Renewable Energy Fire Protection Systems

Prepared for:

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EXECUTIVE SUMMARY

The Bureau of Safety and Environmental Enforcement (BSEE), an agency of the US Department of the Interior (DOI), is charged with ensuring safety, protecting the environment, and conserving resources offshore through regulatory oversight and enforcement of offshore facilities engaged in energy exploration, development, and production operations in the Outer Continental Shelf (OCS). DOI has the responsibility to ensure the safe and responsible development of offshore wind energy resources.

The offshore wind industry, composed of offshore wind turbines and offshore substations, is a relatively new and emerging energy sector in the US without any federal adoption of industry fire protection standards. The Bureau of Ocean Energy Management (BOEM) and BSEE published 30 Code of Federal Regulations (CFR) 585, a federal regulation governing the development of offshore energy facilities, stating that best industry practices should be used without formal adoption of current industry fire protection standards.

A review of current industry standards (international and US) showed that the industry practice emphasizes a fire protection philosophy based on performance-based design (PBD) for application of fire protection systems, fire suppression, fire alarm/detection, and passive fire protection. The PBD approach differs from prescriptive design practices in which a fire protection design is determined after an engineering and risk evaluation has been conducted and approved by the wind energy stakeholders. The PBD process incorporates the following key concepts:

- Stakeholders establish agreed-on fire safety goals and objectives.
- Fire scenarios are created and approved by stakeholders.
- Fire safety design is assessed against fire scenarios in relation to stakeholder goals and objectives.

The fire risk factors for offshore wind energy infrastructure have been identified, with the most significant risk stemming from the presence of combustible liquids essential for wind turbine and substation operation. Approximately 300 to 800 gallons and 8,000 and 12,000 gallons of combustible liquid are present in an offshore wind turbine and substation step-up transformer, respectively. In addition, if a helipad is provided for the offshore substation, up to 850 gallons of aviation fuel could be present within the helicopter. Sources of ignition vary, depending on the specific components; however, failure in the power distribution equipment has the potential to create electrical arcs and hot surfaces capable of generating a sustained high temperature that could lead to ignition. For helipad locations, operator error or helicopter malfunction present a significant ignition risk.

The current available fire protection technologies and engineering practices were compared to determine the suitability of implementation for offshore wind energy systems. The wind turbine and substation consist of various components and areas, each with unique challenges that necessitate a PBD approach for implementation of fire protection technology. A generalized recommendation is provided for offshore wind turbines and substations. For offshore wind turbines, the nacelle and tower base equipment are recommended to be protected via a gas or water mist suppression system with an aspirating smoke detection system. The turbine tower poses low fire risk and no fire protection systems are recommended. For offshore substations, various fire protection technologies are applied based on the substation design and equipment used within; however, common notable high fire risk hazards are step-up transformer/reactors and helipad. The step-up transformer/reactor is recommended to be protected via a compressed air-foam system with an UV/IR radiant energy flame detectors or aspirating smoke detection system. The helipad is recommended to be protected by a foam-water deck integrated firefighting system with UV/IR radiant energy flame detectors.

Fire protection systems require continual inspection, testing, and maintenance (ITM) to ensure proper system operation and reliability. The National Fire Protection Association (NPFA) codes, recommendations, and standards provide the minimum care required to maintain the fire protection systems. A fire protection ITM program should be created and maintained by the offshore wind energy operators that identifies the relevant stakeholders and the adopted codes with modifications and amendments. The ITM program should document the ITM procedures, schedules, frequencies, and deficiency/corrective action tracking.

The remote monitoring of the fire protection systems is achieved using a supervisory control and data acquisition (SCADA) system and remote terminal unit (RTU) equipment located at the offshore wind turbine and substation. SCADA is a collection of software and hardware components that allow both supervision and control of the wind energy processes. The system is designed to examine, collect, and process real-time data gathered by a system of sensors and allow system operators automatic or manual control of the equipment. The fire protection system can be interfaced to the SCADA system via RTU for remote monitoring for normal, trouble, supervisory, and alarm conditions.

The fire protection technologies discussed in this report use existing technologies that could be adopted by the offshore wind energy system. These fire protection technologies are already used in other industries such as electric utility, petroleum, aerospace, sea vessels, etc. No single fire protection technology provides a complete solution to the multi-spectrum fire risk challenges present in each industry. The application of fire protection technology described in this report to other industries requires a systematic fire risk evaluation using PBD principles to apply the most appropriate fire protection technology for each unique fire risk challenge.

1.0 LITERATURE REVIEW

1.1 Offshore Wind Energy Industry Standards and Guideline Review

Various international, national, and industry-specific standards and guidelines oversee the construction and management of the offshore wind energy industry. Offshore wind energy infrastructure is composed of four distinct utilities: offshore wind turbines, offshore substations, onshore substation, and electric grid distribution. This renewable energy fire protection system research examined the offshore wind turbines and offshore substations.

The offshore wind energy standards and guidelines document the industry research, best practices, and lessons learned relating to the design and construction of wind energy systems. The developed industry standards are adopted by the regulatory bodies, and subsequent modifications and additional requirements pertaining to local use have been created and adopted by various international regulatory agencies. However, to date the US has not developed a comprehensive set of offshore wind energy fire protection requirements. In addition, existing documents relating to offshore wind energies are underdeveloped or heavily reliant on current unadopted international standards or industry recommendations.

Given the limited available literature, additional guidelines from different related subsectors such as the American Petroleum Institute (API), Factory Mutual (FM), and Institute of Electrical and Electronics Engineers (IEEE) have been included in the literature review.

1.2 Offshore Wind Energy Literature Review

The offshore wind literature review included the most relevant standards and guidelines pertaining to fire protection of the offshore wind energy industry. The compiled list of literature includes current standards and guidelines providing design, construction, and operation guidance specifically pertaining to offshore wind turbines and substations. The literature review also includes relevant documents pertaining to offshore platforms, onshore wind turbines, and onshore substations as references from further-developed energy sectors. The literature review seeks to study the following topics related to fire protection of offshore wind turbines and offshore substations:

- Document classification and addressed structures
- Fire protection systems
- Passive fire protection
- Fire risk management

The list of international standards and guidelines that were studied for the literature review are provided as follows, with a brief description of the document content and purpose.

International Electrotechnical Commission (IEC)

- **IEC 61400** Wind Turbines: IEC 61400-1 provides standards for all wind turbine design and construction. IEC 61400-3 provide additional requirements for offshore wind turbines and defers to IEC 61400 for above-water requirements.

International Organization for Standardization (ISO)

- **ISO 19900**: Provides general requirements and recommendations for design of fixed and buoyant offshore structures.
- **ISO 19901-3**: Provides requirements for the design and installation of topside structure of oil and gas platforms. It addresses prevention, control, and assessment of fire, explosions and other accidental events.

European Standards (EN) and European Nation Standards

- **EN 50308** Wind Turbines – Protection: Provides requirements for protection measures relating to the health and safety of personnel, relevant to commissioning, operation, and maintenance of wind turbines.
- **BSH SD** Federal Maritime and Hydrographic Agency Standard Design (Germany): Provides requirements for offshore structure and wind turbine nacelle construction located beyond 12 nautical miles from the coast of Germany.
- **CFPA-E No. 22** Confederation of Fire Protection Associations in Europe Wind Turbine Fire Protection Guideline: Provides common guidelines to achieve similar interpretation in European countries with regard to fire protection of onshore and offshore wind turbines. CFPA-E documents are often adopted by European insurers as loss prevention risk management recommendations.
- **CAP 437** Standard for Offshore Helicopter Landing (UK): Provides comprehensive fire protection measures for both manned and unmanned offshore installations. Developed by the UK Civil Aviation Authority (CAA).

Det Norske Veritas (DNV)

- **DNV-ST-0145** Offshore Substations: Provides requirements for the design of substations. Topics covered include safety, fire and explosion protection, and the response of the substation in emergency situations. This standard includes more comprehensive offshore substation requirements compared to DNV-OS-D301: Offshore Standards Fire Protection.
- **DNV-SE-0077** Certification of fire protection systems for wind turbines: Provides guidelines for commissioning and certification of installed fire protection systems for wind turbines.

The list of US standards and guidelines that were studied for the literature review are provided as follows with a brief description of the document content and purpose. The US list contains industry standards that are not offshore but provide applicable requirements pertaining to similar hazards or operations.

National Fire Protection Association (NFPA)

- **NFPA 850** Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations: Provides recommended fire safety practices for gas, oil, and alternative fuel electric generating plants, including offshore wind turbines.
- **NFPA 418** Standard for Heliports: Establishes minimum fire safety requirements for protection for heliports and rooftop hangars. This standard does not apply to ground-level heliports and hangars.

Factory Mutual Global (FM)

- **Data Sheet 13-10** Wind Turbines: Provides design recommendations for both land-based and offshore wind turbines. Additional guidelines are provided for collector substations and other support equipment as part of the wind turbine operation.

Institute of Electrical and Electronics Engineers (IEEE)

- **IEEE 979** – Guide for Substation Fire Protection: Provides design guidance and fire hazard assessment for fire protection of substations. The guidance is mainly directed at onshore substation protection; however, design principles may relate to offshore substations.

American Petroleum Institute (API

- **API RP 14G**: Provides guidance for fire protection of offshore production platforms for petroleum facilities. API standards are written for offshore petroleum facilities and are inherently more conservative that those written for offshore electrical facilities containing smaller amounts of flammable and combustible materials.

American Clean Power Association (ACP)

- **ACP OCRP** Offshore Compliance Recommended Practices (OCRP): Provides a set of guidelines including design, manufacturing, installation, commissioning, operation, and service of commercial windfarm operations. This recommended practice document serves as the de facto reference for offshore wind development within the US and has been drafted to reference international and US standards IEC, ISO, DNV, and NFPA. The document seeks to supplement gaps relating to US-specific conditions.

1.2.1 Offshore Wind Energy International and US Document Summary Tables

Document Classification	IEC 61400	ISO 19901	EN 50308	BSHSD	DNV-ST-0145	DNV-SE-0077	CFPA-E No. 22
Standard	Applicable	Applicable	Applicable	Not applicable	Applicable	Not applicable	Not applicable
Guideline	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Applicable
Commissioning/Certification	Not applicable	Not applicable	Not applicable	Applicable	Not applicable	Applicable	Not applicable

Table 1 – Examined international document classification summary

Addressed Structures	IEC 61400	ISO 19901	EN 50308	BSHSD	DNV-ST-0145	DNV-SE-0077	CFPA-E No. 22
Offshore Wind Turbine	Applicable	Not applicable	Applicable	Applicable	Not applicable	Applicable	Applicable
Offshore Substation	Not applicable	Not applicable	Not applicable	Applicable	Applicable	Not applicable	Not applicable
Offshore Platform	Not applicable	Applicable	Not applicable	Applicable	Not applicable	Not applicable	Not applicable
Onshore Wind Turbine	Applicable	Not applicable	Applicable	Not applicable	Not applicable	Not applicable	Applicable
Onshore Substation	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable

Table 2 – Examined international document addressed offshore wind energy asset summary

Section Reference	Fire Protection Topic	IEC 61400	ISO 19901	EN 50308	BSHSD	DNV-ST-0145	DNV-SE-0077	CFPA-E No. 22
1.2.3.1	**Performance-based Design**	No criteria	No criteria	No criteria	Applicable	Applicable	No criteria	Applicable
1.2.3.2	**Active Fire Suppression System**	No criteria	No criteria	No criteria	No criteria	Applicable	No criteria	Applicable
1.2.3.3	**Fire Detection and Monitoring**	No criteria	No criteria	No criteria	No criteria	Applicable	Applicable	Applicable
1.2.3.4	**Fire Alarm Notification**	No criteria	No criteria	No criteria	No criteria	Applicable	No criteria	No criteria
1.2.3.5	**Fire Extinguishers**	Applicable	No criteria	Applicable	No criteria	Applicable	Applicable	Applicable
Note 1	**Heliport**	No criteria	No criteria	No criteria	No criteria	No criteria	No criteria	No criteria
1.2.4	**Fire Resistance Rating of Spaces**	No criteria	No criteria	No criteria	Applicable	Applicable	Applicable	No criteria
1.2.4	**Noncombustible Construction**	No criteria	No criteria	No criteria	No criteria	Applicable	No criteria	No criteria
1.2.5.1	**Fuel Load Control**	No criteria	No criteria	No criteria	Applicable	Applicable	No criteria	Applicable
1.2.5.2	**Ignition Source Control**	Applicable	No criteria	No criteria	No criteria	Applicable	No criteria	Applicable
1.2.5.3	**Smoke Exhaust/Ventilation**	No criteria	No criteria	No criteria	No criteria	Applicable	No criteria	No criteria
1.2.5.4	**Electrical Wiring Control**	Applicable	No criteria	No criteria	No criteria	Applicable	No criteria	Applicable
1.2.5.5	**Lightning Protection**	Applicable	No criteria	No criteria	Applicable	Applicable	No criteria	Applicable
1.2.5.6	**Power Disconnect System**	No criteria	No criteria	Applicable	No criteria	Applicable	Applicable	No criteria
1.2.5.7	**Emergency Response**	Applicable	No criteria	Applicable	Applicable	Applicable	No criteria	Applicable
Note 2	**Arc Flash**	No criteria	No criteria	No criteria	No criteria	No criteria	No criteria	No criteria

Notes:
1. Heliport fire protection standard is addressed by numerous different standards. See Section 1.2.3.6 for further discussion.
2. Arc flash falls under occupational safety risk management and is not covered under fire protection standards and guidelines. However, arc flash as a source of ignition is discussed in Sections 2.3.1 and 2.3.2.

Table 3 – Examined international document fire protection topic summary

Document Classification	NFPA 850	FM 13-10	API RP14G	IEEE 979	ACP OCRP
Standard	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Guideline	Applicable	Applicable	Applicable	Applicable	Applicable
Commissioning/Certification	Applicable	Not applicable	Not applicable	Not applicable	Applicable

Table 4 – Examined US document classification summary

Addressed Structures	NFPA 850	FM 13-10	API RP14G	IEEE 979	ACP OCRP
Offshore Wind Turbine	Applicable	Applicable	Not applicable	Not applicable	Applicable
Offshore Substation	Not applicable	Applicable	Not applicable	Not applicable	Applicable
Offshore Platform	Not applicable	Not applicable	Applicable	Not applicable	Not applicable
Onshore Wind Turbine	Applicable	Applicable	Not applicable	Not applicable	Not applicable
Onshore Substation	Applicable	Not applicable	Not applicable	Applicable	Not applicable

Table 5 – Examined US document addressed offshore wind energy asset summary

Section Reference	Fire Protection Topic	NFPA 850	FM 13-10	API RP14G	IEEE 979	ACP OCRP
1.2.3.1	**Performance-based Design**	Applicable	No criteria	Applicable	Applicable	Applicable
1.2.3.2	**Active Fire Suppression System**	No criteria	No criteria	No criteria	No criteria	No criteria
1.2.3.3	**Fire Detection and Monitoring**	Applicable	Applicable	Applicable	Applicable	No criteria
1.2.3.4	**Fire Alarm Notification**	Applicable	No criteria	No criteria	No criteria	No criteria
1.2.3.5	**Fire Extinguishers**	No criteria	Applicable	Applicable	Applicable	No criteria
Note 1	**Heliport**	No criteria	No criteria	No criteria	No criteria	No criteria
1.2.4	**Fire Resistance Rating of Spaces**	Applicable	Applicable	No criteria	Applicable	Applicable
1.2.4	**Noncombustible Construction**	Applicable	Applicable	Applicable	Applicable	No criteria
1.2.5.1	**Fuel Load Control**	No criteria	No criteria	No criteria	Applicable	No criteria
1.2.5.2	**Ignition Source Control**	Applicable	Applicable	No criteria	No criteria	No criteria
1.2.5.3	**Smoke Exhaust/Ventilation**	No criteria	No criteria	No criteria	Applicable	No criteria
1.2.5.4	**Electrical Wiring Control**	No criteria	No criteria	No criteria	Applicable	No criteria
1.2.5.5	**Lightning Protection**	Applicable	Applicable	No criteria	Applicable	No criteria
1.2.5.6	**Power Disconnect System**	Applicable	Applicable	No criteria	No criteria	No criteria
1.2.5.7	**Emergency Response**	No criteria	Applicable	No criteria	No criteria	No criteria
Note 2	**Arc Flash**	No criteria	No criteria	No criteria	No criteria	No criteria

Notes:
1. Heliport fire protection standard is addressed by numerous different standards. See Section 1.2.3.6 for further discussion.
2. Arc flash falls under occupational safety risk management and is not covered under fire protection standards and guidelines. However, arc flash as a source of ignition is discussed in Sections 2.3.1 and 2.3.2.

Table 6 – Examined US document fire protection topic summary

1.2.2 Document Classification

The types of documents reviewed for the literature review include standards, guidelines, and commissioning/certification. Standards are created through the consensus of industry stakeholders. Guidelines are also created by industry consensus but are not mandatory and seek to aid the standard where gaps of information exist. Commissioning/Certification documents rely on the standards and guidelines to provide a systemic method to ensure that the structure and included components are correctly designed, documented, and manufactured.

The two major international standards adopted by the international community and widely used in the European Union (EU) are the IEC and ISO documents. These technical documents are often supplemented by nation-specific technical standards such as the German Federal Maritime and Hydrographic Agency Standard Design (BSH SD) or are supplemented by industry standards such as DNV and Confederation of Fire Protection Associations in Europe (CFPA-E) No. 22. The DNV-ST-0145 provides the most comprehensive fire protection requirements for offshore substations. There is no document detailing comprehensive fire protection requirements for offshore wind turbines.

US regulations currently have not adopted a comprehensive fire protection standard to be applied to the offshore wind energy industry. An offshore industry legislation was created by the Minerals Management Services (MMS), later reorganized as the Bureau of Ocean Energy Management (BOEM) and Bureau of Safety and Environmental Enforcement (BSEE), which published 30 Code of Federal Regulations (CFR) 585, a federal regulation governing the development of offshore wind energy facilities. However, the regulation does not adopt any existing standards to be applied within the US—it only requires that those best industry practices be used.

An attempt to create a comprehensive offshore wind energy standard to be used by the US offshore wind industry was led by ACP in collaboration with BOEM and the National Renewable Energy Laboratory (NREL). The first edition of ACP OCRP was published in 2012 with second edition currently being drafted. The ACP OCRP contains recommended practices and application of various international and US standards, supplemented by industry input. For fire protection, the ACP OCRP recommended practices defaults to NFPA 850 and DNV-ST-0145 and provides no additional guidance on specific fire protection technology.

The standards, guidelines, and commissioning/certifications discussed in the literature review include documents specific to offshore wind energy systems and additional documents related to onshore wind energy systems.

1.2.3 Fire Protection Systems

Fire suppression systems are designed to control or extinguish a fire and are characterized as either automatic or manual. Automatic fire suppression systems do not require human interaction and may include a fire sprinkler system, a gaseous clean agent system, water mist system, or foam suppression system. Automatic fire suppression systems initiate using electro-mechanical activation through the fire detection system. Manual fire suppression is typically conducted using handheld fire extinguishers, standpipes, and/or water monitors.

Fire detection systems are designed to automatically detect a fire and may use smoke, gas, or visual signatures. The fire detection system is often interlocked with other electrical mechanical systems to provide auxiliary functions such as power disconnection, smoke ventilation control, and fire alarm signal notification. A fire detection system is often accompanied by a fire alarm notification system to notify occupants of a fire event. Where installed, a fire alarm system must be capable of being monitored by a central supervising station with the capability of receiving fire or fault notifications.

1.2.3.1 Fire Protection – Performance-based Design

Performance-based design (PBD) is a design concept that seeks to use fire hazard risk analysis to identify and mitigate the hazard. The PBD processes and principles are described similarly by both international and US literature. The available industry literature recognizes that offshore wind energy design is a rapidly developing technology with variability between each infrastructure design, in which a strict regulation or prescriptive design process may rapidly become obsolete. The existing literature offers few prescriptive requirements for fire protection systems. Rather, the literature routinely references the PBD process to identify fire risk and mitigation processes through fire protection engineering for offshore wind turbines and substations.

The PBD design concept is also referred to by different literature as *fire risk evaluation*, *fire hazard analysis*, *fire protection design basis*, or *fire and explosion protection concept*, depending on the reference. The PBD process remains consistent within the literature and consists of the following process:

1. Stakeholders establish agreed-on fire safety goals and objectives.
2. Fire scenarios are created and approved by stakeholders.
3. Fire safety design are assessed against fire scenarios in relation to stakeholder goals and objectives.

The international and US standards and guidelines provide the following language regarding offshore substation performance-based fire protection engineering and application of fire protection systems.

> **BSH SD §5.3.1.2** *A fire and explosion protection concept shall be drawn up in accordance with the protection objectives to be laid down in the development phase; the concept deals with the applicable hazards and shall be updated during the course of the project when structural or technical changes are made.*
>
> **DNV-ST-0145 §6.2.4** *Prescriptive requirements exist for offshore platform installations and in addition to these an analysis should be made. The analysis is often following a deterministic process, supplemented by performance-based fire safety engineering.*
>
> **CFPA-E No. 22 §4** *Experience has shown that in order to ensure the required fire safety it is always sensible to prepare a fire protection concept after consulting with all parties involved … According to this concept, all structural, turbine-specific and organizational protection measures shall supplement each other in terms of risk and protection targets …*
>
> **ACP OCRP §5.3.1.2** *The design of offshore wind farm assets for fire safety should take into consideration the operation philosophy and whether the asset classifies as a manned or unmanned facility … Design considerations for fire safety should be taken into account on the basis of fire hazard analysis and/or fire risk assessment.*
>
> **NFPA 850 §4.4.1** *Stakeholder establishes goals and objectives and evaluate whether the recommendations of NFPA 850 are adequate to meet those goals and objectives. The criteria for acceptability of the level of fire protection should consider the perspective of the various stakeholders.*

> **NFPA 850 §13.5.3.2** *The need for automatic fixed fire protection within the nacelle of a wind turbine generator should be based on the Fire Protection Design Basis Document and associated Fire Risk Evaluation.*
>
> **IEEE 979 §9.1** *A fire risk evaluation should be initiated as early in the design process as practical so that the fire prevention and fire protection recommendations as described in this document have been evaluated in view of the substation-specific considerations regarding design, layout, and anticipated operating requirements. The evaluation should result in a list of recommended fire prevention features to be provided … The fire risk evaluation should be approved by the owner prior to final drawings and installation.*

The standardized PBD fire protection methodology is provided in NFPA 850 and DNV-ST-0145, Figure 1. The figure provides documentable guidance for the PBD design process to be used by wind energy system designers and stakeholders. Although the two flow charts differ slightly, the key PBD principles remain consistent between the US and international literature.

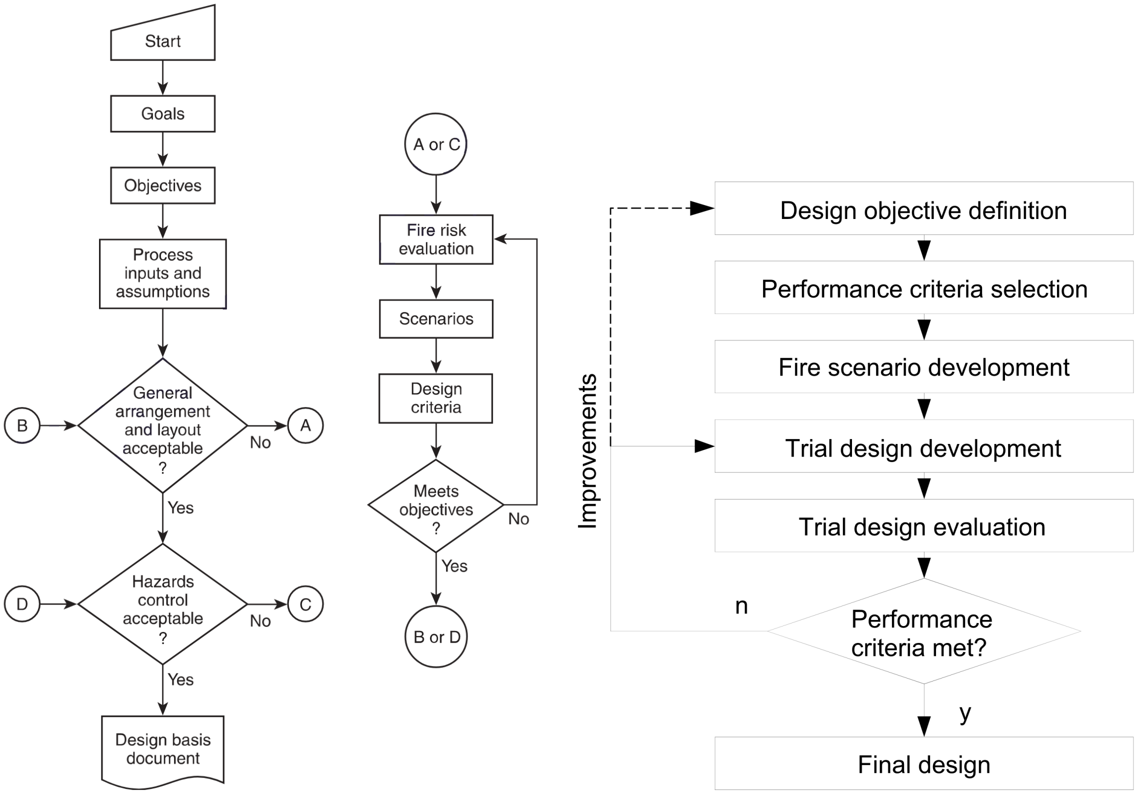


Figure 1 – Performance-based fire protection design objectives, from NFPA 850 (left) and DNV-ST-0145 (right)

In addition to the PBD process diagram, DNV provides minimum PBD design criteria to be considered for offshore substations. No equivalent is provided in the US standards.

