</td>
<td>Hydraulic oil</td>
</tr>
<tr>
<td>Mechanical brake</td>
<td>Carbon fibre</td>
</tr>
<tr>
<td>Hydraulic system</td>
<td>Hydraulic oil</td>
</tr>
<tr>
<td>Blade pitch change mechanism</td>
<td>Hydraulic oil</td>
</tr>
<tr>
<td>Oil pumps</td>
<td>Lubricating oil</td>
</tr>
<tr>
<td>Transformer</td>
<td>Oil filled transformer</td>
</tr>
</tbody>
</table>
4. Fire Protection Systems

There are generally two types of fire protection systems in buildings, structures and vehicles, namely active fire protection and passive fire protection. Both active and passive fire protection systems play an important role in fire safety in wind turbines. Collectively, fire protection systems help to achieve the desired fire safety objectives, whether it is safety of people, property protection, environmental impact, or business continuity. In the context of wind turbines, the basic principles of fire protection systems apply whether the location is onshore or offshore, and hence no further distinction is made in this section of the paper.

4.1 Legislative requirements

An important consideration with regard to fire protection systems in offshore wind turbines is to understand the legislative environment, i.e., what are the mandatory requirements with regard to fire protection systems. Sweden is used as an example of European legislative requirements in this regard. A range of different regulations are potentially applicable to fire protection in offshore wind turbines. They are discussed in the next section. With regard to building regulations, in Sweden a wind turbine is not treated as a building, either onshore or offshore, so hence the Swedish building regulations [41] do not apply. There are however three other pieces of legislation that do apply.

Firstly, the technical provisions of the Planning and Building Act [42] apply to wind turbines. There are two aspects from the Act concerning fire safety that are applicable:

1. Load capacity, stability and durability
2. Safety in case of fire

Secondly, the technical provisions of the Building and Planning Ordinance [43] also apply to wind turbines, as follows:

1. The structure’s fire resistance is likely to persist over a defined time
2. The development and spread of fire and smoke within the structure is limited
3. The spread of fire to nearby constructions is limited
4. Persons who are in the structure when a fire occurs may leave it or be rescued by other means and
5. Consideration has been given to the safety of rescue services in case of fire

Thirdly, the requirements for the Application of European Construction Standards [44] are applicable. The focus of EKS 9 with respect to fire is structural stability in fire, with SS-EN 1991-1-2:2002 [45] being the nominated standard that must be complied with. As such, SS-EN 1991-1-2 [45] does not provide any specific requirements for fire protection systems, but the wind turbine structure must satisfy the structural stability in fire provisions nominated in the standard.

4.2 Reaction to fire

The Swedish building regulations do not apply to wind turbines constructed in Swedish territorial waters, or onshore in Sweden, and hence the construction product classification requirements do not apply. However, the general technical requirements for fire safety in the Planning and Building Act [42] and the Planning and Building Ordinance [43] do apply, and the requirements in the building regulations can be used as guidance to find an appropriate level of safety concerning reaction-to-fire properties for building products.

In Europe, construction products and building elements are classified according to their reaction-to-fire properties, i.e., their ignitability, flame spread and smoke development, according to the European standard EN 13501-1 [52]. There are seven different classes (A1, A2, B, C, D, E and F) which are combined with the additional classifications for smoke production (s1, s2 or s3) and flaming droplets/particles (d0, d1 or d2). The classification is based on four different test methods, which vary depending on the classification:

- EN ISO 1182 – Non combustibility test (classes A1 and A2)
- EN ISO 1716 – Determination of the heat of combustion (classes A1 and A2)
- EN ISO 11925-2 – Ignitability of building products subjected to direct impingement of flame (classes B-F) (Figure 3)
- EN 13823 – Building products exposed to the thermal attack by a single burning item (classes A2-D) (Figure 3)