> **DNV-ST-0145 §6.2.4** *The following typical fire scenarios for an unmanned AC substation should as a minimum be evaluated if relevant:*
>
> - *Main/auxiliary transformer fire e.g. due to overload, faults, oil degradation, or lack of cooling.*
> - *High voltage switchgear fire/explosion due to faults, poor maintenance, or incorrect procedures.*

- *Low voltage equipment fire due to short circuits, or overloads.*
- *Emergency generator fire due to faults, leakage, or malfunction.*

No minimum PBD design criteria for offshore wind turbines are provided within the current literature examined.

1.2.3.2 Active Fire Suppression Systems

Offshore substations and wind turbines are typically unmanned, are not easily accessed, and present a significant delay in response and diminished exterior firefighting capability. Automatic suppression systems provide the capability to limit a fire event without personnel being present.

The examined literature does not explicitly require fire suppression systems; rather, it refers to the PBD process to meet the fire protection design objectives. If a fire protection system is determined to be accepted as a risk mitigation tool, the literature offers additional guidance for design and installation of an offshore substation fire suppression system.

DNV-ST-0145 provides fire protection requirements relating to fire mains (standpipes and hydrants) and deluge systems. Key information for these two systems has been summarized that are unique to the offshore application. For other types of fire suppression system, DNV-ST-0145 points to further guidance using the authority having jurisdiction's installation standards and codes without any additional modifications. For this section, international fire suppression system guidance has been omitted and only US NFPA codes are referenced since this project is overseen by the US federal government. Refer to Section 1.2.3.7 for applicable NFPA codes for specific fire protection systems.

> **DNV-ST-0145 §6.5.2** *Fire main systems (standpipe and hydrant)*
>
> *At least two independently driving power pumps should be provided, each arranged to draw directly from the sea and discharged into a fixed fire main. …*
>
> *Each pump should be capable of delivering at least one jet simultaneously from each of the two fire hydrants, hoses and 19 mm [3/4 inch] nozzles while maintaining a minimum pressure of 0.35 N/mm^2 [50 psi] at any hydrant. In addition, where a foam system is provided for protection of helicopter deck, the pump should be capable of maintaining a pressure of 0.7 N/mm^2 [100 psi] at the foam installation.*
>
> **DNV-ST-0145 §6.5.3** *Deluge systems*
>
> *Release of the deluge systems shall be possible both locally and remotely at the control station where the operating status of the system is monitored.*
>
> *Water supply shall be so arranged that damage to any single section of the main due to fire within a protected area is not to disrupt water supply to adjacent area.*
>
> *Two separate supplies to the deluge fire water distribution pipework shall be provided, the main supply being from the deluge valve. The secondary supply shall preferably be from another section of the fire main. The secondary supply may be manually active.*
>
> *Refer to NFPA 24*
>
> **DNV-ST-0145 §6.5.4** *Automatic sprinkler system*
>
> *Refer to NFPA 13 and NFPA 16*
>
> **DNV-ST-0145 §6.5.5** *Fixed pressure water-spraying and water mist extinguishing system*
>
> *Refer to NFPA 15, NFPA 16, and NFPA 750*

> **DNV-ST-0145 §6.5.6** *Fixed gas fire extinguishing system*
>
> *Refer to NFPA 2001*
>
> **DNV-ST-0145 §6.5.7** [*Foam water extinguishing system*]
>
> *Refer to NFPA 11*

The recommendations for active fire suppression system for offshore wind turbines are found in CFPA-E No. 22 and NFPA 850. CFPA-E No. 22 provides narrative recommendations with regard to active fire suppression within the wind turbine nacelle. The summarized recommendation is as follows.

> **CFPA-E No. 22 §5.2.2** *Fire extinguishing systems*
>
> *For the purpose of effective fire protection of wind turbines, automatic, stationary fire extinguishing systems shall be installed. Gas extinguishing systems as well as fine water spray systems are suitable …*
>
> *Before the fire extinguishing system is active, the air-conditioning or ventilation system must be switched off automatically.*
>
> *With respect to the application at wind turbines, extinguishing agents that are as residue-free, non-corrosive, and non-electro conductive as possible, and which are suitable with respect to the prevalent environmental conditions at wind turbines and the fire loads would be desirable. The following systems can be applied at wind turbines, depending on the intended type of application:*
>
> - *Carbon dioxide (CO_2) fire extinguishing systems*
> - *Inert gas extinguishing systems*
> - *Fine water spray systems (water mist systems)*
>
> *Powder extinguishing systems as well as aerosol extinguishing systems cannot be recommended for application at wind turbines since they may cause consequential loss.*
>
> *Suitability of automatic fire extinguishing systems for the purpose of room and installation protection is to be reviewed for each individual turbine by taking into account the respective operating conditions at the wind turbine and by consulting with the manufacturer.*

NFPA 850 offers recommendations specific to wind turbine fire protection systems.

> **NFPA 850 §13.5.3.2.1** *A local application system is more appropriate for unsealed electrical enclosures and cabinets within the nacelle and tower. Likewise, a local application extinguishing system might be appropriate for the gearbox lubrication system or hydraulic control system. If used, fire suppression capability should be provided for oil piping or any area where oil can flow, accumulate, or spray. Fire extinguishing systems, where provided for hydraulic control equipment, should include protection of reservoirs, pumps, accumulators, piping, and actuating systems.*
>
> **§13.5.3.2.2** *Discharge rates and duration should be such that cooling and shutdown occur to prevent re-ignition of the fire. System operation should be arranged to coincide with automatic shutdown of the wind turbine.*
>
> **§13.5.3.2.3** *The positioning of local application nozzles should be such that maintenance access to the wind turbine components within the nacelle is maintained.*

1.2.3.3 Fire Detection and Monitoring

The examined international and US literature both state that all offshore substations and wind turbines should have a fire detection system. However, the literature does not explicitly state the fire detection technology to be implemented and defers to the PBD process for the specific fire detection system implementation.

Summaries of international standards and guidelines' key requirements are provided below.

> **DNV-ST-0145 §6.2.5** *Minimum requirements*
>
> *Fire detection systems are required on all installations. These, and possible gas detection systems, are described in [§6.7].*
>
> **§6.7.2** *Fire detection system*
>
> *The fire detection system shall be designed to:*
>
> > *1) control and monitor input signals from all connected fire and smoke detectors and manual call points*
> >
> > *2) provide output signals to the navigation bridge, continuously manned central control station or onboard safety center to notify the crew of fire and fault conditions*
> >
> > *3) monitor power supplies and circuits necessary for the operation of the system for loss of power and fault conditions*
>
> **DNV-SE-0077 §3.2.2.3** *Fire alarm system*
>
> *Fire detectors shall be proof against deceptive alarms and shall be adapted to the special design situations of wind turbines; faulty triggering should be prevented by the corresponding measures (e.g. interdependency of two detectors / two detector lines). The special design situations include e.g. nacelle temperatures above 50 °C, condensation, vibration and dust. The components that are used shall comply with the current state of the art and be approved.*
>
> *In a fire protection zone and in one indication group at least 2 fire or smoke sensors of the same type shall be installed*
>
> **CFPA-E No.22 §5.2.1** *Room monitoring – The nacelle and parts of the tower in which the wind turbine technology is installed as well as external transformer and electric power substations are to be monitored by an automatic fire detection system.*
>
> **§5.2.3** *Fault monitoring. Fire detection systems and fire extinguishing systems have to be monitored constantly in order to ensure their operational reliability.*

A summary of US guidelines for fire detection and monitoring system is provided below.

> **NFPA 850 §13.5.3.2.4** *A smoke/fire detection system with occupant notification should be installed throughout the tower and nacelle to provide early warning and alarm functions.*
>
> **FM13-10 §2.6.1.1** *Provide FM Approved detection devices in the nacelle.*
>
> **FM13-10 §2.6.1.3** *Provide detection for collector substations*
>
> **FM13-10 §2.6.1.5** *Arrange detectors to automatically trip the wind turbine, de-energize electrical equipment and disconnect the equipment from the grid, shut off oil systems, and transmit an alarm to a constantly attended location.*

> **FM13-10 §2.6.1.6** *Provide electronic supervision for fire-detection system trouble conditions and annunciate trouble alarms in a constantly attended location.*
>
> **IEEE 979 §6.7** *Fire alarm and detection systems*
>
> *The provision of fire alarm and detection systems may be required by the local building and fire codes based on the size, number of stories, and hazard of the new or existing substation buildings. Even when not specifically required by local codes, detection systems should still be considered for critical areas of substation buildings for the purpose of personnel safety, asset preservation, and business continuity. …*
>
> *Control rooms, computer rooms, communication rooms, switchgear areas, and mineral-oil-insulated equipment areas represent the kinds of critical areas that should be provided with detection. …*
>
> *Consideration should be given to providing remote offsite alarm notification for facilities that are not manned continuously.*

The US industry standard API RP 14G offers some design guidance for fire alarm and detection systems, but lacks specific details provided in other international and US standards and guidelines.

1.2.3.4 Fire Alarm Notification

There is limited information regarding occupant notification for offshore wind turbines and substations. The international standard DNV permits omission of occupant notification for normally unmanned substations. However, NFPA 850 differs and requires that, if a fire detection system is provided, an occupant notification system must also be provided.

> **DNV-ST-0145 §9.3.2** *… Alarm to areas which are not regularly manned (e.g. cofferdams, tanks) may be covered by procedural precautions, e.g. using portable radios.*
>
> **NFPA 850 §13.5.3.2.4** *A smoke/fire detection system with occupant notification should be installed throughout the tower and nacelle to provide early warning and alarm functions.*

1.2.3.5 Portable Fire Extinguishers

Hand-held portable fire extinguishers are intended to serve as the first line of fire fighting defense against fires of limited size (incipient stage). Both international and US standards and guidelines universally recommend the installation of portable fire extinguishers. The requirements for portable fire extinguishers are summarized in this section.

Offshore wind turbine fire extinguisher requirements summary:

> **IEC 61400-1 §13.1** – Requires specification and description of installed portable fire extinguishers to be maintained.
>
> **EN 50308 §4.11** – Provide minimum one 2kg CO_2 extinguisher.
>
> **DNV-SE-0077 §3.2.2.4** – Provide one 5kg CO_2 extinguisher and 9l foam extinguisher in the nacelle. Provide one 5kg CO_2 extinguisher in the tower base.
>
> **CFPA-E §5.2.2** – Provide one 5kg CO_2 extinguisher and 9l foam extinguisher in the nacelle. Provide one 5kg CO_2 extinguisher at the intermediate levels and in the tower base.

FM13-10 §2.6.2 – Provide portable fire extinguishers in nacelle and at the tower base.

Offshore substation fire extinguisher requirement summary:

BSH SD §5.3.1.2 – Requires specification and description of installed portable fire extinguishers to be maintained.

DNV-ST-0145 §6.5.8 – Provide 5kg CO_2 extinguisher or 9l foam extinguisher located adjacent to the hazard with maximum 15 m travel distance.

API RP 14G §6.1 – Provide suitable fire extinguishers based on the hazards present.

ACP OCRP §5.7.5.1 – Provide portable fire extinguishers.

Onshore substation fire extinguisher requirement summary:

NFPA 850 §7.5 – Provide suitable fire extinguishers based on the hazards present.

IEEE §6.9.5 – Provide suitable fire extinguishers based on the hazards present.

1.2.3.6 Heliport

The UK CAA has developed CAP 437 Standards for Offshore Helicopter Landing Areas, which comprehensively describe fire protection measures for both manned and unmanned offshore installations.

CAP 437 Chapter 2 *Key Design Characteristics – Principal Agent*

§2.3 *Foam-making equipment should be of adequate performance and be suitably located to ensure an effective application of foam to any part of the landing area … The design specification for an [Foam Monitor System] FMS should ensure remaining monitors are capable of delivering finished foam to the landing area …*

§2.9 *… in addition to fixed foam system monitor, there should be the ability to deploy at least two deliveries with a hand-controlled foam branch pipes … Where a Deck Integrated Fire Fighting System (DIFFS) capable of delivering foam and/or seawater in a spray pattern to the whole of the landing area … is selected in lieu of an FMS, the provision of additional hand-controlled foam branch pipes may not be necessary … Instead any residual fire may be tackled with the use of hand-held extinguishers.*

CAP 437 Chapter 5 *Normally Unattended Installations*

§5.1 *In the case of new-build [Normally Unattended Installation] NUIs, serious consideration should be given to the selection and provision of foam as the principal agent. For an NUI, where helideck Rescue and Fire Fighting Equipment will be unattended during certain helicopter movements, the pressurized discharge of foam through a manually operated fixed monitor system is not recommended. For installations which are at time unattended the effective delivery of foam to the whole of the lading area is probably best achieved by means of a DIFFs.*

The US fire protection requirements for heliports are determined by NFPA 418, Standards for Heliport, and 46 CFR Part 108 §486, developed by US Coast Guard. 46 CFR Part 108 §487 and §488 provide requirement for helicopter deck fueling operations and fueling facilities, which is not pertinent to offshore installations where no fueling operations take place.

NFPA 418 §8.1 *Plans*

Plans for construction and protection of heliports located on fixed and mobile offshore installations shall be approved by the AHJ [Authority Having Jurisdiction].

> **NFPA 418 §8.2** *Firefighting Access*
>
> **§8.2.1** *The heliport shall have at least one access point for fire-fighting/rescue personnel.*
>
> **§8.2.2** *Where practical, a second access point shall be available and shall be located remotely from the first*
>
> **46 CFR §108.486** *Helicopter decks*
>
> *At least two of the accesses to the helicopter landing deck must each have a fire hydrant on the unit's fire main system located next to them.*

The UK standards on offshore heliports are much stricter compared with the US requirements. CAP 437 requires the use of foam monitors at a minimum, with strong consideration to use a deck-integrated firefighting (DIFF) system; refer to Section 3.2 for additional description. NFPA 418 has no fire suppression system requirements for offshore heliports. 46 CFR Part 108 §486 requires access to a fire hydrant only for manual suppression and is more pertinent to onshore heliports.

1.2.3.7 Applicable US Standards for Fire Suppression and Alarm System Design, Installation, and Commissioning

If fire suppression and fire alarm systems are provided for offshore substations and wind turbines because of the PBD process, the design, installation, and commissioning standards should be based on existing US NFPA standards. NFPA standards for fire protection systems are internationally recognized by various governmental organizations and insurance agencies. These organizations and agencies often adopt NFPA standards if there are no equivalent national counterparts. The list of applicable NFPA codes relating to fire suppression systems and fire alarm detection systems are summarized in this section.

NFPA 10 Standard for Portable Fire Extinguishers: Provides requirements for selection, installation, inspection, maintenance, recharging, and testing of portable fire extinguishers.

NFPA 11 Standard for Low-, Medium-, and High-Expansion Foam: Provides requirements for designing, installing, testing, inspecting, approving, and maintaining foam suppression systems.

NFPA 12 Standard on Carbon Dioxide Extinguishing Systems: Provides requirements for designing, installing, testing, inspecting, approving, and maintaining a carbon dioxide fire-extinguishing system.

NFPA 13 Standard for the Installation of Sprinkler Systems: Provides the minimum requirements for the design and installation of automatic fire sprinkler systems.

NFPA 15 Standard for Water Spray Fixed Systems for Fire Protection: Provides minimum requirements for the design, installation, and system acceptance testing of water spray fixed systems.

NFPA 16 Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray System: Provides installation requirements for foam-water sprinkler and spray systems.

NFPA 72 National Fire Alarm and Signaling Code: Provides requirements for fire alarm signal initiation, transmission, notification, and annunciation and for supervising station alarm systems, public emergency alarm reporting systems, fire detection and warning equipment, emergency communications systems, and their components.

NFPA 750 Standard on Water Mist Fire Protection Systems: Provides requirement for design, installation, maintenance, and testing requirements for water mist fire protection systems.

NFPA 2001 Standard on Clean Agent Fire Extinguishing Systems: Provides requirements for design, installation, testing, approving, and maintaining gaseous clean agent fire extinguishing systems.

1.2.4 Passive Fire Protection

Passive fire protection (PFP), sometimes referred to as structural fire protection, provides increased fire safety by maintaining the structural stability against fire and/or limits the fire spread in the event of fire. The PFP system includes the use of noncombustible or fire-resistant construction materials to create fire compartmentalization zones to slow or prevent the spread of fire from the room of origin. For example, a fire-rated barrier could be used to separate high hazard equipment from mission-critical spaces to delay heat and smoke ingress. The overall goal of PFP is to provide protection for a finite time to allow occupant egress, structural stability, and mission continuity until extinguished (by the responding fire department or a fire suppression system).

The listed effectiveness of PFP is typically expressed in terms of the time that a given PFP system can withstand the heat generated by a fire. The performance of fire rating is compared to a standard time-temperature curve, which in the US is defined by the ASTM E119 test standard. The construction of such an assembly may involve fireproof materials, noncombustible construction materials, fire-rated assemblies (walls, floor, or ceiling), or spray-on fire proofing for structural steel.

1.2.4.1 Offshore Wind Turbine Passive Fire Protection

Both international and US standards and guidelines offer little guidance regarding PFP of offshore wind turbines because of the relatively simplistic interior blocking of wind turbine spaces. The available language recommends using noncombustible construction materials to limit the spread of fire rather than using structural fire proofing measures.

EN 50308 §4.11 *Oil absorbing construction materials shall not be incorporated in the nacelle or in the tower when leak oil could result in oil soaked material.*

DNV-SE-0077 §3.2.3 *Design/engineering measures for fire protection help to prevent fires, to limit them in spatial extent and, in case of fire, to secure the availability of the escape and rescue routes. The design/engineering measures include fire stopping …, fire-resistant claddings and fire protection coatings.*

… It may be necessary to establish different fire protection measures and/or fire zones for various areas of the wind turbine. This shall be considered e.g. concerning the position of the main transformer, control cabinets and/or static converter cabinets in the wind turbine.

CFPA-E No.22 §4 *The risk of an outbreak of fire shall be limited effectively by the following … Use of non-combustible or difficult to ignite materials.*

The application of combustible materials, e.g., foamed plastics such as PUR (polyurethane) or PS (polystyrene) as insulating material or GRP (glass-reinforced plastics) for coverings and other components shall be avoided …

The US guideline FM13-10 offers the following guidance for PFP of wind turbines.

> ***FM13-10 §2.5.1*** *Construct the nacelle as follows:*
>
> A. *Use noncombustible or fire resistant materials*
> B. *If combustible construction is used, provide noncombustible or fire resistant interior lining or barrier to reduce the fire exposure.*
>
> ***§2.5.1.1*** *Separate the nacelle from the tower with noncombustible construction.*
>
> ***§2.5.1.2*** *Provide noncombustible separation for openings that serve as access point between the tower and nacelle.*

The specific requirements for wind turbine PFP are limited in both the international and US literature. The existing literature discourages the use of combustible materials in construction. However, if combustible materials must be used, the literature recommends that additional passive protection such as fire retardants or intumescent treatments be used. The FM13-10 guidelines include an additional requirement that the opening between the nacelle and the tower be sealed with noncombustible construction.

1.2.4.2 Offshore Substation Passive Fire Protection

DNV-ST-0145 provides substantial guidance for offshore substation PFP requirements and recommendations. Requirements include the minimum type of building construction and the required hourly fire resistance rating of the constructed wall assemblies separating critical spaces from hazardous areas.

> ***DNV-ST-0145 §6.2.5*** *Minimum requirements – Substation type A [normally unmanned platform]: Control room … and similar areas shall be isolated from the rest of the platform by suitable passive fire protection for a period compatible with the evacuation time for the installation.*
>
> ***§6.2.5*** *All penetrations in fire rated divisions shall be arranged so as to maintain the fire rating of the division.*

DNV-ST-0145 provides prescriptive requirements for passive fire protection of separating walls and decks, Table 7 and Table 8. Walls are vertical construction separating adjacent spaces and decks are horizontal construction separating adjacent floors. Refer to Table 14 for information regarding the PFP performance of Class A, B, and C walls.

Spaces	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
(1) Control stations	A-0	A-0	A-60	A-60	A-15	A-60	A-15	A-60	A-60	*	A-0
(2) Corridors	A-0	C	B-0	A-0	B-0	A-60	A-0	A-0	A-0	*	B-0
(3) Accommodation spaces	A-60	B-0	C	A-0	B-0	A-60	A-0	A-0	A-0	*	C
(4) Stairways	A-60	A-0	A-0	A-0	A-0	A-60	A-0	A-0	A-0	*	A-0
(5) Service spaces (low risk)	A-15	B-0	B-0	A-0	C	A-60	A-0	A-0	A-0	*	B-0
(6) Machinery spaces of category A	A-60	A-60	A-60	A-60	A-60	*	A-60	A-60	A-60	*	A-0
(7) Other machinery spaces	A-15	A-0	A-0	A-0	A-0	A-60	A-0	A-0	A-0	*	A-0
(8) Hazardous areas	A-60	A-0	A-0	A-0	A-0	A-60	A-0	—	A-0	—	A-0
(9) Service spaces (high risk)	A-60	A-0	A-0	A-0	A-0	A-60	A-0	A-0	A-0	*	A-0
(10) Open decks	*	*	*	*	*	*	*	—	*	—	*
(11) Sanitary and similar spaces	A-0	B-0	C	A-0	B-0	A-0	A-0	A-0	A-0	*	C

Note : "*" class division – divisions of steel or equivalent material and shall prevent the passage of flame and smoke. "-" division – no separation requirement.

Table 7 – DNV-ST-0145 Table 6-1 fire integrity of walls separating adjacent spaces matrix

Spaces	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
(1) Control stations	A-0	A-0	A-0	A-0	A-0	A-60	A-0	A-0	A-0	*	A-0
(2) Corridors	A-0	*	*	A-0	*	A-60	A-0	A-0	A-0	*	*
(3) Accommodation spaces	A-60	A-0	*	A-0	*	A-60	A-0	A-0	A-0	*	*
(4) Stairways	A-0	A-0	A-0	*	A-0	A-60	A-0	A-0	A-0	*	A-0
(5) Service space (low risk)	A-15	A-0	A-0	A-0	*	A-60	A-0	A-0	A-0	*	A-0
(6) Machinery spaces of category A	A-60	A-60	A-60	A-60	A-60	*	A-60	A-60	A-60	*	A-0
(7) Other machinery spaces	A-15	A-0	A-0	A-0	A-0	A-0	*	A-0	A-0	*	A-0
(8) Hazardous areas	A-60	A-0	A-0	A-0	A-0	A-60	A-0	—	A-0	—	A-0
(9) Service spaces (high risk)	A-60	A-0	A-0	A-0	A-0	A-0	A-0	A-0	A-0	*	A-0
(10) Open decks	*	*	*	*	*	*	*	—	*	—	*
(11) Sanitary and similar spaces	A-0	*	*	A-0	A-0	A-0	A-0	A-0	A-0	*	*

Note : "*" class division – divisions of steel or equivalent material and shall prevent the passage of flame and smoke. "-" division – no separation requirement.

Table 8 – DNV-ST-0145 Table 6-2 fire integrity of decks separating adjacent spaces matrix

The DNV defines the spaces of a substation as follows:

1. Control stations – control and communication rooms, uninterruptible power supply (UPS), and SCADA equipment.
2. Corridors – corridors and lobbies.
3. Accommodation spaces – public spaces, recreational rooms, cabins, offices.
4. Stairways – interior stairways, lifts, and escalators (other than those wholly contained within machinery spaces).
5. Service spaces (low risk) – workshop, storage, and working spaces in which flammable materials are not stored.
6. Machinery space of category A – spaces containing internal combustion type (>375 kilowatts [kW]) or fuel-fired units. High-voltage (HV) transformer rooms and diesel generator room.
7. Other machinery spaces – spaces containing internal combustion type (<375 kW). Low-voltage (LV) and HV equipment and utility rooms.
8. Hazardous area – areas with possible presence of flammable atmosphere arising from process operations. Heli fuel skid, diesel tanks, battery storage.
9. Service space (high risk) – lockers, storerooms, and working spaces in which flammable materials are stored.
10. Open decks – areas fully subject to natural ventilation excluding hazardous areas.
11. Sanitary and similar spaces – showers, baths, lavatories, and isolated pantries containing no cooking appliances.

The BSH SD references DNV-ST-0145 for offshore substation design; however, it adds the PBD requirements to involve different fire scenarios to determine whether the PFP strategy achieves the stakeholder-agreed fire protection goals.

> ***BSH SD §5.3.1.2*** *Fire and explosion protection concept – A fire and explosion protection concept shall be drawn up in accordance with the protection objectives to be laid down in the development phase … Description and illustration of the layout of fire-protection compartments and the design of their portioning components, layout and design of smoke compartments, closure of openings in components forming a compartment, and fire resistance of components.*

The US guideline for offshore substation design ACP OCRP references the DNV-ST-0145 for passive fire protection requirements and prescribes no additional requirements.

> **ACP OCRP §5.7.5.13** *For passive fire protection design guidance can be found in DNVGL-ST-0145.*

Requirements pertaining to onshore substation passive fire protection are identified in NFPA 850 and IEEE 979. NFPA 850 Chapter 6 pertains to electric generating plants and HV direct current converter stations and states that the fire areas shall be determined using a Fire Protection Design Basis Document; refer to Section 1.2.3.1. From excerpt §6.1.1.3 below, the most relevant use area is listed from a total list of 18 recommended areas to be separated with passive fire resistance rating. In addition, NFPA 850 further clarifies the interior finish ratings within the substation to be Class A minimum, determined by the ASTM E84 test.

> **NFPA 850 §6.1.1.1** *The electric generating plant and the high voltage direct current converter station should be subdivided into separate fire areas as determined by the Fire Protection Design Basis …*
>
> **§6.1.1.3** *… it is recommended that the fire area boundaries be provided to separate the following:*
>
> > *(2) Control room, computer room, or combined control/computer room from adjacent area.*
> > *(3) Rooms with major concentrations of electrical equipment, such as a switchgear room or relay room, from adjacent area.*
> > *(4) Battery rooms from associated battery chargers, equipment, and adjacent area.*
> > *(9) Emergency generators, combustion turbines, and other internal combustion engines from each other and from adjacent area.*
> > *(14) Telecommunication rooms, supervisory control and data acquisition (SCADA) rooms, and remote terminal unit (RTU) rooms from adjacent areas.*
> > *(18) Switchgear area and sulfur hexafluoride (SF6) switchyard area from adjacent area.*
>
> **§6.1.1.4** *Fire barriers separating fire areas should be a minimum of 2-hour fire resistance rating.*
>
> **§6.3.5.1** *Cellular or foamed plastic materials … should not be used as interior finish*
>
> **§6.3.5.2** *Interior finish in buildings critical to power generation or conversion should be Class A.*

IEEE 979 offers the following guideline in which it is assumed various equipment (SCADA, RTU, batteries, or switchgear) may exist in a single room. It also requires noncombustible construction of the floor and roof assemblies.

> **IEEE 979 §6.6.2** *Fire separation. Fire separation should be installed between adjacent occupancies with different uses within the same building. Required minimum fire-resistance rating for fire separation should be obtained from applicable building codes.*
>
> > *Exception: Self-contained modular substation packages consisting of buildings with switchgear (metal-clad or gas-insulated switchgear), control equipment, and auxiliary equipment may be treated as single use.*
> >
> > *Fire separation may be eliminated between the different areas provided there is a realization that the entire module may be lost if a fire were to occur.*
>
> ***§6.6.3*** *Floor and roof. Flooring should be noncombustible such as steel or concrete …*

The US industry standard API RP 14G offers some design guidance for passive fire protection, but lacks specific details provided in other international and US standards and guidelines.

Both the international standards for offshore substation and US standard for onshore substation require minimum PFP. The DNV-ST-0145 standard requires a 1-hour fire resistance rating protecting critical equipment and hazardous spaces. NFPA 850 and IEEE 979 (developed for onshore substations) requires a minimum of 2-hour fire resistance rating for spaces with different use areas.

1.2.5 Risk Management

Fire risk management for offshore wind turbine and substations includes the following: fuel load control, ignition source control, smoke control, electrical wiring control, lightning protection, power disconnect, and emergency response and planning. The international and US literature offer varying guidance and recommendations for these risk control measures. If risk analysis and PBD is required by the literature, NFPA 551, Guide for the Evaluation of Fire Risk Assessments, provides guidance on a systematic approach.

DNV-ST-0145 provides the most comprehensive risk management requirements for offshore substations and requires a PBD approach to mitigate fire risks through fire risk hazard identification to prescribe a combination of fire prevention, active fire suppression, fire detection, and procedure emergency response acceptable to the wind energy stakeholders.

> **DNV-ST-0145 §2.3.3** *Identified hazards and potential escalation shall be evaluated based on the causes, consequences and probability of occurrence.*
>
> *The evaluation should address the sources and contributors in the chain of events leading to a hazard. Prevention and protection measures should be considered in a realistic way as far as possible. Where the benefit of these measures is uncertain, or their presence cannot be assured, they should be considered to be absent.*
>
> **DNV-ST-0145 §2.3.4** *Risk reduction involves identifying opportunities to reduce the probability and consequence of incidents aiding the decision making on the need to introduce such measures.*
>
> *Risk reduction measures include those:*
> *— to eliminate incidents (by reducing the probability of occurrence to zero)*
> *— to prevent incidents (by lowering the probability of occurrence)*
> *— to control incidents (by limiting the extent and duration of events)*
> *— to mitigate the effects (by reducing the consequences)*

> *Identified hazards should be avoided wherever practicable, e.g. through:*
>
> *— removal of the source of a hazard (without introducing new sources of hazard)*
> *— breaking the sequence of events leading to realization of a hazard*
> *— introduction of inherently safe designs*

There is no comprehensive literature on fire risk management for offshore wind turbines.

1.2.5.1 Fuel Load Control

Fuel load control is an integral part of fire risk management. Fuel load describes the total quantity of combustible materials within a space and is directly related to the resulting fire intensity. The international and US standards and guidelines provide recommendations on reduction on fuel loads and separations from important equipment.

The international standard recommends separating high fuel load areas from the protected zone and limiting the overall fuel load within the offshore substations. In addition, some guidance is provided for avoiding combustible materials for offshore construction and within equipment.

> **BSH SD §5.1.1** *Danger zones with a high risk potential (e. g. zones where there is a risk of explosion, and zones with high fire loads or fire risks) shall be separated from protection zones.*
>
> **DNV-ST-0145 §3.6.3** *Workshops and storage areas. Hazardous substances shall be collected and removed in order not to endanger health or safety of persons on the installation. Stores for hazardous substances shall be segregated from, and located at a safe distance from accommodation spaces and control stations.*
>
> **CFPA-E No. 22 §5.1.3** *Minimizing combustible material. Hydraulic and lubricant oils should be chosen according to the following characteristics: in addition to their technical features required, they should preferably be non-combustible or have a high flash point which is significantly above the operating temperatures of the systems.*
>
> *The application of combustible material, e.g., foamed plastics such as PUR (polyurethane) or PS (polystyrene) as insulating material or GRP (glass-reinforced plastics) for coverings and other components shall be avoided for fire protection reasons.*
>
> *If the application of non-combustible material is impossible in individual cases, the material used shall at least be of low flammability. Moreover, closed-cell material with washable surface shall be used in order to avoid intrusion of impurities, oil leakage, etc., which otherwise would increase the risk of fire in the course of the operating time.*
>
> *Combustible materials as well as auxiliary materials and operating materials are not allowed to be stored within the wind turbine.*

The US standard for onshore substation requires reduction of combustible materials and disposal of combustible accumulation.

> ***IEEE 979 §6.10*** *Combustible materials. The use of combustible materials with flame-spread, fuel-contributed, and smoke-developed ratings greater than 25 should be avoided in the selection of desks, chairs, filing cabinets, storage boxes, display boards building insulation, interior wall panels, mounting boards, and so on.*
>
> *Care should be taken to control the accumulation of combustible materials and refuse in substation buildings. Combustible materials and refuse should be temporarily stored in metal safety refuse cans with self-closing lids or metal garbage cans with metal lids. Any*

> *accumulated combustible materials and refuse should be removed from the substation at least weekly.*

1.2.5.2 Ignition Source Control

Ignition source control attempts to locate and mitigate possible ignition sources capable of starting a fire. Prominent ignition sources identified include lightning, emergency breaks, electrical failures, and spontaneous ignition of oily cloths. Both the international and US standards recommend additional control measures to mitigate the ignition source hazard.

DNV-ST-0145 and CFPA-E No. 22 recommend that the ignition source be identified during the PBD process. The identified ignition sources within the offshore substations and wind turbines can then be mitigated.

> **IEC 61400-1 §9.1** *Load calculation shall be based on simulations including both the mean braking level and a minimum braking level that allows for minimum friction and application pressure predicted for the design. If the brake is able to slip at the minimum braking level, when the brake is applied, it shall be designed to avoid overheating and brake performance impairment and to avoid risk of fire.*
>
> **DNV-ST-0145 §2.3.4** *Where hazards cannot be avoided, installation design and operation should aim at lowering the probability of hazards occurring where practicable, e.g. by: removing or relocating ignition source.*
>
> **CFPA-E No.22 §5.1.4** *Avoidance of possible ignition sources*
>
> *Possible ignition sources include, e.g.; Lightning current; flying sparks occurring during the brake application of a mechanical brake; short circuit and arc, as well as resonant circuit with electrical device and systems; hot surfaces, e.g., bearings, brake disk. Spontaneous ignition through dirty cleaning cloths (e.g., oil, solvents).*
>
> *Components and the before mentioned possible ignition sources must be arranged and executed so that combustible material is not set on fire during normal operation or in case of malfunctions. In order to ensure this, it is necessary to install coverings, baffle plates or the like that are made of non-combustible material. Electrical equipment shall be secluded.*
>
> **NFPA 850 §13.3.3** *High speed brakes (if used) can create a large quantity of sparks. The use of shield(s) should be considered to isolate these sparks from combustible equipment components and locations where leaked combustible fluids can accumulate.*
>
> **FM13-10 §2.6.3** *Ignition source control.*
>
> **§2.6.3.1.1** *Establish a hot work permit and supervision programing …*
>
> **§2.6.3.2.1** *Provide shields to isolate sparks created by mechanical braking mechanisms from combustible materials.*
>
> **§2.6.3.2.2** *Where dynamic braking of the wind turbine is achieved through the use of braking resistors, ensure the resistors are not located adjacent to any combustible construction or material.*

1.2.5.3 Smoke Exhaust/Ventilation

Smoke exhaust/ventilation systems can serve as a life safety or equipment protection feature by providing protection against toxic and corrosive smoke. Active smoke control is not explicitly mentioned in the examined literature. However, consideration of separate rooms and required air supply is provided in DNV-ST-0145 and IEEE 979. Both the international and US literature agree that some mitigation of smoke should be considered for areas housing sensitive electronics and critical communication equipment.

> **DNV-ST-0145 §7.8.2.3** *Control stations. In case a control station is served by a common ventilation system, which serves also other spaces, effective local closing arrangements shall be provided. Effective local closing arrangements mean that the provided ventilation systems shall be fitted with fire dampers or smoke dampers which could be closed easily within the control station in order to maintain the absence of smoke in the event of fire.*
>
> *Alternative and separate means of air supply shall be provided; air inlets of the two sources of supply shall be so disposed that the risk of both inlets drawing in smoke simultaneously is minimized. Such requirements need not be applied to control stations situated on, and opening on to, an open deck and where local closing arrangements would be equally effective.*
>
> **IEEE §6.6.11** *In control rooms, relay rooms, and computer rooms where a dedicated HVAC system serves these spaces, it may be appropriate during fire conditions to continue to run the HVAC in the 100% fresh air and relief air mode to reduce the impact of heat and smoke on the critical electrical and electronic components.*

1.2.5.4 Electric Wiring Control

Electrical wiring has the potential to increase the fire load for energy infrastructure given the presence of power distribution cables and communication lines. The literature is in agreement that an appropriate level of electrical wiring fire resistance and separation of critical communication lines should be considered. For instance, where a power cable is located in the same space as a communication cable, they should be separated such that an accidental fault in the power cable does not compromise the communication cable.

> **IEC 61400-1 §10.8** *Electrical cables. Electrical cables shall be rated for the electrical, flammability, mechanical and environmental applications where they are used and shall be installed in a manner for which they are rated …*
>
> - *Cables shall be protected or rated to mitigate the possible risk of fire in the event of the fault.*
> - *Control cables shall be segregated and or protected from power cables unless insulation failures are specifically addressed in the fault analysis.*
>
> **DNV-ST-0145 §5.4.9.1** *General. Cables are installed on the platform at different locations for different applications. Due to abnormal operation or fire hazards cables, lines and busbars have to be selected carefully to ensure high reliability and safe operation of the overall system also during faulty conditions. Cable fire safety, cable routing, proper fixation as well as special cable penetrations for fire rated walls are the challenges for low-voltage and high-voltage cables on offshore transformer substations.*
>
> **CFPA-E No.22 §5.3.1** *Cables and lines shall be used that preferably; produce only slightly poisonous and corrosive decomposition products; do not cause much smoke and cause only little pollution of the rooms and content; do not support fire spread*
>
> **IEEE 979 §6.6.5** *Grouped electrical cables should be routed away from exposure hazards (major switchgear and sources of flammable and combustible liquids) or provided with suitable fire protection measures to offset the risk. Where possible, high-*

voltage cable trays should be located above or remote from low-voltage cable trays to lessen the exposure hazard to the lower voltage cables.

1.2.5.5 Lightning Protection

Lightning poses a high fire risk for offshore substations and wind turbines. The current international and US literature is in agreement and requires lightning protection installed in accordance with the appropriate authority having jurisdiction.

> **IEC 61400-1 §10.7** *Lightning protection. The lightning protection system of a wind turbine shall be designed in accordance with IEC 61400-24.*
>
> **BSH SD §2.3.2** *The rotor/nacelle assembly and their respective equipment (non-load-bearing steel components (secondary steel), such as boat landings, platforms and ladders) shall be connected to the lightning protection and earthing system.*
>
> **DNV-ST-0145 §5.7.1.2** *The platform and its sub-components shall be protected according to the lightning protection level I (LPL I).*
>
> **CFPA-E No. 22 §5.1.1** *Lightning and surge protection. Wind turbines have to be equipped with comprehensive lightning and surge protection that is adjusted to the individual type of turbine. Systems for lightning and surge protection have to be planned, build and operated like other components of the wind turbine according to the acknowledged rules of technology.*
>
> **NFPA 850 §13.5.2.2** *Lightning protection for blades, nacelles, towers, power lines, transformers, and support structures should be provided …*
>
> **FM 13-10 §2.8.1.1** *Install a lightning detection system or surge counters to detect lightning strikes. Visually inspect wind turbine blades, nacelles, and towers for damage after a lightning storm has passed through the wind farm. Stop wind turbines to repair or replace damaged blades as soon as possible.*
>
> **IEEE 979 §6.6.8** *Lightning protection. Lightning strikes to substations can ignite flammable materials and damage equipment that can lead to fires.*

1.2.5.6 Power Disconnect System

Power disconnection and emergency stop systems are systems that isolate equipment from energized equipment. An electrical fire intensified by energized equipment has the potential for increased fire severity. A fire suppression or fire detection system should be interlocked to shut down the offshore substation and wind turbine operations in a safe procedural manner to decrease the fire hazard risk. The international and US literature recommend power disconnect and emergency stop systems to be incorporated into the substation and wind turbine design.

> **IEC 61400-1 §8.6** *An emergency stop button function shall be implemented using recognized methods and design principles.*
>
> **IEC 61400-1 §10.5** *Disconnection from supply sources. Lockable disconnect device or devices shall be provided to disconnect the equipment from each electrical source of supply that has a hazardous live voltage or exceeds the values for hazardous energy or from which a hazardous live voltage or energy is derived.*
>
> **EN 50308 §4.9** *Emergency stop. An Emergency stop system is intended to divert danger both from persons and from the wind turbine. … activation of a protection system that*

brings all movements of the turbine to a safe sate in the shortest possible time without creating additional hazards.

EN 50308 §4.10 *Power disconnection. … each turbine shall be equipped with provision to disconnect or isolate it from all its power source during inspection and maintenance.*

DNV-ST-0145 §9.4.3 *System shutdown can be required in the case of severe criticality of an incident e.g. in the case of fire in auxiliary generator room.*

System shutdown; should not disconnect the offshore substation from the grid; shall isolate an entire unit or area involved in a fire or other emergency; may not stop or impede the operation of emergency consumers (among others active fire protection, emergency lighting, navigation aids).

DNV-SE-0077 §3.2.2.6 *In case of a fire alarm signal received from the control and indicating equipment an immediate and controlled shutdown of the wind turbine shall be performed without an automatic restart and according to the fire protection concept, see [3.1], a subsequent disconnection from the grid shall be performed, if necessary (e.g. because of fire alarm in high voltage transformer or cable section).*

NFPA 850 §13.4.3 *In the event of a problem with a wind turbine generator, automatic shutdowns should be provided that result in stopping of shaft rotation, braking, and isolation of electrical power to the tower and nacelle. Different methods of equipment shutdown and isolation, operating independently, should be provided. These can include blade pitch control and/or hydraulic braking as well as power isolation in concert with electronic control termination.*

FM 13-10 §2.6.1.5 *Arrange detectors to automatically trip the wind turbine, de-energize electrical equipment and disconnect the equipment from the grid, shut off oil systems, and transmit an alarm to a constantly attended location.*

1.2.5.7 Emergency Response and Planning

Emergency response and planning is a procedural risk management tool designed to set standard operating procedures for when an emergency event occurs. The international and US standards agree that an emergency response must be planned prior to an emergency. Additional requirements are specified by the governing body or the local jurisdiction.

EN 50308 §4.11 *Escape routes including climbing facilities shall maintain their function for a minimum of 30 min in case of fire.*

BSH SD §5.2.1 *Emergency management: Evacuation, e.g. escape routes, primary and secondary rescue appliances. Emergency supply.*

DNV-ST-0145 §9.1 *Requirements for emergency response strategy, rescue and evacuation means and safety equipment are not included in this standard. Relevant local requirements for flagged units and/or coastal state requirements shall be applied. USA: The US Minerals Management Service (MMS) Code of Federal Regulations (CFR) on Mineral Resources including API RP 75 for the Development of Safety and Environmental Management Program for Outer Continental Shelf Operations and Facilities.*

CFPA-E No.22 §5.3 *Preparation of an emergency plan for the case of fire after consulting with fire brigades and police offices in charge and with the insurer.*

1.3 Offshore Wind Emergency Fire Protection Monitoring System

The offshore wind energy infrastructure, similar to other energy sectors such as oil and gas, uses a SCADA system for control and monitoring of the wind energy assets. A SCADA system is a collection of software and hardware components that allow both supervision and control of the wind energy processes. The system is designed to examine, collect, and process real-time data gathered by system of sensors and allow system operators automatic or manual control of the equipment. The data collection is accomplished using an RTU that may also be installed with a programmable logic controller (PLC). The RTU interfaces and interacts with field devices and PLC to provide automatic control of equipment based on the real-time data. The supervision and control are typically accomplished at a remote central monitoring system (CMS) with data transmission using an RTU via fiber, wireless networking, or satellite communications. For the offshore industry, satellite communications between the RTU and CMS is widely used.

The industry standard is to accomplish remote monitoring of offshore wind fire protection systems by interfacing the fire alarm control panel (FACP) with the SCADA RTU for signal transmission to the off-site CMS. The interface between the FACP and SCADA RTU can be accomplished by direct connection using relay switches/modules or proprietary signal converters.

The FACP serves as a local monitoring system that oversees the fire detection, fire notification, and fire suppression systems. The internal logic, programmed by the system designer, allows the FACP to perform specific functions based on activation of certain conditions. For example, an alarm condition notifies the CMS of a fire suppression system activation or a fire condition. Upon receiving the fire signal, CMS begins internal standard operating procedures to respond to the fire condition and notifies the appropriate authority, that is, the US Coast Guard. A supervisory or trouble condition can notify CMS that maintenance may be required. Once a system fault is known, the offshore wind energy operator can assign maintenance to examine the system fault and provide corrective action.

The FACP typically monitors the following conditions:

- Alarm condition – An abnormal condition that poses an immediate threat to life, property, or mission.
- Pre-alarm condition – An abnormal condition that poses a potential threat to life, property, or mission, and time is available for investigation.
- Supervisory condition – An abnormal condition in connection with the supervision of other systems, processes, or equipment.
- Trouble condition – An abnormal condition in a system attributable to a system fault.
- Normal condition – Circuits, systems, and components are functioning as designed and no abnormal conditions exist.

The FACP uses a series of monitor modules to interface with a multitude of sensors provided for the fire alarm and fire suppression system. The monitor modules act as signal converters that translate to FACP compatible signals. Furthermore, fire protection device manufactures may use built-in sensors and internal logic programming to detect problems and transmit appropriate signals to the FACP.

NFPA standards and codes provide guidance on minimum code required supervisory and fault monitoring conditions. Some examples of commonly monitored minimum supervisory and fault conditions are:

- Power supply failures
- Low system/faulty backup batteries
- Cut, broken, or disconnected conduits

- Out of service/removed device
- Shut off water supply
- Low/high pressures and supplies in suppression system
- Fire pump failures

Additional monitoring conditions may be used for specific fire protection system components based on the risk and failure mode analysis concerning offshore wind energy operations.

1.4 Offshore Fire Protection Inspection, Testing, and Maintenance

Fire protection systems installed as part of the offshore wind energy infrastructure require ongoing ITM for continuation of system operation and reliability. Given the lack of federal regulations, the current offshore wind energy ITM requirements are typically dictated by the system operators, complying with requirements put forth by nationally recognized fire protection system codes, standards, and guidelines. The ITM of fire protection systems features the following key concepts:

- Inspection – A visual examination of a system or portion thereof to verity that the system appears to be in operating condition and is free of physical damage.
- Testing – A procedure used to determine the operational status of a component or system by conducting periodic physical checks.
- Maintenance – The work performed to keep equipment operable or to make repairs for deficiencies identified during inspection and testing.

For US wind energy systems, the available NFPA documents provide the industry recognized requirements to maintain the installed fire protection system in operable condition. However, the NFPA documents serve only as baseline requirements and should be modified to fit the need of the offshore wind energy asset. The wind energy system operators may increase the NFPA ITM requirements if the associated risk for a particular component failure is determined to be high with hazardous effect. Similarly, the NFPA ITM requirement may be reduced if the associated risk of failure is low with negligible hazards. Furthermore, the equipment manufacturers and insurance agencies may impose a more stringent ITM requirement compared to the NFPA for warranty and insurance purposes.

Offshore wind operators should create and maintain fire protection ITM documentation that clearly identifies the ITM schedules, frequencies, deficiencies, and corrective actions as well as identifying relevant stakeholders and code modifications. The fire protection ITM must be performed by a qualified person who is competent and capable, has met the requirements and training in servicing a particular fire protection system component, and is knowledgeable regarding offshore wind energy equipment and hazards.

The purpose of fire protection ITM is to document and prevent fire protection system component failures leading to failure in the operation of the fire protection system during an emergency event. The minimum ITM requirements for the fire protection systems discussed in Section 3.0 and Section 4.0 have been compared with the appropriate NFPA documents and references (see Table 9).

Fire Protection Systems	ITM Requirement Reference
Fire sprinkler system	NFPA 25 Chapter 5
Standpipe and hose system	NFPA 25 Chapter 6
Water spray fixed system	NFPA 25 Chapter 10
Water mist system	NFPA 25 Chapter 12
Fire pump system	NFPA 25 Chapter 8
Fire water storage tank system	NFPA 25 Chapter 9
Foam-water sprinkler system	NFPA 25 Chapter 11
Foam monitor system	NFPA 11 Chapter 12
Compressed air foam system	NFPA 11 Chapter 12
Carbon dioxide gas suppression system	NFPA 12 Chapter 4.8
Clean agent gas suppression system	NFPA 2001 Chapter 8
Fire detection and alarm system	NFPA 72 Chapter 14

Table 9 – Fire protection systems and associated ITM requirements

1.5 Industry Survey Questionnaire

An industry survey involving respondents from various areas of the offshore wind energy (including manufacturing, development, utility and consulting) sector was conducted to identify some current industry practices and philosophies. Of the nine participants surveyed, six provided replies. The survey consisted of 20 prompts, with 3 prompts regarding respondent background/experience and 17 prompts involving open-ended questions.