The classification for classes B to F is performed for complete products, and not at the material level. This means that, e.g., a sandwich panel with a core of highly flammable materials can be protected by a layer of non-combustible or low flammable material and achieve class B. Therefore, the classification has the biggest impact in the early stages of a fire, before flashover occurs. Examples of classifications are:

- A1 – Stone, glass, steel
- A2-s1,d0 – Gypsum board (thin paper), mineral wool
- B-s1,d0 – Gypsum board (thick paper), fire treated wood
- C-s2,d0 – Wallpaper on gypsum board, fire treated wood
- D-s2,d0 – Untreated wood
- E – Some plastics and synthetic materials
- F – Unclassified

Generally, the classes B and higher will not lead to flashover in the full scale room corner test according to the test method EN 14390 [53], see Figure 7, while class C or lower will lead to flashover. However, there are exceptions, where some products perform better in the small scale tests compared to the full scale tests, or the other way around.
Electro-mechanical "activation" in the event of a fire. AFP systems have four primary roles:

1. **Active fire protection (AFP)** consists of fire protection systems that have some form of alarm. They are intended to provide warning that a fire has occurred, i.e., some form of alarm. AFP systems have four primary roles:

   - To provide warning that a fire has occurred, i.e., some form of alarm
   - To detect a fire, applying some form of detectors
   - To control or extinguish the fire, where control consists of maintaining the heat output from the fire at a constant level, i.e., the fire stops growing, and extinguish consists of reducing the heat output of the fire, i.e., the fire decays
   - To manage the smoke and gases produced by the fire, e.g., smoke reservoirs, smoke extract, pressurisation, etc.

2. **Smoke detection** systems are intended to detect smoke, typically in areas where flames are unlikely to be present. They are designed to trigger alarms early to avoid the risk of fire in areas where they are not visible.

3. **Heat detection** systems are intended to detect heat, typically in areas where flames are likely to be visible. They are designed to trigger alarms early to avoid the risk of fire.

4. **Flame detection** systems are intended to detect flame, typically in areas where flames are likely to be visible. They are designed to trigger alarms early to avoid the risk of fire.

5. **Water mist** systems are designed to extinguish fires by releasing a fine mist of water, which can be more effective than traditional water sprays in certain situations.

6. **Foam** systems are designed to extinguish fires by releasing a foam, which can be more effective than traditional water sprays in certain situations.

7. **Carbon dioxide** systems are designed to extinguish fires by releasing a gas, which can be more effective than traditional water sprays in certain situations.

8. **Inert gas** systems are designed to extinguish fires by releasing an inert gas, which can be more effective than traditional water sprays in certain situations.

9. **Inert** systems are designed to extinguish fires by releasing an inert gas, which can be more effective than traditional water sprays in certain situations.

10. **Water spray** systems are designed to extinguish fires by releasing a spray of water, which can be more effective than traditional water sprays in certain situations.

11. **Carbon dioxide** systems are designed to extinguish fires by releasing a gas, which can be more effective than traditional water sprays in certain situations.

The CFPA-E [54] suggests that a local fire detection system be installed to automatically detect a fire at its incipient stage, due to no other detecting methods (e.g., observation by staff) being present in an unmanned installation. The purpose for such detection is to trigger the fire extinguishing system, and to shut down the turbine. The CFPA-E recommends that the detection system have two parts – space monitoring and equipment monitoring.

Space monitoring relates to the different areas of the turbine installation being monitored by a fire detection system, such as the interior (nacelle and tower) and the exterior (transformer and substation). For the internal systems, CFPA-E recommends smoke detectors, and that they are designed for the varying ambient conditions that will exist.

Equipment monitoring, relates to individual items of equipment installed in the nacelle and tower, such as transformers, switchgear and inverter cabinets, etc. Such equipment is the most likely source of any fire starting so hence targeted equipment monitoring, in addition to space monitoring, reduces detection time to a practicable minimum. The CFPA-E recommends smoke detectors for general equipment monitoring, but for mineral oil transformers, heat detection in combination with a two-stage relay (pre-alarm and main alarm shutdown).