The industry survey focused specifically on fire protection industry norms pertaining to offshore wind energy industry. The responses were used to verify the information gathered and assumptions of fire protection system technology recommendations. A summary of the questionnaire responses is presented below. The full responses are provided in Appendix 8.3, Survey Questionnaires and Answers.

Q1. What international, national, regional, and/or industry fire protection standards do you follow for fire protection of offshore wind turbines and offshore substations?

> The fire protection standards used for the offshore wind energy industry include documents from the following sources: NFPA, DNV, CFR, FM, Underwriters Laboratories (UL), and API. In addition, other international sources may be applicable depending on the wind energy system: VdS Schadenverhütung GMbH (VdS) and EN54. A respondent also listed shipping standards and mobile platforms, which are outside of the study scope: Mobile Offshore Drilling Units (MODU), Safety of Life at Sea (SOLAS), and International Maritime Organization (IMO).

Q2. Do you have internal fire protection standards for protection of offshore wind turbine generators and offshore substations?

The majority of the respondents did not have internal fire protection standards. However, a single respondent indicated “yes.” The internal fire protection standard has not been shared with the research team.

Q3. How would you characterize any differences between the internal fire protection standards and the other international, national, or regional standards used?

One respondent stated that the difference between the standards is significant, especially in terms of the fire protection design parameter. For example, the volume of water demand required by the standards for protection of oil-filled hazards, such as transformers, may be different between NFPA and international counterparts.

Q4. How important is fire protection in your design of offshore wind turbine generators and offshore substations?

All respondents agree that the fire protection is a very import aspect of offshore wind turbines and offshore substations.

Q5. Do you have manned offshore renewable facilities? Do you have different fire protection engineering practices in place when comparing manned versus unmanned facilities?

Two respondents indicated that they have manned offshore facilities. The different fire protection engineering practices for manned and unmanned facilities are applied to helideck, public address, and emergency evacuations.

Helideck fire protection may use fire monitored systems and DIFFS for manned and unmanned facilities, respectively. Public address systems are different and, for an unmanned facility, a procedural precaution such as communication of emergency situation using portable radios may be used instead of a hard-wired fire alarm system. Evacuation is slightly different for manned and unmanned facilities as very few persons for maintenance purposes are expected to be present.

Q6. What are your fire protection engineering practice design requirements for offshore wind turbines and offshore substations?

The respondents are in agreement that fire protection engineering practices use a combination of active fire protection, PFP, and fire risk management procedures.

PFP involves segregation of areas according to the type of activities and the hazard potential. Areas of high risk potential are separated from low risk potential areas. PFP includes fire rated walls, decks, and penetrations.

Active fire protection involves a range of fire protection equipment, each suitable for the intended use and environment. Active fire protection is carried by performing a risk assessment of the protected equipment. This process may involve fire explosion risk analysis (FERA), hazard identification study (HAZID), and/or hazard and operability analysis.

Q7. What types of passive fire protection are used?

The respondents indicated that 1-hour fire rated construction is used with class A-0, A-15, and A-60 fire partitions. A-60 PFP rated assemblies are used around the transformer rooms in walls and the deck of the substation.

Q8. For offshore wind turbine generators, what types of fire protection systems are used?

Three respondents use automatic gas suppression systems and fire extinguishers in offshore wind turbines. The gas suppression system may use NOVEC 1230 or FM200 agent. One respondent indicated that a water mist system is a viable and recommended option for the wind turbine enclosure.

One respondent indicated that the application of a fire suppression system within the wind turbine nacelle should be based on the PBD process that includes fire protection design basis and associated fire risk evaluation. Hazards to be considered include electrical cabinets, equipment containing combustible liquids, and areas with the potential for combustible liquid accumulation.

Two respondents indicated that CO_2 or dry chemical fire extinguishers should be placed throughout the facility in accordance with NFPA 10 and U.S. Coast Guard (USCG) CFR requirements.

Q9. For offshore substations, what types of fire protection systems are used?

Four respondents indicated that a water suppression system, gas suppression system, foam suppression system, and fire extinguishers are used for the offshore substation.

Deluge spray systems are used for oil-filled devices such as transformers and reactors, diesel generator rooms, flammable gas storage rooms, helipad fuel units, and fire water pump rooms. Gas suppression system are provided for battery rooms, control rooms, HV/LV rooms, and sensitive electronic rooms. Foam suppression systems protect transformers and fuel storage tanks. CO_2 or dry chemical fire extinguishers should be placed throughout the facility in accordance with NFPA 10 and USCG CFR requirements.

Q10. Do you have a current ITM program for fire alarm and fire suppression systems for offshore wind turbines and substations?

Three respondents indicated that they have an ITM program. The respondents indicated that the ITM programs are based on the wind energy system operator's requirements and their adoption of various industry standards such as NFPA, VdS, EN, and manufacturer requirements.

Two respondents indicated that an ITM program based on industry standards is followed. One respondent indicated that an internal corporate ITM program is followed. The corporate ITM program has not been shared with the research team.

Q11. What is the water supply for the water-based fire protection system?

Two respondents indicated than an on-site freshwater storage tank provides the supply for the water-based fire protection system.

The survey respondents did not indicate if seawater supplies the firefighting systems for wind turbines or substations; however, oil and gas platforms use seawater fire pumps. The offshore substation engineering practices discourage the use of seawater for firefighting purposes due to corrosivity and potential damage to the electrical power transmission and distribution systems.

Q12. For offshore wind turbine generators, what types of fire detection systems are used?

Three respondents indicated that smoke/heat detection, linear heat detection, and aspirating smoke detection systems are provided for the offshore wind turbine generators. The location of the smoke/heat detection is provided in accordance with NFPA 72 to protect the gearbox lubrication system, hydraulic control system, and transformers located within the turbine enclosure. Two respondents indicated that flame detection is used within the turbine enclosure.

Q13. For offshore substations, what types of fire detection systems are used?

> Four respondents indicated that smoke/heat detection, linear detection, aspirating smoke detection, visual flame detection, and manual activation are provided for offshore substations.
>
> Smoke/heat detection is located in accordance with NFPA 72 to protect various enclosed spaces located in the offshore substation. Visual flame detection is used for open decks and open areas. Manual activation points are located at the entrance of rooms with active fire protection systems and spaced according to API guidelines.

Q14. Do you provide smoke ventilation systems for wind turbine generators or offshore substations?

> Four respondents indicated that no smoke ventilation systems are used in the offshore wind turbines and offshore generators.

Q15. Is the fire alarm system centralized and monitored with a SCADA system?

> Four respondents indicated that the fire alarm system is monitored by a SCADA system.

Q16. What do you see as the primary fire risk for the unmanned wind turbine generators and/or offshore substations?

> Two respondents indicated that oil-filled equipment such as transformers and reactors present the primary fire risk for offshore wind turbines and substations. One respondent indicated that rotating equipment and loose electrical connections are a fire ignition risk.
>
> One respondent indicated that asset protection and continuing operation is important. The respondent also indicated that the occupancy risks are reduced because of the unmanned nature of wind energy systems.

Q17. Have you experienced a fire loss in an offshore wind turbine generator or offshore substation?

> All respondents indicated that they have not experienced a fire loss.

2.0 OFFSHORE WIND ENERGY FIRE IGNITION SOURCES AND FUEL LOADS

2.1 Fire Ignition Sources and Fuel Load

Offshore wind energy systems differ from traditional power generation systems in terms of fire hazards on account of the high concentration of ignition sources and fuel load. In addition, the remote nature and lack of available firefighting resources increase the risk of total loss scenarios.

The fire losses in the wind energy system may occur in the following locations: wind turbine nacelle, wind turbine tower and base, and wind turbine power substation. Each location presents unique ignition source and fuel loads. The offshore wind energy industry uses the horizontal axis wind turbine (HAWT) type—vertical axis wind turbines (VAWTs) are not typically used. The discussion of ignition sources and fuel loads focuses on HAWT types.

2.2 Historical Fire Loss Incidents

A few selected case studies highlighting ignition and fuel sources were extracted from various literature sources and are presented in chronological order. Few publicly available fire cases for offshore wind energy systems are known. It is hypothesized that many offshore fires are not made public given the remote nature of the infrastructure, which is not easily visible to the public. Given this limitation, the selected case studies include both offshore and onshore wind energy systems. The wind energy system principal function between the offshore and onshore systems is similar. However, offshore wind energy systems are an emerging technology with limited regulatory and manufacturing experience and they operate under very harsh environmental conditions. The risk of malfunction and fire loss is hypothesized to be higher compared with the onshore counterparts [1].

Nissan Factory, Sunderland, UK, 2005

The Nissan Factory completed its first privately owned wind turbine energy system in 2005. The wind energy system at the time consisted of 10 Vestas wind turbines producing a total of 6.6 megawatts (MW) of power [2]. The wind farm is enclosed entirely within the Nissan industrial area.

On December 23, 2005, at 12:30 p.m., a fire occurred on the nacelle of the wind turbine. The fire propagated such that all three of the 75-foot fiberglass blades fell off the structure. The local emergency authorities closed off adjacent roadways, fearing that the wind turbine structure could fall onto nearby roads.

Nissan indicated that an oil leak was detected the previous day. The wind turbine caught on fire when the turbine restarted after the repairs were made. An investigation revealed that a loose bolt jammed a rotating mechanism, which resulted in the overheating of the turbine brakes [3]. The fire resulted in the total loss of the wind turbine.

Maple Ridge Wind Farm, New York, US, 2009

The onshore Maple Ridge Wind Farm was completed and became fully operational in 2006. The wind farm is owned and operated by Avangrid Renewables and EDP Renewables North America. The facility consists of 195 Vestas model V82 1.65 MW wind turbines with a collective energy output of 322 MW [4].

On October 14, 2009, a fire broke out on a transformer located within the wind turbine in the late afternoon. The local fire department was dispatched to the substation around 5 p.m. Firefighting operations were withheld until the substation was deenergized [5]. The fire resulted in total loss of the transformer and damaged the substation building.

Windpark Groß Eilstorf, Lower Saxony, Germany, 2012

The onshore Windpark Groß Eilstorf project was completed and began full operation in 2012. The wind energy system consists of 17 Danish Vestas V-112 3 MW wind turbines, with a total collective energy output of 51 MW [6].

On March 30, 2012, one of the newly installed wind turbines caught fire (Figure 2). The subsequent investigation found that the fire started in the harmonic filter due to a loose connection in the electrical system, which created an arc flash. Vestas has responded to the issue by using a different type of washer on the electrical connection in the wind turbine's harmonics filter to prevent further accidental arc flashes. The fire resulted in a total loss of the nacelle. The wind turbine nacelle and the blades were replaced and recommissioned [7].

Figure 2 – Windpark Groß Eilstorf wind turbine fire [8]

SPIC Binhai North, Jiangsu Province, China, 2017

The Binhai wind farm project was completed in 2016. It is operated and owned by the State Power Investment Corporation (SPIC), was designed by Ramboll, and constructed by Huadian Heavy Industries. The wind farm consists of 100 offshore turbines and an offshore substation with a capacity of 400 MW. The wind farm is located 22 kilometers (13.7 miles) off the coast of Jiangsu Province [9].

On July 14, 2017, a fire broke out on a manned offshore substation because of a lightning strike, which caused a failure of a 35 kV cable (Figure 3). The substation staff attempted firefighting operations but could not control the fire and abandoned the substation. The local maritime authority extinguished the fire and rescued 18 of 19 substation staff [10]. The fire resulted in a total loss of the offshore substation and one fatality.

Figure 3 – SPIC Binhai North offshore substation fire [10]

Ipswich, Massachusetts, US, 2018

This incident involved an onshore wind turbine constructed by D&C Construction that was privately owned by Ipswich Wind Independence, LLC. The town of Ipswich agreed to purchase power from the private wind turbine at a fixed rate for 20 years [11].

Around 1:35 p.m. on October 18, 2018, wind turbine staff reported an electrical fire to the local fire dispatch center. The staffer indicated that he had no fire extinguisher when the incident was reported. The fire was confined to the electrical equipment at the bottom of the wind turbine prior to the extinguishment. The smoke filled the tower and eventually vented from the top of the 260-foot structure [12]. The fire resulted in a total loss of the wind turbine.

2.3 Fire Ignition Sources in Offshore Wind Turbines and Substations

Multiple possible ignition sources are present in offshore wind turbines and substations that may result in a fire event. Most common ignition sources include lightning strike, equipment malfunction (electrical or mechanical), hot surface ignition, and hot work [13]. Other less common sources of ignition include human error, cable failure, and battery failure. Each wind energy component is susceptible to different modes of ignition based on equipment design and personnel accessibility. This section examines offshore wind turbine and offshore substation components and potential modes of ignition.

2.3.1 Fire Ignition Sources and Fuel Loads in Offshore Wind Turbine Components

The components within the offshore wind turbines are identified with potential ignition sources and fuel loads that may trigger a fire event. Refer to Figure 4 for a diagram of offshore wind turbine components, ignition sources, and fuel loads.

Blade and Nacelle Cover

Lightning is the most common ignition source for offshore wind turbines based on incident reports [14]. In conjunction with operating in very challenging weather conditions, the height of the wind turbines has historically been increasing and is projected to reach a hub height of 495 feet and rotor diameter of 820 feet by 2035 [15]. The combination of these two factors, height and weather conditions, vastly increases the risk of lightning strikes.

Lightning protection is required by applicable standards and guidelines. However, failure of the lightning protection system can occur as a result of improper manufacturing, external damage, moisture ingress, blade surface erosion, or detachment of lightning diverter strips. Failure of lightning protection may provide an ignition source through the overheating of the strike surface, causing ignition of the surface material. Another cause for ignition is short circuit and failure of the nacelle internal electrical components, creating an ignition source through electrical arcing.

The wind turbine blade and the nacelle cover pose the largest fuel load on the exterior of the assembly. They are typically constructed of a composite material composed of fiberglass and epoxy resin. Some manufacturers incorporate composite material, that is, carbon fiber with polyester resin. Although fiberglass and carbon fiber are not flammable, the composite is flammable through the vaporization of the resin material. Miscellaneous combustible storage within the nacelle, such as staging equipment, trash, waste oils, and cleaning oils, provides additional fuel load within the nacelle.

The most significant fuel load within the wind turbine is the presence of lubricating oil, cooling fluid, and transformer insulation oil. These flammable liquids provide the fuel load necessary for an incipient fire that may eventually ignite surrounding combustibles and the external composite construction.

The nacelle construction may also incorporate non-combustible acoustical foam [1]. Oil leaks or oil spillage may contaminate the acoustical foam, creating a flammable fuel. The wind turbine hydraulic system contains approximately 85 gallons of hydraulic oil [16], which is classified as a combustible Class IIIB liquid, according to NFPA 30.

Control System

The control system houses the offshore wind turbine SCADA system for system control and data acquisition. The control system contains manufacturer hardware designed to interface with sensors and auxiliary systems for the wind turbines. It also may house an override safety system designed to protect against SCADA or operator error.

HV conduits are not anticipated to be used within the control system. Nevertheless, the electrical system contained within may fail because of a loose connection, component failure, or improper maintenance, which can cause a short circuit or hot surface and lead to ignition.

The control system also may house a UPS battery backup system. Common battery types found for UPS systems are lead-acid and lithium-ion type, provided with combustible electrolytes. The battery or the battery charger may fail, providing an ignition source through electrical arcs, super-heated gases, and/or hot surfaces.

The control system is composed of cabinets housing the SCADA equipment and other auxiliary equipment. The main fuel load is polymers used for cabinet housing and components and electrical cabling.

Generator and Gear Box

The generator system converts the rotational wind turbine mechanical energy to electrical energy. A coupling is provided that connects the generator system to the gearbox. The generator and the converter system are provided with a cooling system. Currently, two types of cooling systems exist: air cooling and liquid cooling. An air cooling system operates by opening the nacelle to the external environment, with mechanical fans forcing air over the components. A closed-circuit liquid system removes heat from the lubrication oil through a heat exchanger. The heated cooling medium will be pumped into a radiator to remove the heat to the exterior. Commonly used cooling liquid mediums include oil and a water/ethylene glycol solution [17].

Equipment malfunctions, such as a cooling system failure, may result in a hot surface that leads to fire ignition. The partially exposed junction between the generator and power cables, connected by bushings, is an ignition source where a damaged bushing may fail and cause an arc flash within the nacelle. Potential hot work required to repair a damaged generator system is another source of potential ignition. Human error, such as improper maintenance or repair work, may damage the generator and the inverter system, leading to cascading failures of the turbine components and ultimately to ignition.

The gear box converts the rotational speed provided by the wind turbine blades at about 5 to 15 rotations per minute (rpm) into a speed of 600 to 1,500 rpm through the step-up gear drives. The gear box is provided with lubricating oil. In cold climates, the lubricating oil must be heated prior to wind turbine startup. A cooling system is also provided, which is commonly combined with the generator cooling system.

The gear box is a potential source of a hot surface where high temperatures may occur if there is a cooling system failure. Another source of a hot surface is a brake system malfunction in high wind conditions where the breaks are unable to stop the rotation of the wind turbines, causing elevated temperature through friction. Faulty repair work on the gear box, such as loose components, may cause cascading failures that result in hot surfaces. Hot work that may be required for gear box repair is another source of potential ignition.

The largest fuel load provided by the generator and the gear box system is the synthetic lubrication oil. Typical wind turbines use between 30 and 200 gallons of lubrication oil contained within the nacelle [18] [19]. The lubrication oils have high flash points of approximately 410 degrees Fahrenheit (°F) [20] and are classified as a Class IIIB combustible liquid, according to NFPA 30. A liquid cooling system of approximately 50 gallons of cooling oil or water/ethylene glycol solution is provided [16]. Water/ethylene glycol, depending on the solution ratio, has the potential to contribute to the fire growth.

Personnel Access and Tower

Personnel access for large offshore wind turbines is provided by ladders and elevator systems. The elevator motor may fail and cause a hot surface for ignition.

The tower is typically constructed with noncombustible materials such as steel. However, within the personnel access tower, electrical power cables span between the nacelle and the tower base. The power cables are typically encased within a bus system that provides an increased level of fire resistance. The polymer cable insulation may serve as a fuel load if a fire from the nacelle or tower base equipment spreads into the tower cavity.

The fire risk within the wind turbine tower is low due to lack of power transmission equipment.

Power Take-off

Power take-off equipment consists of a power converter, transformer, switchgear, and power cables. The current generation of the wind turbine energy system uses an AC-DC-AC power converter system. A step-up transformer is provided for easier distribution to the offshore substation. Switchgear acts as a circuit breaker to isolate the wind turbine in the event of a power fault; air-insulated or gas-insulated switchgear may be used. Power cables are connected to the converter and the switchgear system by bushings.

Given the equipment involved, multiple modes of ignition exist for the power take-off equipment. A cooling system must be provided for the power converter and step-up transformer. A failure in the cooling system may lead to overheating of system components and result in equipment failure (electrical arcs through exposed junctions). Electrical arc flash is also possible when improper procedures are followed when servicing the switchgear cabinets. Power cable connections to equipment, notably bushings, are prone to failure as a result of improper manufacturing or mechanical damage, leading to electrical arcs and arc-flash potential. For gas-insulated switchgear, loss of the insulating medium may lead to electrical arcs providing a source of ignition. Any hot work required for repair is another potential ignition source.

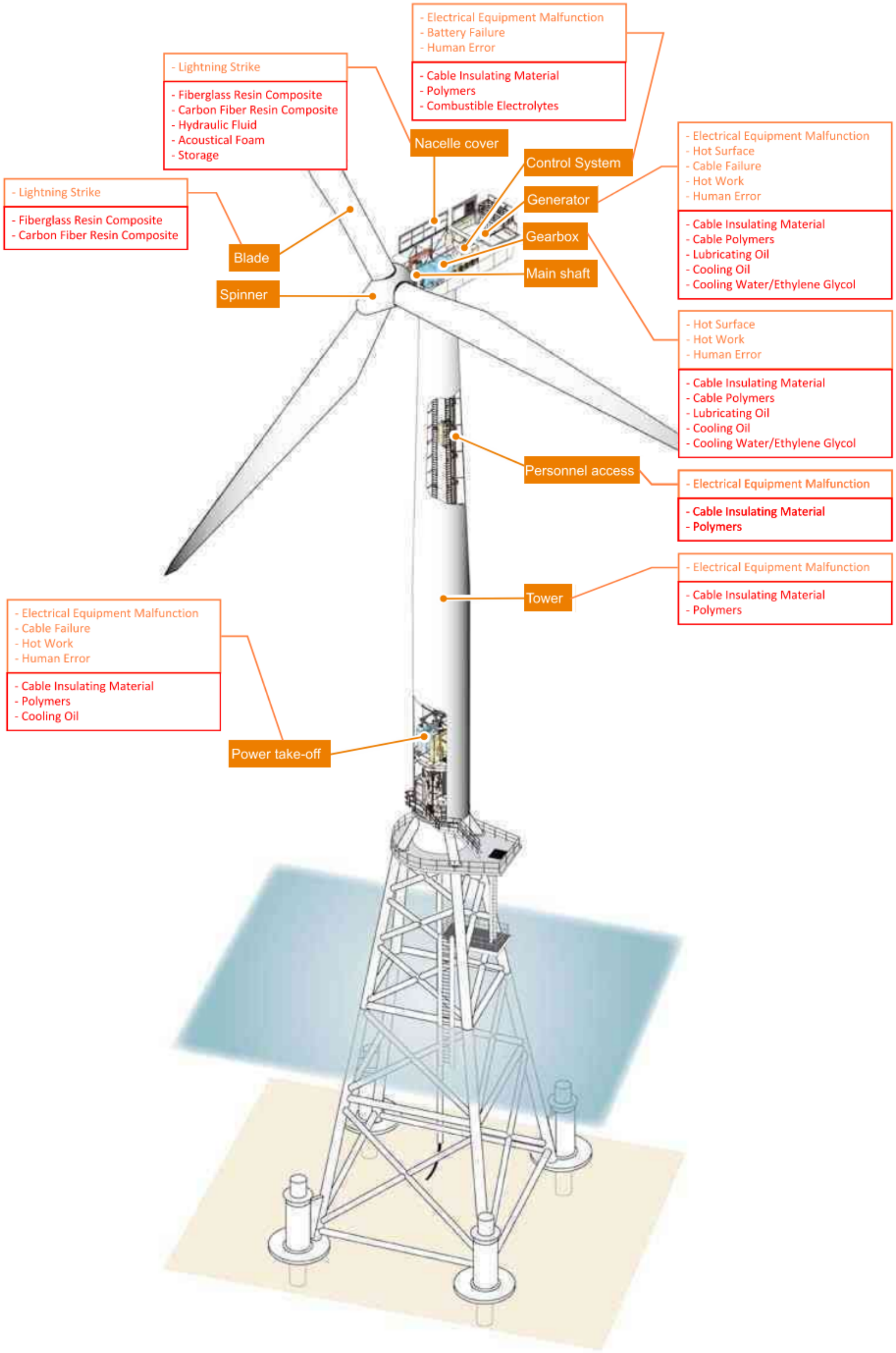


Figure 4 – Offshore wind turbine components (Source: The Crown Estate [21]), with the ignition source noted in the top box and the fuel source in the bottom box

The power converter and the switchgear fuel loads are increased by power cable insulation and polymers. The step-up transformer used within the turbine system may employ air cooling or oil cooling, depending on the manufacturer. The fuel load for an air-cooled transformer is minimal and consists of electrical cable insulations. Oil-cooled transformers containing 300 to 600 gallons of combustible oil are the most significant fuel load for the wind turbine.

2.3.2 Fire Ignition Sources and Fuel Loads in Offshore Substation Components

The components within offshore wind substations include potential ignition sources and fuel loads that may trigger a fire event. Refer to Figure 5 for a diagram of offshore wind substation components, ignition sources, and fuel loads.

Common ignition factors within offshore substations are lightning strikes, hot work, and human error. These ignition sources are applicable to various equipment and processes that exist in the substation.

Lightning strikes are the most common ignition source and may cause dielectric faults, cable insulation breakdown, and electrical surges. Hot work is a high-risk operation that unites oxygen, fuel, and ignition. Direct and indirect application of heat in conjunction with generated sparks traveling to a distant fuel source may cause ignition long after hot work has been completed. Human error, such as loose electrical connections and improper maintenance, may cause electrical arcs and overheating of electrical components. Forced manual emergency switching operations and maintenance work on life electrical equipment have the potential to create arc flashes. These common ignition sources are applicable to the entire substation.

Control Container

The offshore substation's primary function is to reduce the electrical losses caused by transmission of power to the onshore substation. The substation acts as a node in which the generated power from the wind turbines is collected and the low voltage generated by the wind turbines is stepped up to higher voltage and transmitted with lower power losses.

The control container houses SCADA and communication equipment for substation monitoring and control of the substation electrical transmission equipment. Depending on the substation design, a single control container may house both switchgear and SCADA equipment or separate containers may be provided for each. The control container may house batteries and UPS systems for backup operation.

The primary ignition source within the control container is an electrical equipment malfunction. The SCADA and communication equipment operate with low voltage. However, ignition may still occur on account of improperly manufactured devices, loose connections, or electrical wire failures leading to short-circuit electrical arcs and hot surfaces. Switchgear, when provided, has HV transmission cables connected. An HV cable failure is possible, leading to electrical arcs and overheated surfaces. Where gas-insulated switchgears are provided, loss of the insulating medium may lead to an electrical arc and overheating of the transmission cables. Within the limited workshop and accommodation space, improperly disposed waste may ignite, such as oil-soaked rags.

The fuel load within the control container is composed of polymer materials used in equipment components and electrical cable insulation. Another source of fuel load could arise from unmanaged waste or combustible storage.

High-side GIS and Low-side GIS Container

A gas-insulated switchgear (GIS) consists of circuit breakers and disconnectors insulated by SF_6 gas. GIS is typically constructed with mostly noncombustible materials. Limited fuel loads may be present through cable insulation for HV conduits.

The cable bushings connecting to the GIS are a possible source of failure attributable to faulty manufacturing or physical damage. When bushings fail, electrical arcs are the likely outcome and can lead to ignition of surrounding combustible materials.

Capacitor banks may be provided depending on substation design. Capacitor banks are used for power factor-correction to counteract inductive loading from transmission lines. Capacitor banks could be air cooled or oil insulated, and as with many electronics plastic polymers and cable insulations are used throughout. Loss of cooling may cause capacitor banks to overheat and fail, igniting surrounding combustible materials. Loss connections or improper maintenance may lead to arc flash capable of igniting insulating oil medium.

Step-up Transformer and Shunt Reactors

A large step-up transformer is provided at offshore substations where it is used to step up the low voltage current generated by the turbine to a high voltage for easier power transmission to an onshore substation with lower losses. The transformer is connected by transmission cables in two locations: low side and high side with bushings.

The transformer presents the largest fuel load and presents the most significant fire hazard in the wind energy system infrastructure. Transformers have multiple failure modes in the following components: winding, busing, load tap changer, core components, exterior tank, fault protection system, and cooling system. When these failure modes occur, it has the potential to create high temperature, electrical arcs, and arc-flash.

220/66 kV step-up transformers typically contain approximately 8,000 to 12,000 gallons of oil for insulation and cooling. They are typically nitrogen topped, which provides further insulation. For offshore applications, highly refined mineral oils or synthetic esters are used with flash points of 428°F [22] and 500°F [23], respectively. The oils and esters are classified as Class IIIB combustible liquids in accordance with NFPA 30. Even though the insulating liquids provide excellent fire resistance, transformer failures can create the potential for electrical arcs and arc flashes capable of generating sustained very high temperatures that can easily ignite the fluids.

An oil-cooled shunt reactor of similar construction and hazard to a step-up transformer may be provided for the offshore substation based on offshore wind farm design using very long power transmission lines. The reactor absorbs reactive power generated by capacitance created by the long power transmission lines and regulates power transmission line system voltage thereby increasing the overall system stability.

High-side and Low-side Bus Duct

The electrical transmission cables are protected and encased within a bus duct system, which provides increased fire resistance. However, the exposed connections leading to the transformer with bushings can fail on account of manufacturer defects or physical damage. When failed, electrical arcs and/or arc flash are very likely, leading to ignition of surrounding combustible materials.

The power transmission cables use to connect the offshore wind turbines to the substations are not filled with oil, unlike onshore counterparts [24]. The hazard and fuel load present in the power transmission cables are minimal.

Air Core Reactor

Reactors on the high side of the transformer provide methods to limit voltage spikes. The reactor is constructed of wire coils with HV transmission cables with polymer insulation. The air core reactor performs same function of an oil-cooled shunt, but on more limited scale.

The power transmission cable bushings connected to the reactor are prone to failure on account of faulty manufacturing or physical damage. The HV spikes may significantly heat up the reactors, damaging insulation and leading to electrical arc.

Auxiliary Transformer and Earthing Transformer

A small auxiliary transformer is provided for offshore substations to step down the voltage to power substation equipment. An earthing transformer is a type of auxiliary transformer that provides a ground path to the substation as part of an earthing system.

The auxiliary transformer shares common failure modes similar to its large transformer counterparts. However, each auxiliary transformer contains approximately 200 to 500 gallons of mineral oil or synthetic esters, depending on the required size.

Diesel Generator and Temporary Diesel Generator

The diesel generators provide back-up power to the substation in the event of power loss. Diesel generator failure can result from high temperature and fuel leaks. The offshore substation contains approximately 500 gallons of diesel fuel.

Helipad

The helipad provides an offshore transport helicopter landing platform for the substation. An accident during helicopter operations resulting from human error or equipment malfunction may release fuel onto the platform and provide a source of ignition. Typical helicopter fuel capacities range from 150 gallons for small single-engine crafts and 850 gallons for super heavy engine crafts [25]. Helicopter fuel may be aviation diesel or Jet-A kerosene, a flammable liquid Class II per NFPA 30, depending on the aircraft manufacturer.

Accommodation Container

The accommodation container may be designed to provide temporary or permanent shelter for maintenance personnel. The container can also serve as a refuge area during emergencies. Accommodation areas are prone to general storage and combustible waste build up. Ignition may occur as a result of human error, such as inadvertent cooking operations or smoking.

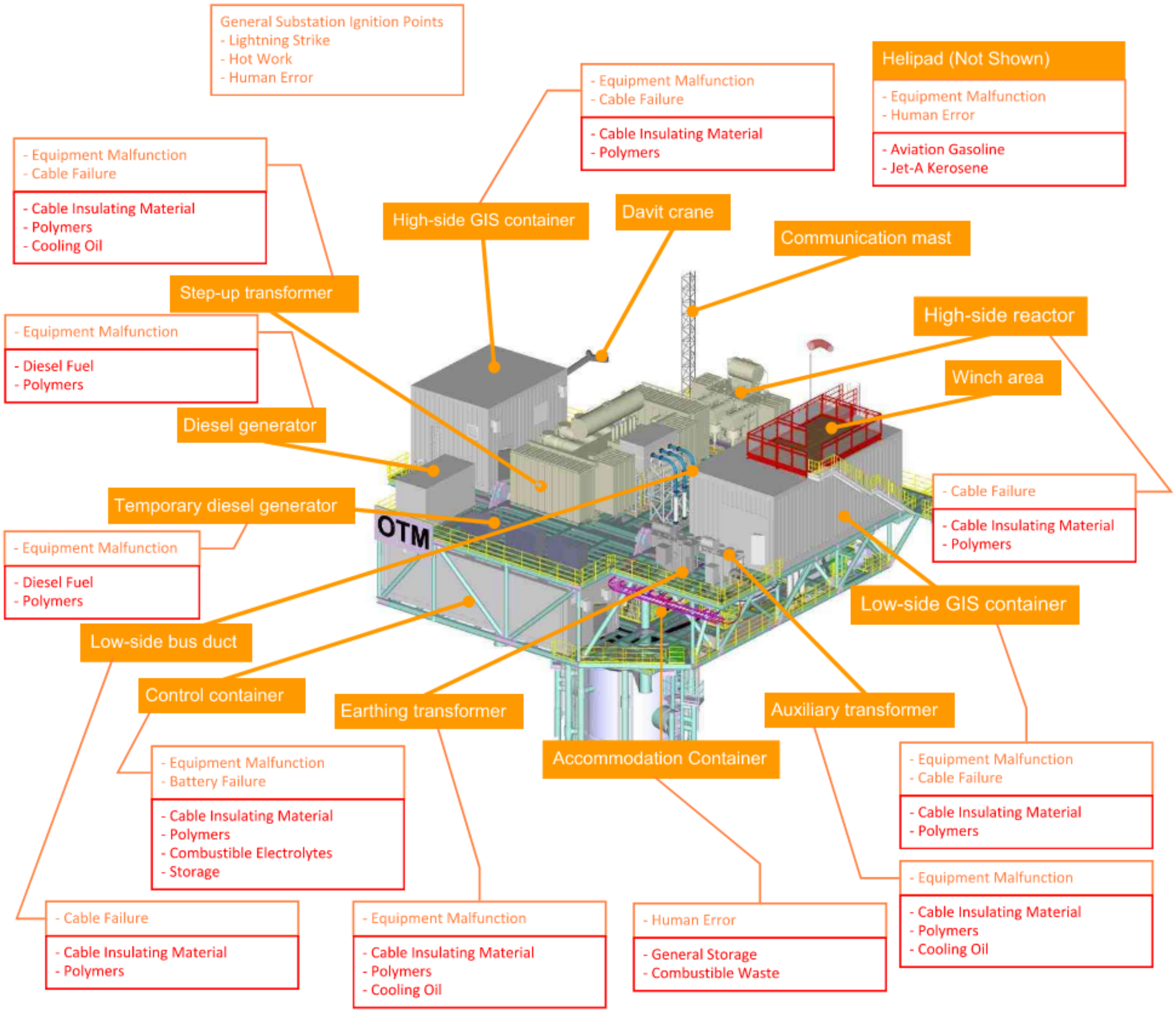


Figure 5 – Offshore substation components (Source: The Crown Estate [26]), with the ignition source noted in the top box and the fuel source in the bottom box

2.4 Fire Protection Philosophy for Offshore Wind Energy Systems

Fire protection engineering refers to the application of scientific and engineering principles, rules, and expert judgement, based on an understanding of the fire phenomena to formulate an engineering solution. The offshore wind energy lacks fully developed prescriptive engineering solutions and instead uses a PBD engineering approach. The offshore wind energy system has the following fire protection challenges that increase the severity of hazards: limited occupant evacuation capacity, concentration and congestion of equipment, harsh environmental conditions, and lack of available manpower. Exterior manual firefighting operations are virtually nonexistent for offshore facilities. A potential fire event that occurs on an offshore wind turbine or substation has the potential to result in a total loss.

The fire protection philosophy for wind energy systems requires a heavy focus on fire prevention, automatic fire suppression, and PFP, with minimized reliance on active exterior firefighting operations. A fire protection approach requires automatic suppression and control of small incipient fires rather than fighting a large, fully developed fire. Nevertheless, an adequate level of fire suppression should be provided for the largest fire that is most likely to occur. The fire protection philosophy is summarized by the following key concepts:

- Minimize fire ignition and growth
- Limit fire consequence
- Ensure rapid fire detection and fire suppression

The application of the fire protection philosophy is challenging for a rapidly developing and emerging industry such as offshore energy. A prescriptive requirement is not likely to keep pace with the technology development and has the potential to become obsolete. Therefore, the fire protection philosophy should place a greater emphasis on a PBD approach based on a fire risk assessment and fire hazard analysis, such that an appropriate fire protection system is applied for the correct hazard mitigation strategy.

It is impractical to assume that a prescriptive regulatory requirement can capture all the fire protection measures needed. Therefore, the fire protection philosophy should take a performance-based approach that allows an appropriate level of fire protection to be applied based on a fire hazard analysis in conjunction with a fire risk assessment.

NFPA 850 is the most relevant existing US standard for the offshore energy industry. The document recommends that the PBD process take the form of a Fire Protection Design Basis Document (DBD) that is developed early in the project where all stakeholders establish the fire protection goals and objectives along with criteria for an acceptable level of fire protection, Figure 1. This document should be referenced throughout the project, such that each identified hazard is addressed either by a prescriptive or performance-based approach that is agreed upon by the stakeholders.

2.4.1 Minimize Fire Ignition and Growth

A fire is a chemical reaction that requires three elements, commonly represented as the fire triangle: heat/ignition, fuel, and oxygen (Figure 6). Effective fire prevention requires removal or reduction of at least one element of the fire triangle. Control of oxygen is not possible for the offshore wind energy industry. However, control of heat and fuel should be taken into account to minimize the possibility of fire and subsequent growth.

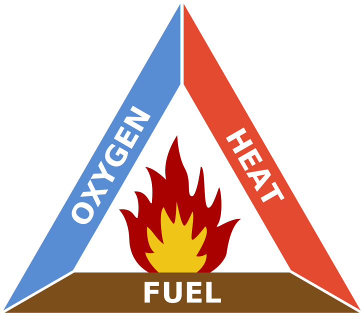


Figure 6 – Fire Triangle [27]

Multiple fire ignition sources are found within an offshore wind turbine and offshore substation (see Figure 4 and Figure 5). Ignition sources include lightning strikes, equipment malfunction, hot surface ignition, hot work, and human error. Of these ignition sources, lightning strikes pose the most prevalent source of ignition. Lightning protection system must be provided. Guidance on lightning protection system is found in DNV-ST-0145 describing recommended engineering practices and refers to local lightning protection regulations. NFPA 780 and National Electrical Code (NEC) provides additional details regarding lightning protection engineering pertinent to US industries. Engineering of lightning protection systems falls outside of fire protection engineering practices.

Equipment malfunction is a significant source of ignition present throughout the wind turbine and substation facility. The electrical system should be designed and installed in accordance with the NEC to provide appropriate seals, materials, enclosures, and construction methods that minimize electrical faults. Methods to identify faults in the system that automatically switch off faulty system components must be provided. Noncombustible metallic electrical enclosures should be used throughout, such that ignition by electrical faults of hot surfaces caused by internal components is contained within the enclosure.

A hot surface ignition hazard is present in the wind turbine nacelle from the gear box and generator. Loss of the cooling system or application of mechanical breaks has the potential for creating a hot surface that could lead to ignition. Another source of a hot surface may occur if mechanical breaks are applied prior to turbine speed reduction through alternative means, such as with blade adjustment and electrical breaks. NFPA 850 §13.3.3 recommends that the braking system be physically covered to isolate the hot surface and possible sparks.

Hot work involving burning, welding, and other heat-producing operations must be avoided to the fullest extent possible. Hot work, by nature, combines all three parts of the fire triangle, posing immediate ignition concerns. Sparks caused by hot work are known to cause incipient fires far away from the work location that can start a fire long after hot work has been finished. If hot work must be conducted, a hot work permit notifying the personnel of the required action and appropriate welding screen use and fire watch should be created. After hot work has been completed, the facility should be monitored closely for any abnormal conditions indicative of incipient fires. Additional guidance on hot work is found in NFPA 51B.

Combustible materials must be reduced to the full extent possible within the wind turbine and substation. Specific storage locations should be designated to isolate the combustible materials.

2.4.2 Limit Fire Consequence

Offshore wind turbines and substations are very congested by nature. If a fire occurs, it has the potential to spread rapidly if adjacent equipment is not designed to resist fire conditions. In addition, for offshore substations, the power transformer central to the transmission process is one of the highest-risk electrical components because of the quantity of oil contained within (approximately 15,000 gallons) and the direct connection with HV equipment. Transformers pose the most prominent fire and explosion hazard within the substation.

To limit the fire consequence, a PFP system should be provided to compartmentalize the facility to slow and contain the fire event. Proper equipment spacing, equipment location, and separation of redundant systems should be considered. If provided, proper containment sizing and appropriate drainage should be considered.

Passive fire protection systems for offshore substations should follow the guidelines set forth in DNV-ST-0145, NFPA 850, and IEEE 979. Each control container shown in Figure 5 should be provided with fire separation. The step-up transformer or oil-filled shunt reactor must be separated from other areas and processes within the substation on account of its fire and explosion potential. Each distinct use area should be protected with fire resistance rated walls. Special consideration should be provided for the mission critical control area and life safety accommodation area.

PFP systems for offshore wind turbines are limited on account of the simplistic nature of construction. Fire separation should be provided between nacelle and the tower to reduce the fire and smoke spread.

2.4.3 Rapid Fire Detection and Fire Suppression

The application of fire detection and fire suppression systems to offshore wind turbines and substations should be based on the result of the fire protection DBD and agreed on by the stakeholders. The DBD should address acceptable losses and protection measures for the likely fire scenarios. In general, where an active fire detection and fire suppression is used, the system should quickly detect and control the fire at the small incipient stage. The relatively large oil-filled equipment requires closer inspection in the DBD process because of its potential for leaks and ability to sustain a fire.

The offshore wind turbine fire locations are likely to be in the nacelle and in the tower base because of the contents and/or equipment. Fire detection and suppression, if provided, should focus on this area. Occupant notification alarms should be provided throughout the facility. Oil-filled equipment includes the generator, gear box, and transformers.

The offshore substation has a more complex arrangement that includes multiple systems in a limited area. An appropriate fire detection system should be considered for each enclosed area. Occupant notification alarms are very low-cost items that are relatively easy to implement and improves overall life safety. Notification systems should be provided throughout the manned substation and is strongly encouraged to be provided for unmanned substations.

A fire suppression system should be provided as a result of the DBD process evaluating the risks and mitigation measures. Oil-filled equipment such as the step-up transformer, shunt reactor, diesel generators, and station service transformers should be evaluated such that they are protected by distance or radiant shielding.

Step-up transformers may use oil, natural ester, or synthetic ester fluid depending on the manufacturer. Each transformer arrangement should be provided with an appropriate fire suppression system unless the DBD process demonstrates that the fire scenario stemming from the insulating liquid can be contained and would not harm surrounding equipment.

2.4.4 Performance-based Design Stakeholder Roles

The fire protection PBD design process requires a holistic approach that involves close coordination between all relevant offshore wind energy stakeholders: AHJ, fire protection engineers, and wind energy owners. The adoption of the PBD design process requires the AHJ to accept a level of performance, considered as a benchmark of acceptable level of fire protection. Fire protection engineers and the wind energy operators must engage with the AHJ at an early concept of the project to develop a consensus of fire protection goals and objectives. All stakeholders involved in the PBD process, must be aware of the risks involved and the rationale of the proposed fire protection engineering mitigating measures. The early engagement between the stakeholders ensures that the goals and objectives developed by the fire protection engineers are acceptable by the AHJ and realistic by the wind energy operators. This process must be documented in the fire protection DBD to ensure commitment to the fire protection goals and objectives throughout the life cycle of the wind energy asset.

The AHJ serves as the approving authority of wind energy asset design that has a stake in fire protection safety. The adoption of fire protection PBD design requires the AHJ to process engineering designs, vet fire engineering reports and studies, and conduct fire protection system acceptance inspections. Regular reviews of the fire protection design and DBD should be conducted to streamline the design process and ensure compliance with the fire protection goals and objectives. The AHJ should aim to create an environment to promote healthy development of the fire protection engineering process. Proactive engagement with wind energy stakeholders through regular technical seminars and meetings is recommended to develop a sustainable fire protection engineering environment, promoting fire safety for the offshore wind energy industry.

Fire protection engineers apply engineering principles, rules and expert judgement based on a scientific understanding of fire phenomena and effects of fires to formulate an engineering solution. Fire protection engineers should be engaged in all aspect of the design, construction, and testing/commissioning as it relates to fire protection and life safety. At the early concept design phase, a HAZID and hazard and operability (HAZOP) study should be conducted to identify all fire risk hazard associated with the offshore wind asset design. Fire protection goals and objectives should be documented and risk mitigating strategies should be proposed based on the identified risks. The proposed risk mitigation strategies must be vetted by using a combination of fire modelling, engineering calculation, and engineering judgement. A DBD should be created by the fire protection engineer documenting the risk analysis and risk mitigation strategies to be approved by the regulators.

The wind energy owners are responsible for maintaining fire safety of the wind energy asset through regular inspection, testing and maintenance. The wind energy owners should engage with the fire protection engineer to aid in the development of the DBD and be fully aware of the associated fire risks and risk mitigation strategies. Based on the finalized DBD, the owners should ensure strict implementation of the developed fire safety strategies throughout the wind energy asset life cycle.

3.0 FIRE PROTECTION ENGINEERING TECHNOLOGIES

The current state-of-the-art fire safety technologies used to protect offshore wind energy facilities have been investigated and compiled, including new technology or approaches that may be under consideration or used in other industries.

3.1 Fire Detection Technologies

Fire detection technologies use various fire signatures such as smoke, heat, and radiation to detect a presence of a fire event. Fire detection, together with fire suppression systems are used to limit the fire and fire growth. Fire detection signals from the FACP are monitored at the CMS, where the protection and control function for the wind energy system can be applied remotely and initiate shutdown procedures. Three main fire detection functions currently exist in the fire protection field: smoke detection, heat sensing, and radiant energy detectors. Each of the detection technologies are further discussed in the following sections.

Smoke-sensing Detectors

Smoke-sensing detectors are designed to initiate fire signals upon the detection of smoke signatures associated with combustion. Three types of smoke-sensing detector mechanisms are briefly described in terms of their operating methods.

Point smoke detectors are ceiling-mounted detectors most used in the fire protection industry. The point smoke detector consists of either an ionization or photoelectric technology within the device's internal detection chamber. An ionization smoke detector uses a harmless radioisotope that detects the presence of smoke through current change via ionized particles. Ionization detectors are more sensitive to flaming fire. A photoelectric smoke detector consists of a light-emitting diode and a photocell that detect the presence of smoke through current change with smoke obscuration. Photoelectric detectors are more sensitive to smoldering fires. For wind energy use, a photoelectric smoke detector is recommended, where applicable, because of the higher likelihood of smoldering fires from heated electrical equipment rather than flaming fires. For this report, a point smoke detector reference refers to a photoelectric type.

Beam smoke detection uses similar operating mechanisms as a photoelectric smoke detector, but the sensing of the smoke occurs in the open air between the light emitter unit and light receiver unit. Beam smoke detection can span long distances—upwards of 500 feet in length.

Aspirating detectors use continuous air sampling through a central detection unit that draws air through a network of pipes to detect a smoke. The sampling chamber uses an aerosol photometer that can detect minute quantities of smoke particles. Aspirating detectors are extremely sensitive and are able to detect a fire at a very early stage, even when smoke is not noticeable by smell or sight. An electrical fire may progress for days prior to emitting sufficient smoke signatures for detection by point smoke detectors. Another advantage is the ability to detect fire in high airflow conditions. Typically, the sensitivity of point detection decreases with high airflow. Aspirating detectors function through the active aspiration of air via sampling pipes.

Heat-sensing Detectors

Heat-sensing detectors are designed to initiate fire signals upon the detection of heat. Three types of heat-sensing detector mechanisms are briefly described in terms of their operating methods.

Point heat detectors are ceiling-mounted detectors that are designed to respond through external thermal energy. Point heat detectors use either fixed temperature (FT) or rate-of-rise (ROR) technology. FT detectors are the most common type of heat detector, using a heat-sensitive alloy that melts with heat to produce a fire signal. ROR detectors detect a rapid rise of temperature and consist of two internal thermocouples to sense temperature differences.

Linear heat detectors operate similarly to FT heat detectors. Linear heat detection includes a two-core cable separated by a polymer plastic insulation. The insulation is designed to melt with external heat. The subsequent short circuit of the two cables provides a fire signal.

Radiant Energy Detectors

Radiant energy detectors consist of ultraviolet (UV) and/or infrared (IR) sensors that detect the radiation emitted by a hydrocarbon fire. Radiant energy detectors may also use video analytics that capture smoke signatures analyzed by computer algorithms.

3.1.1 Fire Detection Technologies for Offshore Wind Turbines

The application of the fire detection technologies for the offshore wind turbine application have been examined. Three main locations of the wind turbines have been identified for fire detection application study. A summary of fire detection technology application to offshore wind turbine structure is shown in Table 10. Overall, beam smoke detectors and radiant energy detectors are not recommended on account of the relatively confined architecture of the wind turbine. A narrow body creates an environment where beam smoke detectors of UV/IR detectors cannot function as intended. Heat detectors are generally slow to respond compared to point smoke detectors and are not recommended.

Aspirating smoke detectors are recommended for the nacelle. The nacelle has several characteristics in which aspirating smoke detectors provide significant advantages to the other detectors. In nacelles, the mechanical and electrical components are condensed into a small enclosure with very high airflow.