In relation to the Construction Products Regulation (CPR), the applicable European standard for CE-marking of fire detection/alarm systems is EN 54 Fire Detection and Fire Alarm Systems series of standards.

The CFPA-E recommends the following fire extinguishing systems in wind turbines, subject to suitability for the specific installation conditions:

- Carbon dioxide
- Inert gas
- Water mist
- Water spray
- Foam

The CFPA-E specifically excludes powder and aerosol extinguishing systems from its recommendation since they cause consequential losses, i.e., they contain higher levels of residue and are corrosive.


The CFPA-E also has prescriptive recommendations for fire extinguishers, nominating at least 1x6 kg CO2 and 1x9 l foam extinguisher in the nacelle and 1x6 kg CO2 at each intermediate level and the base of the tower.

The International Association of Engineering Insurers [64] makes recommendation on active fire protection systems that closely match those of the CFPA-E. The only real difference is that a range of detection options are provided, namely:

- Smoke
- Heat
- Flame
- Multi-sensor

Urban notes that as turbines are unoccupied for the majority of the time, detection systems are essential. A “double knock” system, consisting of two or more detectors, to be triggered independently for activation, should be employed. This should trigger a suppression system that is suitable for the wind turbine in question, namely; water mist, foam, gaseous, dry chemical, and condensed aerosol [63].
4.4 Passive fire protection

Passive fire protection (PFP) forms part of the fabric of a building, structure or vehicle, and has three primary roles:

- Limiting the effects of the fire to the area where the fire starts, known as compartmentation or containment
- Minimising the development and impact of the fire by selecting materials with fire performance that is either inherently better, or is enhanced in some way, and generally known as reaction-to-fire properties
- Achieving a certain level of fire resistance so as to maintain structural (load-bearing) performance and avoid premature collapse

PFP “achieves safety by design, which includes material selection, compartmentalisation and other measures to minimise the fire spread” (p. 18 in Ref. [63]). Containment is achieved by the use of fire- and smoke-rated elements of construction such as walls, floors, doors, fire-stopping, protective coatings, etc. Reaction-to-fire performance characteristics are achieved by selecting materials that have low combustibility and smoke production properties, which is either inherent or due to modification of the materials’ fire performance. Fire resistance is generally achieved by protecting vulnerable elements of construction and/or designing for residual performance. There are various sources in the international literature of guidance and recommendations on how PFP systems can improve fire safety in wind turbines.

The CPFA-E guide [54] describes a range of measures to reduce the risk of outbreak of fire, which fall primarily into the category of fire prevention, but with some PFP measures also.

With regard to fire prevention:

1. Lightning and surge protection
2. Minimise risk from electrical systems
3. Safely managing work that involves flammable liquids
4. No storage of combustible materials
5. Avoid possible ignition sources
6. Avoid hot work
7. Monitoring, inspections, servicing and maintenance
8. No smoking policy
9. Training of staff

In relation to PFP:

1. Minimise combustible materials by elimination, use of low flammability materials and non-absorbent materials
2. Use of cabling that meets certain reaction-to-fire requirements

In a similar vein, the International Association of Engineering Insurers suggests that relevant measures relating to fire prevention, are [64]:

- In the event of a leak/spill of combustible fluid, ensure the material is safely collected and disposed of
- No combustible materials should be stored in the nacelle
- All cables and wiring should have strict reaction to fire requirements relating to toxicity, emissions and fire propagation
- Potential ignition sources should be avoided by appropriate design, compliance with earthing rules and regulations, and the use of brake disc covers to prevent any sparks igniting combustible materials

With regard to “non-combustible” hydraulic oils and lubricants noted previously, the definition for “non-combustible” given in ISO 13943 is “not capable of undergoing combustion under specified conditions”. There is an important note in ISO 13943 which clarifies what is meant by the phrase “under specified conditions” in the definition, stating that “in some regulations a material is classified as being non-combustible even if it is capable of combustion, provided that its heat of combustion is less than a defined amount” (definition 4.239, p. 28 in Ref. [66]).