The wind turbine tower is a long shaft and may reach a height of up to 500 feet. Fire detection may not be needed due to low ignition risks and fuel loads. If detection is desired, a linear heat detection system can provide limited fire detection for the shaft by locating the sensing wire close to the power cables. Smoke or heat sensing detectors are not recommended due to the stack effect created by the tall open shaft that causes smoke stratifications.

The tower base houses important wind turbine power takeoff equipment. If the tower base is provided with a separated ceiling from the tower, point smoke, point heat, or aspirating smoke detection systems can be provided. An aspirating smoke detection system is recommended for the nacelle and the tower base since it can detect fires at their incipient stage and provides an additional flexibility to monitor individual cabinets via sampling tubes.

Location	Point Smoke Detection	Beam Smoke Detection	Aspirating Smoke Detection	Point Heat (FT) Detection	Point Heat (ROR) Detection	Linear Heat Detection	UV/IR Radiant Energy Detection
Nacelle	Not suitable	Not suitable	Preferred	Not suitable	Not suitable	Not suitable	Not suitable
Tower	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Preferred	Not suitable
Tower Base	Suitable	Not suitable	Preferred	Suitable	Not suitable	Not suitable	Not suitable

Table 10 – Offshore wind turbine fire detection application suitability chart

3.1.2 Fire Detection Technologies for Offshore Substations

The typical offshore substation offers a more complex architecture with different components installed on the topside structure. The offshore substation is provided with separate distinct containers that house different substation equipment and processes. It is anticipated that there will be various containers that house different electrical transmission equipment depending on the substation design and manufacturer. Fire detection of these miscellaneous containers will vary depending on whether the containers are conditioned or unconditioned. The main step-up transformer and helipad are exposed to the environment. The substation may also be provided with miscellaneous external areas that are composed of electrical distribution cables/bushings, backup generators, station service transformers, and reactors. The summary of recommended fire detection technology application to offshore substation is shown in Table 11.

For the offshore substation, beam smoke detectors and linear heat detectors are not recommended given the complex, small, and congested architecture.

The control container is provided with SCADA, communication equipment, and wind energy system control equipment. Because of the various system equipment environment requirements, the control container is likely to be conditioned. A point smoke detector or aspirating smoke detection can be provided. The aspirating smoke detection is recommended over the smoke detector on account of the faster response times.

A point smoke detector is recommended for the accommodation container for offshore maintenance personnel and other miscellaneous containers, if conditioned. Point heat detectors are recommended for electrical transmission containers and other miscellaneous containers that are unconditioned. Aspirating smoke detectors could also be provided for these containers; however, these areas are expected to have simple open ceilings with low fuel load and importance where the benefits provided by aspirating smoke detectors are not as apparent.

Visual radiant energy detectors provide excellent fire detection for exposed open areas of the substation that include the step-up transformer, helipad, and other miscellaneous exposed areas. Unlike the smoke sensing and heat sensing detectors, radiant energy detectors can operate in open exposed conditions without the need for active collection of smoke or heat via enclosed spaces. If the transformer is housed in an enclosed container, an aspirating smoke detection is recommended. Similarly, ROR heat detectors could be provided for the step-up transformers and shunt reactors.

Location	Point Smoke Detection	Beam Smoke Detection	Aspirating Smoke Detection	Point Heat (FT) Detection	Point Heat (ROR) Detection	Linear Heat Detection	UV/IR Radiant Energy Detection
Control Container	Suitable	Not suitable	Preferred	Not suitable	Not suitable	Not suitable	Not suitable
Accommodation Container	Preferred	Not suitable	Suitable	Suitable	Not suitable	Not suitable	Not suitable
Electrical Transmission Container (GIS)	Not suitable	Not suitable	Suitable	Preferred	Not suitable	Not suitable	Not suitable
Misc. Containers (Conditioned)	Preferred	Not suitable	Suitable	Suitable	Not suitable	Not suitable	Not suitable
Misc. Containers (Unconditioned)	Not suitable	Not suitable	Suitable	Preferred	Not suitable	Not suitable	Not suitable
Step-up Transformer	Not suitable	Not suitable	Preferred (Note 1)	Not suitable	Suitable	Not suitable	Preferred
Helipad	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Preferred
Miscellaneous External Areas	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Preferred

Note 1: For enclosed transformers in containers

Table 11 – Offshore substation fire detection application suitability chart

3.2 Fire Suppression Technologies

Fire suppression technologies are designed to release a suppression agent to control a fire upon fire detection system activation that requires no human intervention. The types of fire suppression technologies are organized by the type of suppression media.

Water Suppression System

A water-based fire sprinkler system is the most used fire suppression system throughout the fire protection industry. The fire sprinkler system controls the fire by directly cooling the fire. It relies on a water supply system that provides adequate pressure and water flow to a piping system, where each fire sprinkler is connected. A wet-pipe fire sprinkler system is connected to pipes that are filled with water with closed fire sprinklers equipped with heat sensitive elements. The system releases water automatically when the heat generated from a fire opens the sprinkler heat element. A pre-action sprinkler system is filled with compressed air with closed sprinklers, and the water is held back by a pre-action valve. A pre-action sprinkler system is used in-lieu of wet-pipe sprinklers when the system is exposed to freezing ambient temperatures or if water filled pipes are not desirable due to the type of equipment being protected.

A water spray system is a modified water sprinkler system where specialized fire sprinklers are used to spray the water in specific directions to protect against three-dimensional hazards such as step-up transformers and shunt reactors.

A water mist system consists of specialized fire sprinklers in conjunction with high-pressure fire pumps to generate water mist with droplet sizes less than 1,000 microns in diameter. As an alternative to the high-pressure fire pumps, nitrogen gas cylinders may be used to generate the required pressure. The water mist system does not wet the protected surface and extinguishes the fire by cooling the fire via entrainment of water mist particles into the fire and/or plume. A water mist system can be used in-lieu of conventional sprinkler systems but is often seen where water supply is limited or where water damage to sensitive electronics would be detrimental to mission continuity.

A fire water tank system and fire pump system are required to supply the water and pressure to water-based fire suppression systems. A freshwater tank is recommended as a suitable water supply. Drawing seawater for fire suppression is possible but is not recommended due to potential damaging properties of corrosive seawater to the power transmission equipment. A fire pump system should be provided with engineered redundancy. The redundancy could be provided with a primary and backup fire pump using an electric motor and diesel engine, respectively. As an alternative, a single electric motor driven fire pump could be provided using two station service transformers with independent power source taken from the offshore wind farm.

Foam Suppression System

A foam suppression system delivers a mixture of foam concentrate and water through specialized nozzles/sprinklers to separate the fuel source from the fire and to provide cooling. Foam suppression systems are an excellent fire protection technology to control Class B combustible and flammable liquid fires. Although many different types of foam generation technologies are available for fire protection, foam-water and air-compressed foam are best suited for offshore wind energy systems.

A water monitor system, also referred to as a deluge gun, is an aimable and controllable high-capacity water jet used for manual firefighting purposes. For the aviation and marine industries, the monitors combine water with a foam concentrate to create a foam solution. The monitors can be arranged as an automatic fire protection system; however, monitors are only recommended for a manned substation where they can be directly controlled by trained emergency response personnel.

A foam-water system is a type of water spray system where water is combined with a foam concentrate to generate a foam solution. A fire pump is required for a foam-water system on account of the high pressure requirement. For helipad protection, foam-water suppression system nozzles may be provided on the landing platform.

A compressed air foam system contains a mixing chamber with rotary air compressor. The resulting foam has a more homogeneous foam structure that can absorb more heat compared to a water-based fire suppression system. The water demand is vastly decreased compared to a foam-water spray system (Table 18). A fire pump is required to provide the required pressure.

For helipads, foam-water system application is achieved using a DIFF system using water spray system, foam-water spray system, or compressed air foam. For offshore applications, a DIFF system using compressed air foam system is preferred because of the lower water demand and ease of containment. The DIFF components consist of recessed nozzles that are integrated into the helideck surface. Upon introduction of pressure and water, the recessed nozzles pop up and provide a vertical paraboloid distribution of extinguishing agent throughout the helipad landing area. If the fire protection PBD process determines additional cooling is required due to the size of the expected aircraft, a DIFF using a foam-water spray system supplied by a seawater fire pump is suitable. A manual DIFF activation is recommended for manned substations. An automatic DIFF activation using UV/IR radiant flame detectors is recommended for unmanned substations.

Gas Suppression System

A gas suppression system consists of inert gases or gaseous chemical agents to extinguish a fire that does not leave a residue upon discharge. Gas suppression systems can be arranged to provide total flood protection for the entire volume of enclosed area such as nacelle or cabinet protection for individual electrical and communication cabinets. The application of the gas suppression system arrangement must be based on fire protection PBD process for the type of equipment being protected. For offshore wind turbines, total flood protection provides suitable fire protection for fires involving oil-filled equipment with leaking combustible oils. For offshore substation, total floor protection is suitable for container level protection housing sensitive communication equipment and UPS systems, where fire can occur outside of individual cabinets. Cabinet level protection may be more suitable for protection of oil-filled capacitor banks with well-defined enclosures.

Common clean agents used are FM 200, 3M Novec 1230, and Inergen. FM 200 and 3M Novec 1230 are chemical gas suppression systems that extinguish a fire by using the gaseous agent to quickly absorb the heat from a fire. Inergen is a mixture of nitrogen, argon, and CO_2 that extinguishes a fire by lowering the oxygen content below the level that supports active combustion. The production of FM 200 clean agent is currently being phased down as a result of the American Innovation and Manufacturing Act of 2020 due to its high global warming potential.

Gas suppression systems can also use compressed CO_2 gas for fire suppression. CO_2 is considered a clean agent that extinguishes a fire by lowering the oxygen content. Special life safety considerations must be taken when using CO_2 because it is highly toxic to humans in high concentrations and has a history of lethal accidents.

Gas suppression system requires a level of enclosure integrity where the gas suppression systems have to be designed in relation to the discharge agent hold-time. Enclosures must be sufficiently leak free to hold the gaseous agent to extinguish the fire and withhold against peak discharge pressure that may destroy the enclosure integrity.

Powder Suppression System

A powder suppression system uses aerosolized particulates to extinguish a fire and is usually self-contained with a fire detection and suppression media. The powder suppression system typically consists of compressed nitrogen cylinders to discharge the extinguishing medium.

A dry chemical powder system releases the extinguishing media such as sodium bicarbonate or mono-ammonium phosphate to extinguish the fire. When heated, sodium bicarbonate produces carbon dioxide gas that suffocates a fire. Mono-ammonium phosphates adhere to the fuel, separating the fire from the fuel source.

An aerosol system is a relatively newer technology that uses an aerosol-generating chemical consisting of an oxidizer, combustible binder, and additives. Once activated, an internal combustion takes place within the aerosol system that generates potassium carbonate, carbon dioxide, nitrogen, and water. The combustion generates positive pressure within the system that propels the extinguishing medium.

3.2.1 Fire Suppression Technologies for Offshore Wind Turbines

Offshore wind turbines challenge the effectiveness of fire suppression systems through their confined spaces, very tall shafts, concentration of sensitive electronics, and exposure to cold temperatures. Table 12 summarizes applicable fire suppression technology identifying suitable and recommended technology for the wind turbine components.

The nacelle is located approximately 500 feet above the tower base for the largest offshore wind turbines. Water and foam-based fire suppression systems that require significant amounts of water delivered to the fire are not suitable for this environment on account of height limitations and lack of available equipment space. Powder suppression systems are not recommended on account of the inadvertent potential damage caused by aerosolized particulates to sensitive electronic systems.

For nacelle protection, a fire suppression system that does not require a fire pump and can self-propel extinguishing media is suitable. A water-mist suppression system utilizing nitrogen as a propellent or gas suppression system is suitable. Given the potential operation in below-freezing weather conditions, water storage tank must be heated to prevent freezing. Clean agent systems and water mist systems offer protection of the nacelle with a compact footprint and resistance to below-freezing weather conditions. If a fire suppression system is applied to the nacelle, a clean agent system is recommended.

The wind turbine tower, because of its architecture, is very difficult to protect with a fire suppression system. However, the tower is characterized by low fire risk with low combustible fuel loads. Fire suppression system may not be warranted.

The tower base holds key power take-off equipment vital for wind turbine operation, power transmission, and communication equipment. A water and foam-based fire suppression system is a suitable candidate but would require a fire pump and water source. A water-mist system or gas suppression system are recommended.

Location	Water Sprinkler	Water Spray	Water Mist	Foam-Water	Air-Foam	CO_2 Gas	Clean Agent Gas	Dry Chem. Powder	Aerosol Powder
Nacelle	Not suitable	Not suitable	Suitable	Not suitable	Not suitable	Suitable	Preferred	Not suitable	Not suitable
Tower	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable
Tower Base	Suitable	Not suitable	Preferred	Not suitable	Not suitable	Suitable	Preferred	Not suitable	Not suitable

Table 12 – Offshore wind turbine fire suppression application suitability chart

3.2.2 Fire Suppression Technologies for Offshore Substation

The architecture of the offshore substation is provided with containers housing power transmission, communication, and accommodation containers. The offshore substation open platform deck may house exposed power transmission equipment, power transmission and communication lines, and accessory substation equipment. In addition, the offshore substation may be equipped with a helideck.

The application of fire suppression systems should be based on the fire protection DBD process where the fire risk and mitigation measures are compared and selected to provide the appropriate level of fire protection. Some substation power transmission fire hazards may be sufficiently addressed with protection measures such as a power disconnect system with the acknowledgement that risk of fire ignition to surrounding materials is low. Similarly, no fire protection system may be needed for accommodation and shelter containers if the fire hazards are addressed by operating procedures, separation of ignition and fuel, and handheld manual extinguishers. Table 13 summarizes the suitable and recommended fire protection technology.

In general, a powder suppression system is not recommended for offshore substations because of inadvertent damage to sensitive electronic equipment by the aerosolized particles. Minimal benefit is gained by providing a full fire suppression system for the entirety of the substation open platform deck. Equipment and processes on the open platform deck include power transmission lines, communication lines, exposed power transmission equipment, and accessory substation equipment. The benefit gained by active suppression systems of these equipment and processes is minimized on account of exposed weather conditions and hindrance to substation operation. Passive protection described in Section 3.3 is better suited.

Water-based suppression systems are suitable for the protection of various areas of the offshore substation that include the control container, accommodation container, electric transmission equipment container, and other miscellaneous conditioned containers. Water sprinkler systems are a suitable option; however, their practicality is decreased by the large water storage tank requirement or addition of a seawater fire pump and potential for inadvertent damage to surrounding electrical equipment by corrosive seawater. If a water-based fire suppression system is desired as an outcome of the fire protection DBD, a water mist system should be considered as a more applicable technology for the offshore substation. The water mist system has an advantage of a smaller equipment footprint and can be configured to discharge the extinguishing agent via compressed gas without the need for a fire pump. The very small water particulates can suppress the fire and minimize water damage. In general, any water-based suppression technology must be protected from freezing weather conditions.

A gas suppression is suitable and recommended for all enclosed spaces except for the accommodation container. A clean agent system with low toxicity is recommended over a CO_2 system.

The transformer is the largest fire risk hazard for the offshore substation with the highest likelihood and the most consequential failure. It contains the largest fire load for the substation of up to 15,000 gallons of combustible liquid. Special consideration must be taken due to the quantity of combustible liquid contained within the transformer. If a water spray system is provided, a seawater fire pump with a deluge water spray system is required given the large quantity of water required to cool and extinguish a transformer fire. An alternative to the deluge water spray is a foam suppression system. A foam-water system controls the transformer fire with less water. The oil-foam-water solution would be contained s for proper disposal. Seawater is not recommended to supply the foam-water system given the likelihood of corrosion and increased maintenance required for the fire pump system. A compressed air-foam system is not expected to suffer from corrosion issues, uses less water compared to a foam-water system, and is the overall recommended suppression system for transformers.

The helideck serves as another large fire risk hazard for the offshore substation because of the potential for an aircraft incident leading to large spills of flammable fuel. In a manned substation, a manual water monitor system could provide coverage during helicopter landing and takeoff operations. For unmanned substations, an automatic system consisting of a DIFF water spray, foam-water spray, or compressed air-foam fire protection system is suitable. The DIFF system uses a specialized nozzle built into the helideck platform that sprays water vertically and covers the entire helideck upon activation. The large water requirement of water spray and foam-water spray system would likely require a seawater fire pump. An engineering analysis is required to determine the suitability of the recommended DIFF system type. A large aircraft with heavy fuel load may warrant significant cooling and rely upon water spray or foam-water spray system for suppression. A fire involving a small aircraft could be controlled by a compressed air-foam system with small water usage.

Miscellaneous external areas for offshore substation includes walkways, open decks, miscellaneous exterior equipment, and air cooled power transmission equipment that are open to the atmosphere. These areas and equipment are typically of low fire risk with low combustible fuel loads. Fire protection is typically not warranted.

Location	Water Sprinkler	Water Spray	Water Mist	Foam-Water	Air-Foam	CO_2 Gas	Clean Agent Gas	Dry Chem. Powder	Aerosol Powder
Control Container	Suitable	Not suitable	Preferred	Not suitable	Not suitable	Suitable	Preferred	Not suitable	Not suitable
Accommodation Container	Suitable	Not suitable	Preferred	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable
Electrical Transmission Container (GIS)	Suitable	Not suitable	Suitable	Not suitable	Not suitable	Suitable	Preferred	Not suitable	Not suitable
Misc. Containers (Conditioned)	Suitable	Not suitable	Preferred	Not suitable	Not suitable	Suitable	Preferred	Not suitable	Not suitable
Misc. Containers (Unconditioned)	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Suitable	Preferred	Not suitable	Not suitable
Step-up Transformer	Not suitable	Suitable	Not suitable	Suitable	Preferred	Not suitable	Not suitable	Not suitable	Not suitable
Helipad	Not suitable	Suitable	Not suitable	Suitable	Preferred	Not suitable	Not suitable	Not suitable	Not suitable

Table 13 – Offshore substation fire suppression application suitability chart

3.2.3 Oil Filled Equipment Containment and Foam Use Considerations

Oil-filled equipment present in the offshore wind turbines and substations presents a risk to the environment in the event of an oil spill. In accordance with 40 CFR 112, all oil storage facilities that contain over 1,320 gallons of oil in an above-ground tank of any kind requires secondary containment. The volume of oil present in the wind turbine, although significant, is expected to fall below the limit. However, offshore substations use equipment that contains oil volumes greater than the limit and must be provided with secondary containment.

The secondary containment volume should address the oil volumes within the protected equipment plus fire suppression system discharge. The containment volume is applicable for the step-up transformers and shunt reactors provided with fire suppression systems. NFPA 850 provides the following recommendations for the containment volume:

> **NFPA 850 §6.5.1** *Provisions should be made in all fire areas of the plant for removal of liquids directly to safe areas or for containment in the fire area without flooding of equipment and without endangering other areas…*
>
> **NFPA 850 §6.5.1.1** *The provisions for drainage and any associated drain-age facilities should be sized to accommodate all of the following:*
>
> 1. *The spill of the largest single container of any flammable or combustible liquids in the area*
> 2. *The maximum expected number of fire hose operating for a minimum of 10 minutes*
> 3. *The maximum design discharge of fixed fire suppression systems operating for a minimum of 10 minutes*

NFPA 850 §6.5.1.1(2) is not applicable for the offshore applications as fire hose operations are not anticipated in the event of transformer fires.

The fire protection system recommended to protect the step-up transformer and the helipad includes foam system utilizing aqueous film-forming foam (AFFF), a highly effective foam intended for fighting flammable liquid oil fires using hydrocarbon foaming agent with fluorinated surfactants. When mixed with water, the resulting solution produce an aqueous film that spreads across the surface of a hydrocarbon fuel to extinguish the flame. The film forms a vapor barrier between the fuel and the atmospheric oxygen to prevent re-ignition. Two classes of firefighting foam area used: Class A and Class B. The recommended fire protection system in Table 13 utilizes Class B foams, containing fluorine based polyfluoroalkyl substances (PFAS) as the active ingredients.

Class B PFAS containing foams have the potential to create adverse environmental impact if released uncontrolled to the environment. PFAS are highly stable and persistent chemical that cannot be removed or destroyed by conventional wastewater treatment processes [28]. Studies of PFAS have shown to cause negative health effects in humans and aquatic life [29]. Increased public awareness of PFAS containing firefighting foam has led to restrictions on its use with regard to groundwater contamination by various stale legislatures and the US military; however, there is no current restriction of PFAS use in the offshore industry.

Ongoing research and development effort by various foam manufactures has resulted in introduction of fluorine free foam products. The firefighting performance of current fluorine free foams are inefficient compared to Class B PFAS containing foam; there exists no suitable equivalent replacement.

If AFFF foam products are utilized for the offshore wind industry, a best management practice (BMP) should be established by the wind energy operators. The BMP should document the process of using any firefighting foam and provide mitigation procedures for possible foam releases to the environment. The development of BMP should consider the following:

- Identify fire hazards requiring the use of foam fire suppression systems.
- Determine if there are fluorine free foam able to meet the firefighting performance requirements
- Assess potential environmental, human health, and financial liabilities associated with AFFF release
- Consider implementation of foam containment system in the event of foam suppression system discharge

3.3 Passive Fire Protection Technologies

PFP technologies consist of fire-resistant rated construction, walls, floors, doors, and fire stopping materials to contain or slow the spread of fire. Typically, the objectives of PFP are to protect life safety, to maintain structural integrity, to limit the spread of fire and smoke for sufficient occupant evacuation time, and to allow adequate time for fire department response. However, for normally unmanned electrical utilities and offshore wind energy systems, the PFP's primary purpose is protection of critical equipment and continuity of operations.

The fire protection properties of PFP are achieved using an assembly of materials and components. Commonly seen materials are mineral wool, ceramic fiber, concrete, vermiculite, phenolic syntactic foam, and epoxy intumescent materials [30]. Components for a PFP may consist of fire dampers, fire doors, and various fire-stopping products for opening protection. A common practice of constructing a fire-resistant rated wall in the offshore industry uses PFP prefabricated panels that are encased by a metal exterior. Additional increases in the fire resistance rating can be achieved by increasing the thickness of the wall or intumescent material surface treatment. Intumescent material, when exposed to fire, forms a thick char, reducing heat transfer and increasing the fire resistance of the assembly.

PFP technology for exposed structural steel can be achieved using application of intumescent material, spray-on fire proofing, and enclosing with PFP assembly. The temperature rise in the exposed surface of the structural steel is prevented or slowed during a fire, thereby limiting the thermal stress level in the structural steel and maintaining the load-bearing ability. For the offshore industry, a combination of structural PFP can be applied for protection of structural steel, with intumescent material surface treatment being the most common.

The step-up transformer situated in the offshore substation may present a blast hazard depending on the design of the enclosure due to the volume of insulating oil or synthetic ether contained within. Blast protection of the step-up transformer and adjoining equipment and egress access can be made by means of blast-resistant enclosures that are specifically designed and tested to withstand and deflect the blast overpressure.

The application PFP and blast mitigation requirements for offshore substation is more complex because of the congestion of equipment and multiple possible design variations. Some guidance on application of minimum performance requirement of PFP systems is provided by DNV (refer to Table 7 and Table 8), but the prescriptive guidance alone is not comprehensive or may be too conservative to capture all design intricacies and variation of the offshore substations. The final determination of the PFP requirement must be made after a fire protection DBD has been completed and accepted by the stakeholders that includes assessment of structural analysis, HAZID, and possible fire mitigation measures.