With a focus on fire properties of materials in the nacelle, Uadiale et al. [3] and Uadiale [65] provide a list of PFP (including fire prevention) measures that can be taken:

1. Non-combustible hydraulic oil and lubricants be used
2. Radiation barriers be installed to protect combustible solids
3. Flame-retarded materials be used
4. Installation of comprehensive lightning protection systems
5. Avoiding the use of combustible materials
6. Avoidance of hot work activities
7. Monitoring and maintenance of critical systems
8. The installation of electric overvoltage protection
9. The use of flame retardant materials
10. The use of materials that have washable surfaces, so that foreign matter such as oil will not accumulate

PFP measures such as radiant barriers should be used in conjunction with AFP systems.
5. Requirements for Manufacturing, Health and Safety and Evacuation

In this section design requirements and guidelines concerning manufacturing the turbine, health and safety (H&S) relating to the operation of the turbine, as well as evacuation from turbine structure, are presented.

5.1 Manufacturing

The primary systems of a wind turbine (i.e., excluding the wind turbine structure) are considered, from a regulatory perspective, as machinery. In Europe, product-related safety issues for machinery are regulated by the Machinery Directive [61] which has in turn been adopted into Swedish legislation [62].

The manufacturer is responsible for complying with the product-related safety requirements in the Machinery Directive and other relevant directives. The manufacturer is also responsible for the provision of a technical risk assessment which should take into account all the risks that could be associated with the machine when in use. The turbine manufacturer is obliged to inform the user if risks cannot be reduced by technical measures or construction. The manufacturer should furthermore provide information and suggestions as to how the risk can be prevented or/and minimized. Practical guidance and examples of technical risk assessments are provided in the EN ISO 12100-1 [60].

The requirements of the Machinery Directive [62] are formulated in a general manner. Detailed descriptions of how the requirements of Machinery Directive AFS 2008:3 [62] can be complied with, are mentioned in the so-called “harmonized standards”. It is not mandatory to apply a harmonized standard, but if the manufacturer decides to use a standard, all machines have to comply with the basic health and safety requirements of the Machinery Directive. Relevant standard for wind turbines are, for example:

- EN 50308, Wind turbines - Protective Measures - Requirements for design, operation and maintenance
- EN 61400-1 Wind turbines - Design requirements

Furthermore, some standards for the construction of the tower and the turbine are:

- IEC 61400-1, Wind turbines - Part 1: Design requirements
- IEC 61400-3, Wind turbines - Part 3: Design requirements for offshore wind turbines
- IEC 61400-22, Wind turbines - Part 22: Conformity testing and certification
- ISO 19900 General requirements for offshore structures
- ISO 19902 Fixed steel offshore structures

Due to the fact that wind power plants are covered by AFS 2008:3 [62], all electronically parts must be CE-marked. The CE-mark means that wind turbines comply with the corresponding EU-directives (e.g. Machinery Directive 2006/42/EC and the EMC Directive 2004/108 EC). Electronic parts which are covered by the AFS 2008:3 [62] may not be sold or used without the CE-marking.

5.2 H&S requirements

The Swedish Work Environment Authority, Arbetsmiljöverket, verifies that the AFS 2008:3 [62] requirements are followed by conducting market inspections and checks within wind energy projects. If the Arbetsmiljöverket determines that a CE-marked wind turbine has such defects that it may compromise safety regulations, the Arbetsmiljöverket has the right to take appropriate measures, such as to prohibit the work. EU member states are not allowed to impose additional requirements for CE-marked products beyond those that are mentioned in the Machinery Directive.