3.3.1 Passive Fire Protection Assembly Performance

The listed performance of the PFP assembly is measured in terms of time (for example, ⅓, ¾, 1, 1 ½, 2, 3, and 4 hours). The hourly performance is determined based on a certification listing that tests and certifies the assembly under a standard time-temperature (STT) curve by a certified test laboratory (CTL). The application of PFP must conform to the manufacturer's specification that has been listed and approved. The two STT curves used for listing of PFP assemblies are the cellulosic curve and hydrocarbon curve; they are defined in the following standards and are graphically represented in Figure 7:

- Cellulosic STT

    A. ISO 834-1 (International):
    $T = 20 + 345 * \log(8t + 1)$

    B. ASTM E119 (US): Discrete points

- Hydrocarbon STT

    A. ISO 834-4 (International):
    $T = 20 + 1080 * (1 - 0.325e^{-0.167t} - 0.675e^{-2.5t})$

    B. UL 1709 (US): 1093°C within 5 min and held constant

Where:

T = *temperature (°C)*

t = *time (min)*

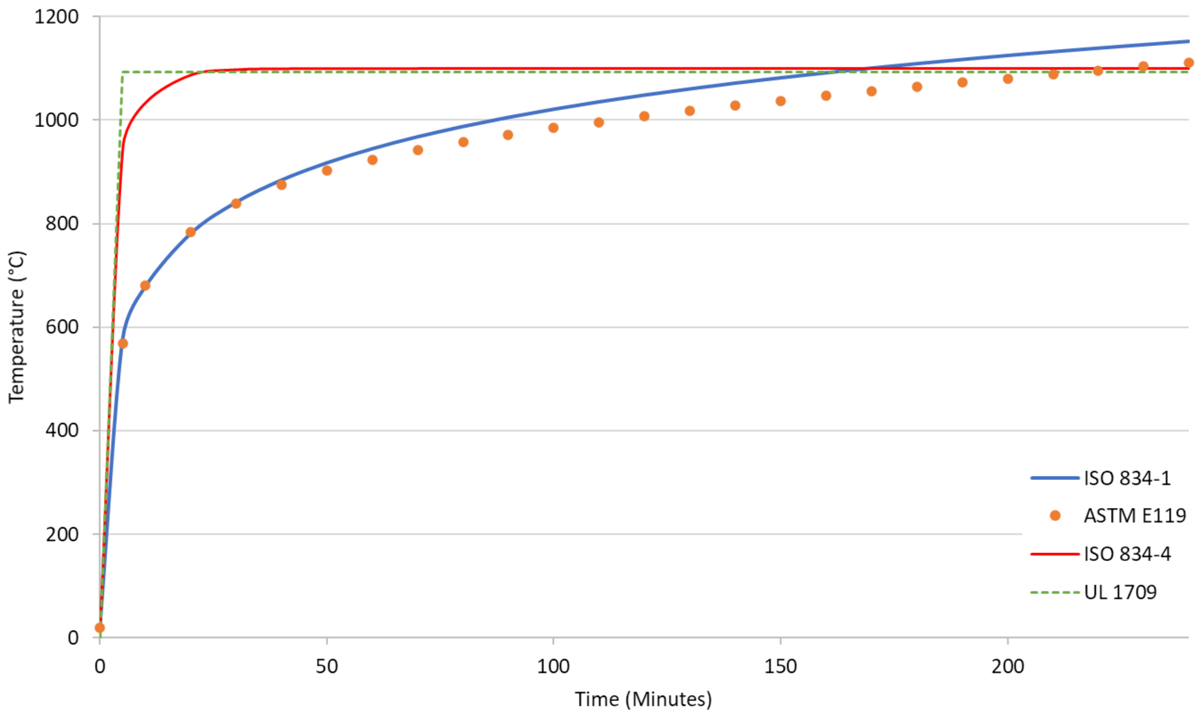


Figure 7 – Cellulosic and hydrocarbon standard time temperature curves

The international and US STT requirements under which the PFP assemblies are tested are similar for both cellulosic and hydrocarbon fires. The listed time ratings of PFP assemblies are interchangeable if acceptable by the appropriate regulatory authority.

The offshore industry uses the following ratings for PFP assemblies tested under STT and have been listed by a competent authority [30]:

- B Class – Maintains stability and integrity for at least 30 minutes when exposed to a cellulose fire. The temperature rise of the cold face is limited to 140°C (284°F) for the period in minutes specified in the rating.
- A Class – Maintains stability and integrity for at least 60 minutes when exposed to a cellulose fire. The temperature rise of the cold face is limited to 140°C (284°F) for the period specified in the rating.
- H Class – Maintains stability and integrity for a period of 120 minutes when exposed to a hydrocarbon fire. The temperature rise of the cold face is limited to 140°C (284°F) for the period specified in the rating.
- C Class – Not tested assemblies consisting of noncombustible materials.

For concentrated jet fires, the time for temperature rise on the cold face is cut by half.

The phrase 'stability and integrity' means that the passage of smoke and flame is prevented for the listed time. The ratings of the PFP assembly classification used in the offshore industry are outlined in Table 14. The wall assembly stability and integrity are reduced by half for concentrated jet fires.

Wall Assembly Rating	Stability and Integrity (minutes)	Time for Temperature to Rise to 284°F (140°C) on Cold Face (minutes)
H120	120	120
H60	120	60
H0	120	0
A60	60	60
A30	60	30
A15	60	15
A0	60	0
B15	30	15
B0	30	0
C	0	0

Table 14 – Offshore industry performance standard for fire walls by rating [30]

The step-up transformer has a potential to pose as a blast hazard depending on the design of the substation to surrounding equipment, accommodation shelters, and the offshore structure itself. The current offshore industry standards do not address blast hazard mitigation from the step-up transformer; however, minimum recommendations have been developed within the oil and gas industry (see Table 15). The design blast overpressure of 0.5 barg for large or congested process areas is the most applicable for the offshore substation. The DNV-ST-0145 offshore substation standard acknowledges the lack of available direction for transformer blast protection and recommends that the blast protection be applied by the designer through HAZID analysis and determination of the explosion risks [31]. The transformer blast overpressure could be simulated by fire protection engineer using computational fluid dynamics computer models.

Item	Design Blast Overpressure (barg)	Pulse Duration (seconds)
Totally enclosed compartment (critical structure only)	4	120
Shale shaker room (volume <1,000 m^3)	2	0.2
Process area, large or congested	0.5	0.2
Process area, small (<20 m × 20 m) and not congested	0.2	0.2
Open drill floor	0.1	0.2

Table 15 – Oil and gas offshore industry minimum recommended overpressure [30]

3.4 Fire Protection System Certification

Fire protection system products, consisting of active fire suppression, fire alarm/detection, and PFP, must be listed by a nationally recognized certification agency and approved for use by the AHJ. No publicly available information has been identified that suggests the offshore wind energy industry conduct its own integrity testing of fire protection systems for fit-for-purpose prior to installation on the wind energy system turbines and substations.

Fire protection systems used in the US should follow the industry recognized relevant NFPA standards. The NFPA codes and standards required that the fire protection products be listed by a third-party organization that is acceptable to the AHJ. The definition of a listed product is extracted from NFPA 13, which states:

> ***Listed.*** *Equipment materials, or services included in a list published by an organization that is acceptable to the AHJ and concerned with evaluation of products or services, that maintains periodic inspection of product of listed equipment or materials or periodic evaluation of services, and whose listing states that either the equipment, material, or service meets appropriate designated standards or has been tested and found suitable for a specified purpose.* [32]

Prominent internationally recognized fire protection third-party listing agencies are UL, FM Global, Loss Prevention Certification Board (LPCB), DNV, and VdS. These listing agencies determine, through testing, that the fire protection product meets the defined product performance and abilities as described in relevant sections of fire protection codes and standards such as NFPA, EN, IEC, and ISO. The listing process ensures confidence that only high-quality and reliable fire protection products are used.

The USCG does not provide oversite of the offshore renewable energy installations and its jurisdiction listed to exploration, development, or production minerals in the outer continental shelf per 33 CRF Subchapter N. However, the USCG Life Saving and Fire Safety Division CC-ENG-4 maintains extensive fire protection equipment approval process for maritime environment using USCG Type Approvals. For fire protection equipment to receive USCG Type Approval, they must be demonstrated to comply with the USCG set forth requirements, successfully completed specified tests, and enrolled in a quality control or follow up programs. An approved fire protection equipment will be issued a Certificate of Approval (COA) for 5 years period. The USGC has been establishing technical and testing requirements for more than 50 years and USGC Type Approvals are widely accepted by the fire protection industry. The application of USGC Type Approvals for fire protection equipment used by the wind energy industry should be considered due to similar environmental challenges faced by the maritime industry.

The NFPA codes and standards defer the responsibility for approving which third-party listing is appropriate to the AHJ. It is a common misconception that NFPA permits US-based listing only. NFPA documents leaves the approval of the listing agency open and allows solutions that provide an equivalent level of safety by including an equivalency clause that states the following:

> ***Equivalency.*** *Nothing in this standard is intended to prevent the use of systems, methods, or devices of equivalent or superior quality, strength, fire resistance, effectiveness, durability, and safety over those prescribed by this standard. Technical documentation shall be submitted to the authority having jurisdiction to demonstrate equivalency. The system, method, or device shall be approved for the intended purpose by the authority having jurisdiction.* [32]

The equivalency clause is notable for the US offshore wind energy industry, which lags behind further developed international counterparts. It provides a pathway for the US AHJ to accept and approve fire protection products that have been listed by international listing agencies such as LPCB, DNV, and VdS in lieu of US-based listing agencies.

The USCG maintains Mutual Recognition Agreement (MRA) with the EU, European Free Trade Association (EFTA) member countries, and the United Kingdom (UK) per Title 46 CFR subpart 159.003. The MRA allows fire protection product manufacturers to reach multiple compact nations on the basis of demonstrating compliance with one set of regulatory requirements. The USCG allows use of maritime fire protection productions that have been approved by foreign MRA compact nations.

No publicly available information exists that suggests internal integrity testing of fire protection system is conducted by the offshore wind energy industry. However, the industry relies on listed fire protection products as an assurance that the components have already been tested for proper performance and reliability. For application to offshore wind energy assets characterized by a wet, corrosive environment and freezing ambient temperatures, engineering means and methods have already been developed to address environmental conditions.

4.0 FIRE PROTECTION ENGINEERING PRACTICES

The active and passive minimum design objectives for the offshore wind energy infrastructure are discussed in this section. These design practices are based on the appropriate NFPA references, which are widely adopted internationally by governmental approving organizations and insurance agencies. The application of these fire protection technologies should be based on the fire protection DBD, where the stakeholders agree on the appropriate risk reduction fire protection measures to address a specific fire risk.

If a fire protection technology is implemented as a risk reduction tool, the engineering practices described here should be considered as a minimum design requirement that must be vetted against the hazards associated with a particular wind energy infrastructure design. A more stringent requirement should be considered if the outcome of the fire protection DBD suggests additional risk reduction measures need to be applied.

The engineering practice for water and foam-water suppression systems are summarized in terms of design density (gallons per minute per square foot [gpm/ft^2]), design area (ft^2), and design duration (minutes). Gas suppression system design bases are summarized in terms of design concentration (%) of the agent discharged into an enclosure and minimum hold times (minutes) required to maintain the design concentration for extinguishment.

4.1 Active Fire Protection System

4.1.1 Water Suppression Systems

Fire Water Sprinkler System – NFPA 13

Typical fire sprinkler system designs use a design density and area criteria intended to provide a specified volume of water to a protected area. If a fire water sprinkler system is provided, the design requirements contained in NFPA 13 should be followed. NPFA 13 provides different design densities based on the occupancy hazard of the protected area: light hazard, ordinary hazard group 1, ordinary hazard group 2, extra hazard group 1, and extra hazard group 2. Figure 8 shows the relation between the occupancy hazard and the design density and area. In accordance with NFPA 13, these curves are modified based on the specific system function and the projected hazard.

The occupancy hazard design density is also associated with the required hose stream allowance for manual firefighting and a minimum water supply duration, Table 16.

Occupancy	Total Combined Inside and Outside Hose (gpm)	Duration (minutes)
Light hazard	100	30
Ordinary hazard	250	60–90
Extra hazard	500	90–120

Table 16 – NFPA 13 hose stream allowance and water supply duration

Based on the quantity and type of fuel loads expected for the areas identified in Table 12 and Table 14, the fire water sprinkler system and its required system peripherals, if applicable, should be designed to support a design density of 0.20 gpm/ft^2 over a design area of at least 1,500 ft^2 (ordinary hazard group 2) for a duration of at least 60 minutes.

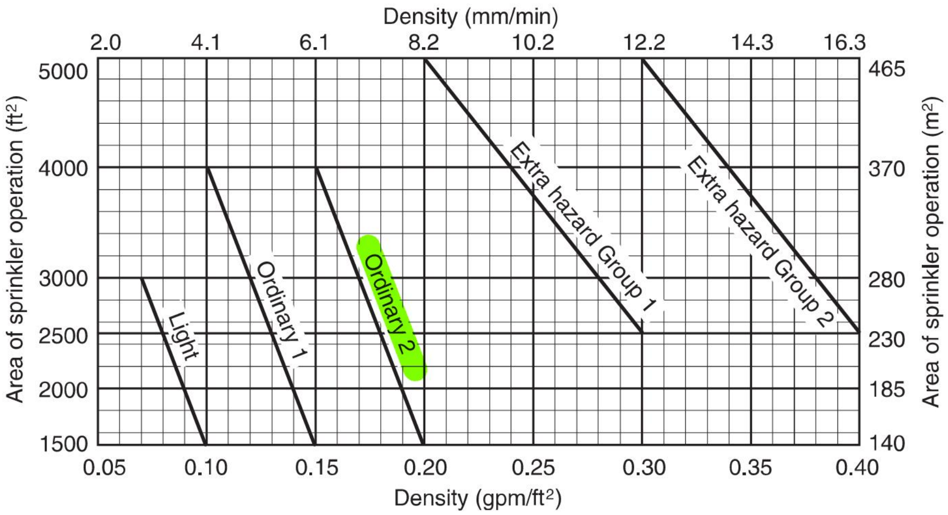


Figure 8 – NFPA 13 design density and area of sprinkler operation curves, with shading indicating recommended minimum hazard occupancy for the wind energy industry

Fire Water Spray System – NFPA 15

A fire water spray system is viable for protecting the step-up transformer. Similar to the fire sprinkler system, the water spray system uses the design density approach. However, the area of application is the transformer rectangular prism envelope and the transformer ground surface area.

NFPA 15 requires a minimum design density of 0.25 gpm/ft^2 for the transformer envelope and 0.15 gpm/ft^2 for the ground surface area with a hose stream rate of 250 gpm for a duration of 60 minutes.

Fire Water Mist System – NFPA 750

Fire water mist system design criteria are defined by the required discharge duration. The design duration of 30 minute of mist discharge is required. If a pre-engineered system is provided, design duration must be per the manufacturer's listing requirements, minimum 2 times the time needed for extinguishment a fire via life fire test, or the rundown time of the rotating turbine, whichever is greater.

Water Suppression System	Offshore Wind Turbine	Offshore Substation	Minimum Design Criteria	Minimum Design Duration
Water Sprinkler	Tower Base	Control container Accommodation container Elec. transmission container Misc. container (conditioned)	0.20 gpm/ft^2	60 minutes
Water Spray	Not applicable	Step-up transformer	0.25 gpm/ft^2 (TR surface) 0.15 gpm/ft^2 (TR ground)	60 minutes
Water Mist	Nacelle Tower Base	Control container Accommodation container Elec. transmission container Misc. container (conditioned)	Not Applicable[1]	30 minutes[2]

Note 1: The water demand is determined based on the number of nozzles and the design duration
Note 2: For pre-engineered systems, the design quantities, additives, and atomizing media shall be capable of two complete discharges, or per manufacturer listing, or 2 times the period to extinguish the fire during test, the rundown time of turbine, whichever is greater

Table 17 – Water fire suppression system design practice summary

4.1.2 Foam Suppression Systems

Foam Monitor System – NFPA 16 and NFPA 418

The foam monitor system should be provided only for manned substations since the system is required to be operated by trained personnel. The foam system typically uses aqueous film foaming foam (AFFF): a fire suppression foam agent designed to mix with water to create a foam-water solution. The minimum discharge rate of 0.10 gpm/ft^2 should be provided by the foam monitor for the entirety of the helipad surface. The minimum discharge duration should be 10 minutes.

Foam Water Spray System – NFPA 16 and NFPA 418

A foam water spray system for the helipad using a DIFFS should be provided for unmanned offshore installation given the system's limited dependence on trained personnel and activated by UV/IR radiant flame detectors. The DIFFS should use an AFFF foam-water solution and be designed to create a minimum discharge rate of 0.10 gpm/ft^2 for a minimum duration of 10 minutes.

Compressed Air Foam System – NFPA 11

A compressed air foam system is suitable for the protection of the offshore step-up transformer. Different design criteria are based on the time of insulating medium contained within the transformer. If mineral oil is used as an insulating medium, a design criterion of 0.04 gpm/ft^2 should be applied for the entire transformer surface area. If a synthetic ester is used as an insulating medium, a design criterion of 0.06 gpm/ft^2 should be applied for the entire transformer surface area. The minimum design duration of 10 minutes should be used for both design criteria.

Foam Suppression System	Offshore Wind Turbine	Offshore Substation	Minimum Design Criteria	Minimum Design Duration
Foam Monitor	Not applicable	Helipad	0.10 gpm/ft^2	10 minutes
Foam Water	Not applicable	Helipad	0.10 gpm/ft^2	10 minutes
Compressed Air Foam	Not applicable	Step-up transformer	0.04 gpm/ft^2 (hydrocarbon) 0.06 gpm/ft^2 (alcohol)	5 minutes

Table 18 – Foam suppression system design practice summary

4.1.3 Gas Suppression Systems

Carbon Dioxide System – NFPA 12

Total flooding CO_2 suppression systems for wind energy application should be reserved for enclosed spaces. A supply of CO_2 cylinders and discharge manifold should be arranged to completely fill the enclosed spaced up to a specified design concentration level of 50%. The room enclosure should be designed such that it is able to hold the CO_2 gas for 20 minutes to completely extinguish the fire. For surface fires, the design concentration must be achieved within 1 minute from the start of discharge.

CO_2 gas is highly toxic to humans in high concentrations. If a CO_2 system is provided, careful consideration must be taken to account for warning labels, pre-discharge warning, egress routes, lock-out systems, and safety shut-off switches.

Clean Agent Fire Extinguishing System – NPFA 2001

The design practices for the three most widely used clean agent gas suppression agents are discussed. The minimum design concentrations differ between the gaseous agents because of different gas formulations and extinguishing mechanisms. Similar to the CO_2 system, a supply of gas cylinders and discharge manifold should be arranged to completely fill the enclosed space to a specified design concentration level. The design concentration should be held for a minimum of 10 minutes for the fire to be completely extinguished. For offshore applications, extended hold durations should be considered due to anticipated delay of response by emergency personnel.

For halocarbon agents, the discharge time required to achieve 95 percent of the minimum design concentration must be reached 10 seconds from the start of discharge. For inert gas agents, the discharge time to achieve 95 percent of the minimum design concentration must be reached 60 seconds for Class B flammable liquid fuel hazards and 120 seconds for Class C electrical hazards.

Although not as toxic as CO_2, clean agent gaseous agents have the potential to create an asphyxiating environment for humans. The warning labels, pre-discharge warning, egress routes, lock-out system, and safety shut-off switch associated with the selected agent must be taken into consideration.

Table 19 summarizes the gas suppression system design practice.

Gas Suppression System	Offshore Wind Turbine	Offshore Substation	Minimum Design Concentration (Class B)	Minimum Design Concentration (Class C)	Minimum Design Hold Time
CO_2	Nacelle Tower Base	Control container Elec. transmission container Misc. container (conditioned) Misc. container (unconditioned)	40.8%	50%	20 minutes
FM200 (HFC-227ea)	Nacelle Tower Base	Control container Elec. transmission container Misc. container (conditioned) Misc. container (unconditioned)	6.6%	7%	10 minutes
3M Novec 1230 (FK-5-1-12)	Nacelle Tower Base	Control container Elec. transmission container Misc. container (conditioned) Misc. container (unconditioned)	4.5%	4.5%	10 minutes
Ansul Inergen (IG-541)	Nacelle Tower Base	Control container Elec. transmission container Misc. container (conditioned) Misc. container (unconditioned)	31%	38.5%	10 minutes

Table 19 – Gas suppression system design practice summary

4.2 Passive Fire Protection System

PFP provides inherent protection of vulnerable components for a finite period and is often used in conjunction with active fire protection systems and architectural design. The application of PFP system guidance is limited for offshore wind turbines. Some guidance is provided for offshore substations and is found in DNV-ST-0145 Table 6-1 and Table 6-2 (see Table 7 and Table 8 in this report). The offshore wind energy system uses A-Class and B-Class PFP assemblies tested for a cellulose fire. H-Class is not used given that hydrocarbon fuels and concentrated jet fires are not present. In general, the PFP assemblies' fire resistance rating must be tested and listed by a nationally recognized testing agency for the hourly fire resistance rating.

PFP systems are not typically used within offshore wind turbines on account of the simplistic architecture of its internal components. Some standards and guidelines recommend providing a barrier between the nacelle and the tower for smoke protection of the sensitive components within the nacelle. However, the wind turbine design does not provide the opportunity for application of PFP systems.

PFP systems provide beneficial risk reduction for offshore substations on account of the proximity of electrical transmission components to other sensitive control equipment, safety equipment, and accommodation spaces. As a risk reduction measure, the substation design should seek to categorize substation components according to similar risks and hazard potential. High-risk components and equipment (transformers, power transmission equipment, power distribution cables/junctions, etc.) should be separated from areas of low-risk potential and areas containing importation safety functions (accommodation spaces, SCADA equipment, communication equipment, fire pumps, UPS systems, and emergency generators).

Two main types of PFP assemblies are provided in the offshore industry: fire rated bulkheads/decks and intumescent coating. Offshore fire-resistant assembly designs commonly use composite panels that are tested and listed for a specific PFP assembly rating by a listing agency. Intumescent coatings expand upon presence of heat to insulate the protected structure. They are applied to steel structures, decks, and bulk heads. A fire resistance listing may also include application of intumescent coating to increase the fire resistance.

The continuity of the PFP assembly must be maintained for the protected enclosure and surface. All openings within the PFP assembly have the capability to jeopardize the fire resistance integrity and must be protected. Opening protection includes products that are listed and tested for the same fire resistance rating of the protected PFP assembly and may include fire doors, fire dampers, fire stopping materials, and fire stopping systems.

5.0 WIND ENERGY FIRE PROTECTION COMPARISON

The current fire protection technologies discussed in Sections 3.0 and 4.0 use existing technologies that could be adopted for offshore wind energy facilities. These fire protection technologies have already been adopted in other industries such as petroleum, aerospace, sea vessels, etc. The adoption of these fire protection technologies must be based on an outcome of the fire protection design basis process discussed in Section 2.4. For example, industry-specific hazards are identified, and the most suitable fire protection technology is provided to reduce the fire hazard risk.

Using this fire protection approach, Table 20 presents a simple case study where different fire protection technologies are applied to different industries to reduce the hypothetical fire risk scenarios.

Industry	Fire Hazard Risk Scenario	Fire Risk Reduction Approach
Oil and Gas	High quantity of flammable fuels on deck with possible explosion hazards.	• Provide PFP fire walls and blast walls to shield mission-critical operations/areas from flammable and explosion hazards on deck. • Provide radiant energy flame detectors to quickly identify flame signatures on open deck areas for early intervention. • Provide water monitor system on open decks to suppress fires.
Aerospace	Large open hangar space for aircraft storage creates difficult environment for typical smoke detectors. Aircraft wings may shield liquid pool fires from fire sprinklers.	• Provide beam smoke detectors or radiant energy flame detectors for early fire detection. • Provide high or low expansion foam suppression system that fills the hangar to protect aircraft from shadow area liquid pool fires.
Data Centers	High-value and sensitive electronics are prone to water damage. High airflow for cooling electronics creates difficult smoke detection environment.	• Provide aspirating smoke detectors, which are effective in high airflow spaces. • Provide gas suppression system designed to extinguish the fire without applying water. • Provide a water-based suppression system to activate if the gas suppression system fails—water-based suppression system would prevent the fire from spreading to adjacent areas.
Submarines	Limited space creates difficult implementation of traditional sprinkler systems. Complex compact interior geometry creates environment where detection and suppression are difficult. Personnel safety against suppression agent asphyxiant and pressurization hazards must be considered.	• Provide aspirating smoke detectors to quickly detect fires in incipient stages. • Provide compact water mist system with high pressure pumps to provide fire suppression with very small volume of water. • Avoid gas suppression system, which may present suffocation and pressurization hazard when discharged.
Manufacturing	Large open floor manufacturing facility with majority noncombustible fuel loads with low fire risk operations.	• Consider reduction in fire suppression system requirements given the low fire hazard/low-risk operations.

Table 20 – Other industry fire hazard risk and risk reduction approach select case studies

No single fire protection technology provides a complete solution to the multi-spectrum fire risk challenges faced by each industry. The recommendation of fire protection technology provided in Section 3.0 should be applied to another industry only when a risk evaluation has been conducted and it has determined that the technology is appropriate for use. A fire risk evaluation should be conducted to apply the correct fire protection technology for each unique set of challenges.

6.0 OFFSHORE WIND TURBINE RISK EVALUATION

Information on ignition sources, fuel load, and risk management approaches were discussed in detail in prior sections of this report. This section of the report discusses failure frequencies and potential fire risk contributors; however, this effort is complicated by the fact that publicly reported data on loss statistics and causes are limited. There is a lack of publicly reported data for fire loss, therefore the fire risk analysis is limited to generalized narrative assumptions. The risk evaluation analysis uses available industry data to determine realized cost benefit by improving failure detection within the wind turbine subassemblies.