There are only a limited number of official rules which regulate the health and safety of organization offshore. In many cases it is only possible to refer to a recommendation or a guideline. Therefore, the company carrying out work is required to conduct risk assessments for each non-regulated or unsafe situation (Directive 89/391 OSH Framework) [71]. In the Swedish legislation it refers to the Work Environment Act, Arbetsmiljölagen [59]. There are no regulations for risk assessments, except for the obligatory TOP-ranking (Hierarchy for risk assessment measures T-technical, O-organization, P-personal). Thus, the nature of a risk assessment is essentially up to the company required to carry out the assessment.

There are some standards that deal with risk assessments:

- ISO 31000 - Risk management [77]
- IMO - MSC/Circ.1023 MEPC/Circ.392 Guidelines for Formal Safety Assessment (FSA) [76] HSE plan

The H&S policy is usually mentioned within the HSE-Plan. But the plan is just a management tool and not officially required by the current legislation.

Possible topics for a H&S plan are:

- H&S representatives
- Legal frame for the operation
- Conduction of risk assessments
- Emergency response plan
- Rescue drill
- Access plan (for the platforms)
- Fire Safety concept including (ERP and EEP)
- Etc.

In Anglo-Saxon countries the H&S plan is often a part the CDM (Construction Design and Management) Plan Regulations 2007. This regulation places specific duties on clients, designers and contractors, to plan their approach for health and safety throughout offshore construction projects.
6. Fire safety and evacuation

Offshore evacuation in Sweden is provided by two services according to Swedish legislation.

According to Lagen om Skydd mot Olyckor (2003:778) (the Swedish Law on Protection from Accidents) [70] the Swedish rescue service is responsible for conducting rescue operations both on-shore and offshore but the Sjöfartsverket (Swedish Maritime Administration) is responsible in case of distress at sea. The area of responsibility includes not only the land but also lakes and the sea. The territorial limit is a distance of 12 nautical miles (22.2 km) from the coastline (alternatively from the Swedish border).

At the same time the client is responsible to provide rescue equipment for first aid, firefighting and self-evacuation.

6.1 Fire safety plan (FSP)

An offshore wind turbine is considered to be the same as any land-based place of work, and hence H&S requirements apply in the same way. As part of a broader H&S Plan, an offshore wind turbine facility should have a Fire Safety Plan (FSP), which can include the following:

- Emergency Response Plan
- Emergency Escape Plan
- Dangerous stored materials
- Connections to sprinkler system (if available)
- Layout drawing and site plan of building
- Maintenance Schedules for life safety systems
- Personnel training and fire drill procedure
- Etc.

6.2 Emergency response plan (ERP)

An Emergency Response Plan (ERP) is a plan developed by the owner/operator of a wind turbine facility that provides details of how to respond to an emergency situation. An ERP can address the following aspects:

- Fire fighting
- Active fire protection
- Measures to minimize fire spread
- Facility notification
- Emergency communications
- Personnel responsibilities
- Etc.

6.3 Emergency escape plan (EEP)

When a wind turbine is initially being built, it is considered to be a construction site. According to European Directive 92/57/EEC [74] for temporary or mobile construction sites and Directive 89/654/EEC [73] relating to workplace requirements, it is the client’s duty to organize the evacuation of construction sites.

The area of responsibility includes not only the land but also lakes and the sea. The territorial limit is a distance of 12 nautical miles (22.2 km) from the coastline (alternatively from the Swedish border).

At the same time the client is responsible to provide rescue equipment for first aid, firefighting and self-evacuation.

Whether during the construction phase, or in service, an Evacuation Escape Plan (EEP) is recommended in several Swedish and international documents [35], [54], [56]. A flow chart on such a process is given in Figure 5. No more prescriptive requirements are given in the documents.

According to ISO 23601:2009 [84] an Emergency Escape Plan has to include the following information:

- Current site and facility plan drawings with key features of the facility as verified by site visit
- Identification of all escape routes
- Evaluation planning documentation including expected people movement
- Location of all firefighting and emergency equipment including alarm buttons
- Required actions to be taken in case of emergency or fire (Emergency chain)
- Assembly points
- Etc.
7. Concluding Remarks

Wind power stations present an important source of renewable energy in Northern Europe. Due to their high efficiency in comparison to onshore installations, offshore power stations are important and hence, the number of offshore power stations is increasing. Fire can be a serious threat to the operation of an offshore power station since they are difficult to reach from shore. Available data show that fires do occur in offshore wind power stations but the frequency of such events is uncertain. For the current work it was difficult to obtain a reliable estimate of fire incidents for offshore power stations. In order to conduct a credible risk assessment exercise, comprehensive data on the number of fires in the nacelle/turbine, tower, transformer units and control rooms, as well as the material used in the particular designs, would be essential.

There are no good sources of fire incident data that can be used for scientific research purposes where there is both a large sample size and accurate reporting. For offshore turbines the situation is further complicated by the limited number of turbine years. The statistics that were identified during this research indicate a range of between 0.05 and 0.5 fires per 1000 turbines per year, which is relatively low compared to, say, the rate of building fires. This points to an average rate of approximately 0.3 fires per 1000 turbines per year, mainly in relation to onshore installations. Anecdotal evidence suggests that offshore turbines fires have a similar frequency.

In spite of the restrictions caused by limited data, the current study has the following findings:

Combustible materials as well as ignition mechanisms have been identified through statistical and material analysis. Although the blades are constructed from combustible materials, potential ignition sources are mainly inside the nacelle, where there are hot surfaces are in the gearbox, generator, brake system, pumps and transformer. In combination with the possible presence of combustible hydraulic and lubricant oil and solid combustible material in the nacelle, a fire can ignite and develop, leading to the possible complete destruction of the power station.

Appropriate fire safety engineering is important. The impact of fires in offshore wind turbines can be mitigated by using active and passive fire protection measures. The active fire protection measures can consist of multi detection systems that react to smoke, heat and flames, together with sprinkler and water mist systems. The passive fire protection measures can consist of the utilization of low flammable and non-absorbent materials, as well as cabling that meets certain reaction-to-fire requirements. Potential ignition sources should be avoided by appropriate design, compliance with earthing rules and regulations, and the use of brake disc covers to prevent any sparks igniting combustible materials. Fire compartmentation could also mitigate some possible problems, especially since modern, large-scale wind power stations have multi-storey nacelles.

National regulations specifically for offshore wind power stations do not exist in Nordic countries such as Sweden. A set of other regulations such as H&S requirements do however apply. There are also a series of international guidelines and standards providing guidance on the construction of the station. It is recommended that the operator of an offshore wind facility provide a detailed Fire Safety Plan, which contains details such as an Emergency Response Plan and an Emergency Evacuation Plan. This documentation should be developed in collaboration with the relevant rescue services. Furthermore, it is recommended to carry out relevant training for workers as well as possible fire fighters. Technical standards for a number of the features of offshore wind turbines, such as escape routes and safety systems (alarm signals, etc.) could be of use.


[67] EN 50308, Wind turbines - Protective Measures - Requirements for design, operation and maintenance, European Commission, 2005

[68] EN 61400-1 Wind turbines - Design requirements, European Commission, 2005


[72] AFS 1999:3, Arbetsmiljöverket, 1999


[82] ISO 19900 General requirements for offshore structures, International Organization for Standardization, 2002


[88] Hutchinson C., Emergency Evacuation Plan V90, OFFSHORE WINDPARK EGMOND AAN ZEE, NoordZee Wind, 2006

[89] SpanSet GmbH & Co. KG, Jülicher Str. 49-51 52531 Übach-Palenberg, Tel. +49-2451 / 4831-0, Fax +49-2451 / 4831 - 8191, info@spanset.de, www.spanset.de

[90] Project Procedure, Emergency Evacuation Plan V90, VESTAS, 2015
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