While detailed statistics of offshore turbine fires are not readily available, it is estimated that fires occur at an approximate rate of 1 fire per 2,500 wind power stations per year and that 10% to 30% of all loss-of-power-generation incidents in wind power plants are attributable to fire [33]. Causes of fire incidents in onshore and offshore installations are similar. Hence, the frequency for onshore and offshore wind turbines may be assumed to be comparable [33]; however, the impact of these events is exacerbated in offshore wind power stations. This is a result of several factors: offshore turbines are more difficult to access, are typically larger and more costly to install and repair, and incur much higher costs in the event of a fire incident compared to onshore turbines. This increased repair/replacement cost leads to a higher assessed risk even though the failure rates are similar.

As shown in Figure 10, the sub-assemblies of the turbine each have associated failure rates, with offshore components having a slightly higher overall combined failure rate per year (1.38 versus 1.22). The failure rate data has been collected from SCADA database, automated fault logs, and O&M reports. The cause of failure has not been identified for the presented data set. An example fault tree for specific failures (gearbox, generator, and blade) is provided in Figure 11. This illustrates a method that may be used to determine the failure modes for each of the subassemblies. If failure frequencies are known either from published data or from company experience, then the failure frequencies shown in Figure 10 may be updated.

According to Figure 10, the subassemblies with the highest failure rates are “Others,” which is the balance of components without an explicitly defined failure rate. The rotor blades, gearbox, and generator have the next highest failure rates. It is important to note that the failure rates depicted do not necessarily result in a fire; they are simply indicative of a failure involving the subassembly in question.

One of the biggest sources of fire risk is the nacelle, which contains highly flammable materials located near machinery and electrical wiring. There is a lack of wind energy industry fire probability risk dataset, therefore the analysis is limited to generalized narrative assumptions. The nacelle risk is tied to the materials associated with it, such as hydraulic oil and plastics. In general, there is typically 600 liters of oil per 1 MW consisting of various quantities of hydraulic oil, cooling oil, and die-electric oil. The nacelle is also typically made from flammable fiber-reinforced plastic and acoustic insulation. As a result, the determination of risk from fire is tied to the failure frequency, the resulting consequences, and the associated monetary damages and business interruption costs.

For offshore turbine fires, the loss figures indicate that the repair/replacement cost often will exceed the initial cost of construction (estimated at $9 million US dollars) and result in 12 to 18 months of downtime. While typical methods of risk evaluation such as the failure mode and effects analysis (FMEA) or fault tree analysis (FTA) produce risk rankings, such as the Risk Priority Numbers depicted in Table 21, these rankings are associated with an individual system and can vary between site, manufacturer, and model, making comparisons between turbines difficult. However, when the same basic approach is taken but the cost of the outcome is considered, a new metric, the Cost Priority Number (CPN), can be used for ranking and direct comparison of risk based on the anticipated loss outcomes.

CPN is defined as the *Probability of Occurrence x Cost of Failure x Failure to Detect* [34] and results in a continuous monetary function that allows for relatively easy comparison between outcomes and cost of consequences.

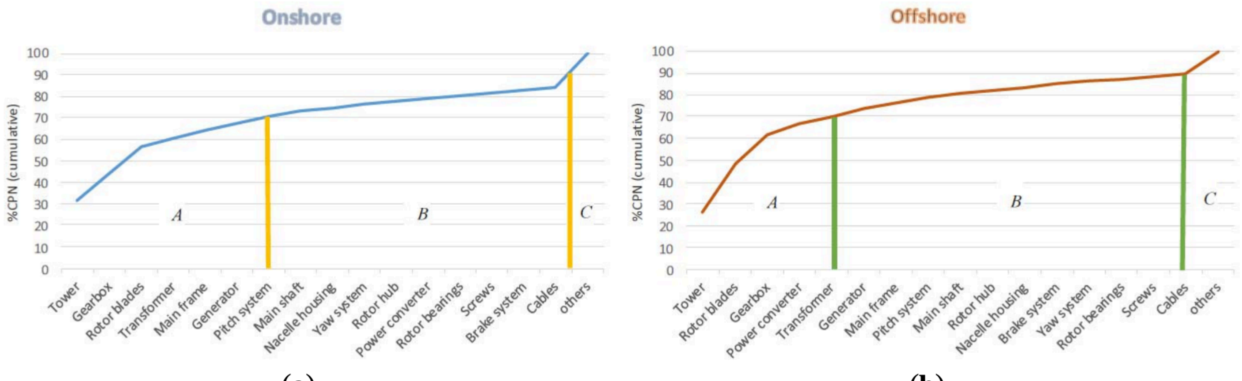
$$CPN_i = O_i \times C_i \times D_i$$

Where O_i is the probability of occurrence, C_i is the cost consequences of failure in monetary units, and D_i is the failure to detect and mitigate the situation. [34]

It has been recommended that after performing a CPN analysis, three different groups or types of failures be identified:

- Group A. Significant savings can be obtained by reducing their failure frequency and/or the resulting downtime. These failure modes account for around 70% of the overall CPN.
- Group B. A medium CPN reduction can be obtained using an effective preventive maintenance strategy. These failure modes account for around 20% of the overall CPN.
- Group C. Low levels of savings can be obtained through reduction of failure consequences. These failure modes account for around 10% of the overall CP

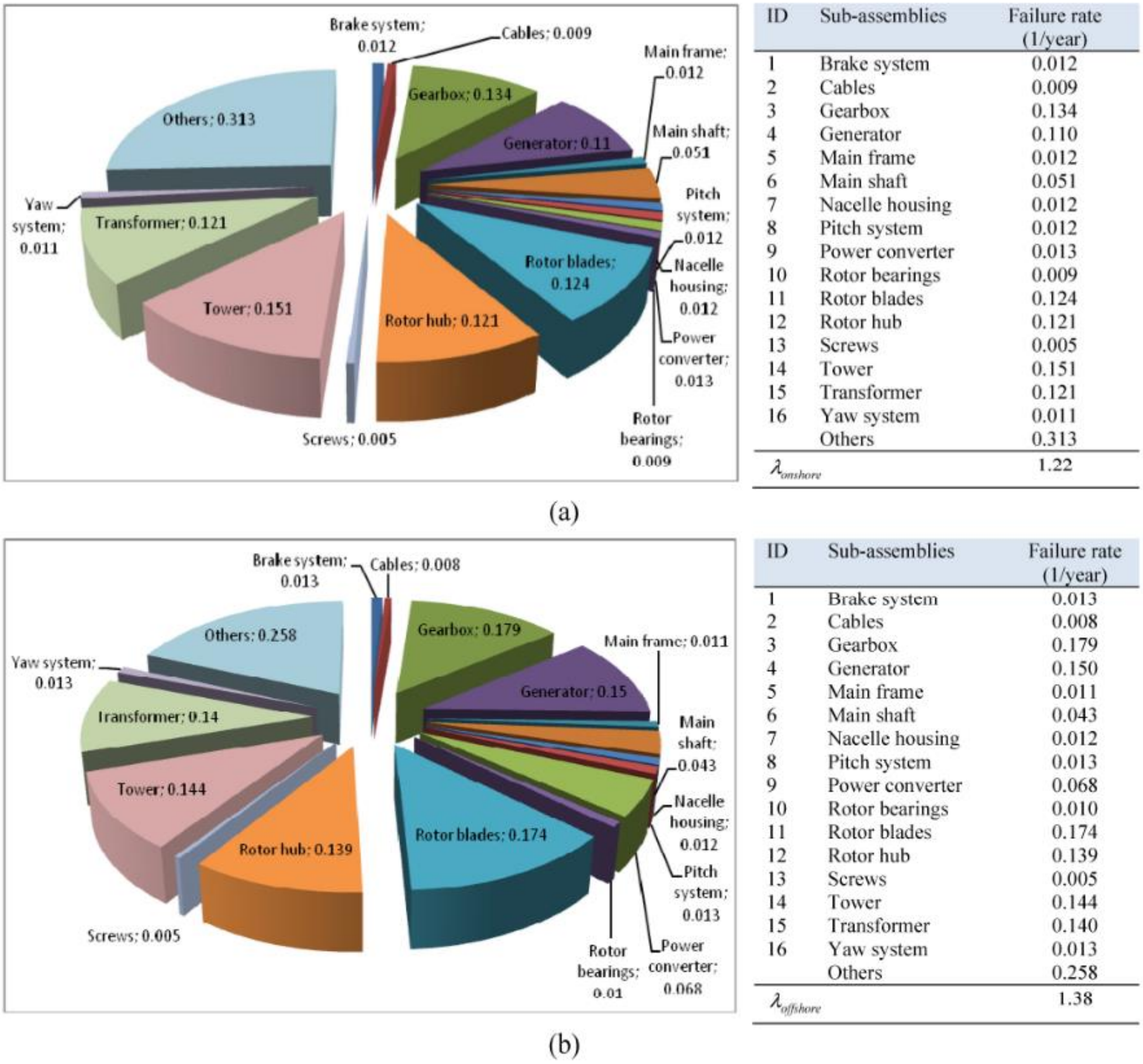
By examining each of these groups and the cost for reducing the probability of failure, failure to detect, or the cost of an incident through mitigation, a cost-benefit analysis can be performed on mitigation measures. Table 22 shows the component values as well as the individual and combined CPN for sample onshore and offshore wind turbines. These data show that the anticipated cost of loss is estimated to be 25% greater for offshore wind turbine subassemblies compared to onshore. The cumulative CPN and the CPN groupings are shown visually in Figure 9. The CPN groupings are distinguished by Group A, Group B, Group C assemblies by vertical lines and illustrates subassembly CPN contribution to the cumulative CPN.



(a) **(b)**

Figure 9 – Cumulative % CPN for the subassemblies of (a) onshore (b) offshore [34]

Finally, if mitigation can be implemented, such as shown in Table 23, a direct reduction in CPN can be shown. Then, the cost for implementation can be evaluated against the potential cost savings. By comparing Table 22 and Table 23, a 10% improvement in detection for Group A assemblies (Figure 9) can result in a 6.61% and 7.69% reduction in the onshore and offshore wind turbine's annual CPN, respectively. If the implementation cost is less than the savings, it would have a positive return on investment.



ID	Sub-assemblies	Failure rate (1/year)
1	Brake system	0.012
2	Cables	0.009
3	Gearbox	0.134
4	Generator	0.110
5	Main frame	0.012
6	Main shaft	0.051
7	Nacelle housing	0.012
8	Pitch system	0.012
9	Power converter	0.013
10	Rotor bearings	0.009
11	Rotor blades	0.124
12	Rotor hub	0.121
13	Screws	0.005
14	Tower	0.151
15	Transformer	0.121
16	Yaw system	0.011
	Others	0.313
$\lambda_{onshore}$		1.22

(a)

ID	Sub-assemblies	Failure rate (1/year)
1	Brake system	0.013
2	Cables	0.008
3	Gearbox	0.179
4	Generator	0.150
5	Main frame	0.011
6	Main shaft	0.043
7	Nacelle housing	0.012
8	Pitch system	0.013
9	Power converter	0.068
10	Rotor bearings	0.010
11	Rotor blades	0.174
12	Rotor hub	0.139
13	Screws	0.005
14	Tower	0.144
15	Transformer	0.140
16	Yaw system	0.013
	Others	0.258
$\lambda_{offshore}$		1.38

(b)

Figure 10 – Failure rates for the subassemblies of (a) onshore and (b) offshore wind facilities [34]

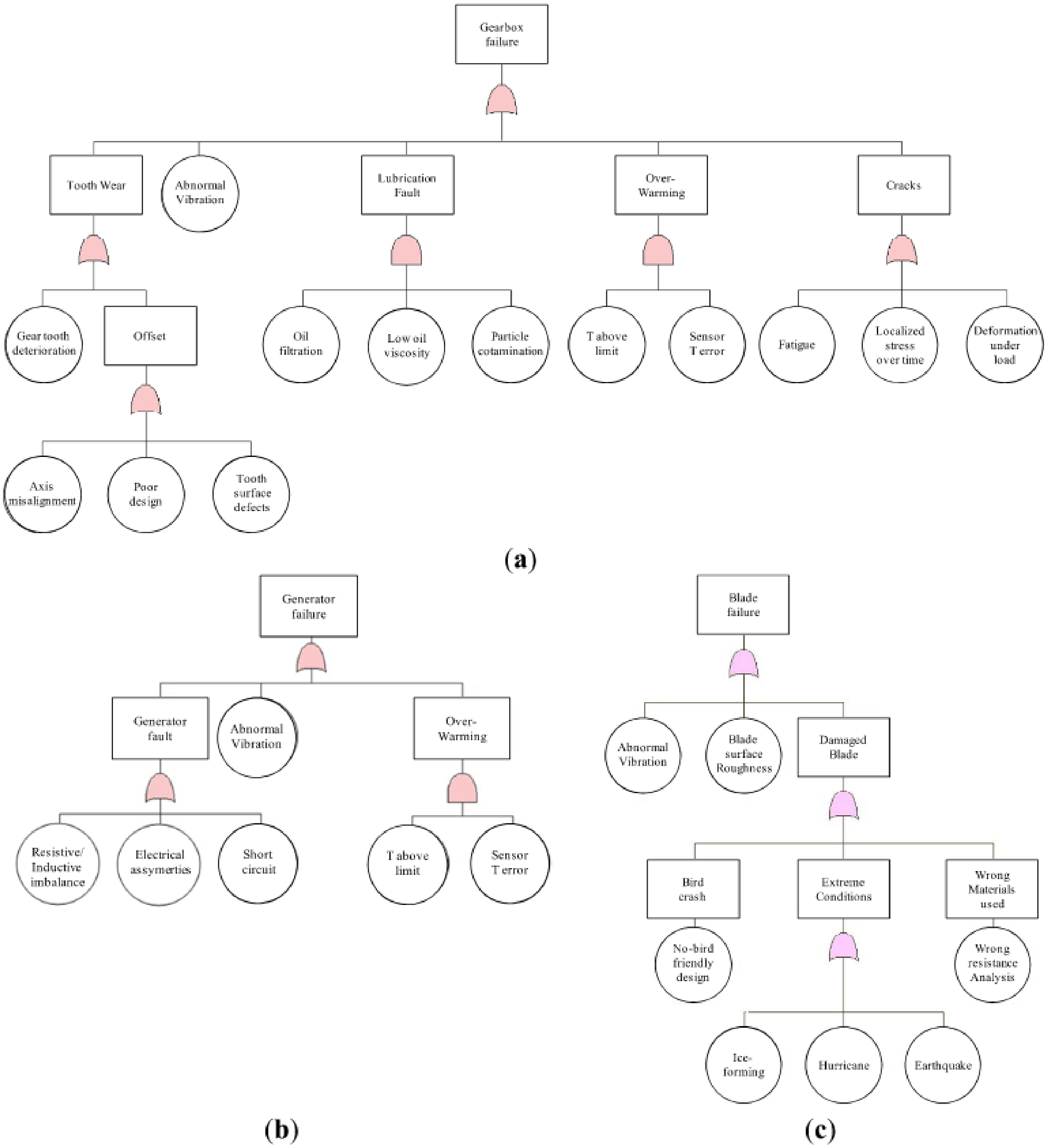


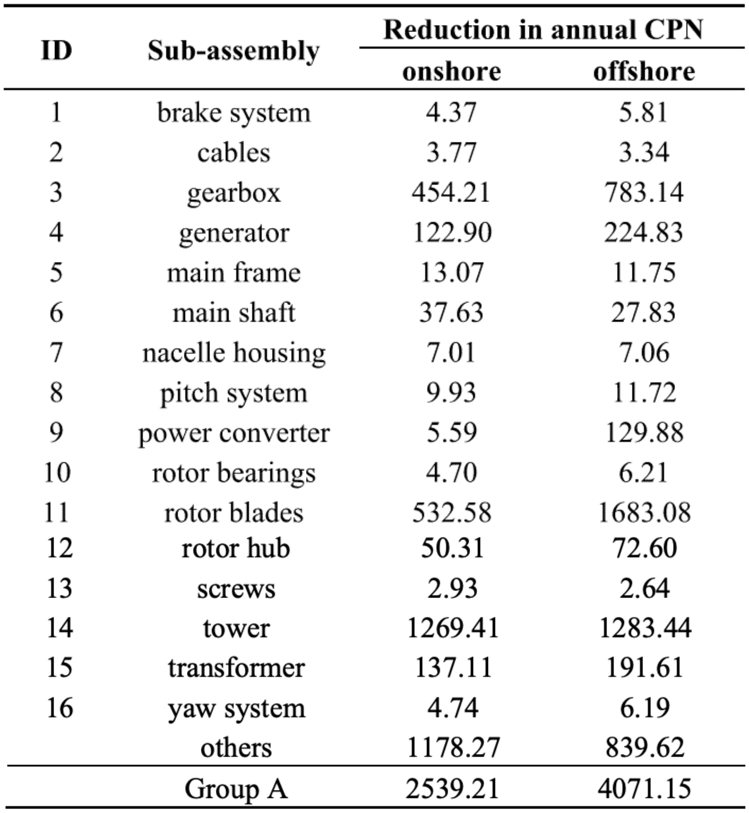
Figure 11 – Failure pathways for specific turbine subassemblies

# ID	Sub-assembly	Some components	Onshore					Offshore				
			S_f	S	S_d	RPN	Rank	S_f	S	S_d	RPN	Rank
1	Brake system	Brake disk, Spring, Motor	2	1	7	14	13	2	2	7	28	11
2	Cables	Cable	2	2	1	4	15	2	3	1	6	14
3	Gearbox	Toothed gear wheels, Pump, Oil heater/cooler, Hoses	3	4	7	84	2	5	3	7	105	2
4	Generator	Shaft, Bearings, Rotor, Stator, Coil	3	3	7	63	4	5	2	7	70	5
5	Main frame	-	2	3	4	24	10	2	4	4	32	10
6	Main shaft	Shaft, Bearings, Couplings	2	2	7	28	9	3	2	7	42	8
7	Nacelle housing	Nacelle	2	3	1	6	14	2	3	1	6	14
8	Pitch system	Pitch motor, Gears	2	3	7	42	7	2	4	7	56	7
9	Power converter	Power electronic switch, cable, DC bus	2	4	7	56	5	3	4	7	84	4
10	Rotor bearings	-	2	2	4	16	11	2	3	4	24	12
11	Rotor blades	Blades	5	2	7	70	3	5	3	7	105	2
12	Rotor hub	Hub, Air brake	3	3	4	36	8	5	2	4	40	9
13	Screws	Screw	2	1	1	2	16	2	1	1	2	16
14	Tower	Tower, Foundation	5	3	7	105	1	5	4	7	140	1
15	Transformer	-	3	4	4	48	6	5	3	4	60	6
16	Yaw system	Yaw drive, Yaw motor	2	2	4	16	11	2	2	4	16	13

Table 21 – Risk Priority Numbers for example onshore/offshore wind turbine subassemblies [34]

ID	Sub-assembly	Onshore					Offshore				
		O	*C*	*D*	CPN	Rank	*O*	*C*	*D*	CPN	Rank
1	brake system	0.0100	35,880	0.9	322.92	15	0.00942	47,488	0.9	402.60	12
2	cables	0.0071	61,299	0.7	304.66	16	0.00580	72,118	0.7	292.80	16
3	gearbox	0.1102	30,657	0.9	3,040.56	2	0.12971	33,730	0.9	3,937.55	3
4	generator	0.0901	12,410	0.7	782.70	6	0.10870	13,789	0.7	1,049.20	6
5	main frame	0.0097	113,849	0.8	883.47	5	0.00797	133,940	0.8	854.00	7
6	main shaft	0.0418	17,657	0.9	664.26	8	0.03116	20,773	0.9	582.55	9
7	nacelle housing	0.0100	57,469	0.7	402.28	9	0.00870	67,611	0.7	411.75	11
8	pitch system	0.0100	81,341	0.9	732.07	7	0.00942	95,695	0.9	811.30	8
9	power converter	0.0110	37,883	0.8	333.37	11	0.04928	38,759	0.8	1,528.05	4
10	rotor bearings	0.007	78,709	0.6	330.58	13	0.00725	85,540	0.6	372.10	14
11	rotor blades	0.1017	42,207	0.7	3,004.72	3	0.12609	76,714	0.7	6,771.00	2
12	rotor hub	0.0990	4,208	0.8	333.27	12	0.10072	5,186	0.8	417.85	10
13	screws	0.0044	124,135	0.6	327.72	14	0.00362	146,041	0.6	317.20	15
14	tower	0.1234	68,330	0.9	7,588.73	1	0.10435	85,412	0.9	8,021.50	1
15	transformer	0.0990	11,467	0.8	908.19	4	0.10145	13,491	0.8	1,094.95	5
16	yaw system	0.0090	48,002	0.8	345.61	10	0.00942	50,590	0.8	381.25	13
-	others	0.2566	14,668	1	3,763.81	-	0.18696	17,407	1	3,254.35	-
-	overal CPN (€)	-	-	-	24,069	-	-	-	-	30,500	-

Table 22 – CPN values for the onshore/offshore wind turbine subassemblies [34]



ID	Sub-assembly	Reduction in annual CPN	
		onshore	offshore
1	brake system	4.37	5.81
2	cables	3.77	3.34
3	gearbox	454.21	783.14
4	generator	122.90	224.83
5	main frame	13.07	11.75
6	main shaft	37.63	27.83
7	nacelle housing	7.01	7.06
8	pitch system	9.93	11.72
9	power converter	5.59	129.88
10	rotor bearings	4.70	6.21
11	rotor blades	532.58	1683.08
12	rotor hub	50.31	72.60
13	screws	2.93	2.64
14	tower	1269.41	1283.44
15	transformer	137.11	191.61
16	yaw system	4.74	6.19
	others	1178.27	839.62
	Group A	2539.21	4071.15

Table 23 – Example reduction in the annual CPN by a 10 percent improvement in fault detection [34]

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8.0 APPENDIX

8.1 List of Codes and Standards

National Fire Protection Association (NFPA)

- NFPA 10: Standard for Portable Fire Extinguishers 2018 Edition
- NFPA 11: Standard for Low-, Medium-, and High-Expansion Foam 2021 Edition
- NFPA 12: Standard on Carbon Dioxide Extinguishing Systems 2018 Edition
- NFPA 13: Standard for the Installation of Sprinkler Systems 2019 Edition
- NFPA 15: Standard for Water Spray Fixed Systems for Fire Protection 2017 Edition
- NFPA 16: Standard for the Installation of Foam-Water Sprinkler and Foam-Water Spray Systems 2019 Edition
- NFPA 17: Standard for Dry Chemical Extinguishing Systems 2021 Edition
- NFPA 25: Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems 2020 Edition
- NFPA 30: Flammable and Combustible Liquids Code 2021 Edition
- NFPA 51B: Standard for Fire Prevention During Welding, Cutting, and Other Hot Work 2019 Edition
- NFPA 70: National Electrical Code (NEC)
- NFPA 72: National Fire Alarm and Signaling Code 2019 Edition
- NFPA 418: Standard for Heliports 2021 Edition
- NFPA 551: Guide for the Evaluation of Fire Risk Assessments 2017 Edition
- NFPA 750: Standard on Water Mist Fire Protection Systems 2019 Edition
- NFPA 780: Standard for the Installation of Lightning Protection Systems 2020 Edition
- NFPA 850: Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations 2020 Edition
- NFPA 2001: Standard on Clean Agent Fire Extinguishing Systems 2018 Edition

American Society for Testing and Materials (ASTM)

- ASTM E119: Standard Test Methods for Fire Tests of Building Materials 2020 Edition
- ASTM E84: Standard Test Method for Surface Burning Characteristics of Building Materials 2021 Edition

Factory Mutual Global (FM)

- Safety Data Sheet 13-10: Wind Turbines 2021 Edition

Institute of Electrical and Electronics Engineers (IEEE)

- IEEE 979: Guide for Substation Fire Protection 2012 Edition

American Petroleum Institute (API)

- API RP 14G: Recommended Practice for Fire Prevention and Control on Fixed Open-type Offshore Production Platforms 2019 Edition

American Clean Power Association (ACP)

- ACP OCRP: Offshore Compliance Recommended Practices 2012 Edition

International Electrotechnical Commission (IEC)

- IEC 61400: Wind Turbines 2019 Edition

International Organization for Standardization (ISO)

- ISO 19900: General Requirements for Offshore Structures 2019 Edition
- ISO 19901: Petroleum and Natural Gas Industries - Specific Requirements for Offshore Structures 2019 Edition

European Standards (EN)

- EN 54: Fire Detection and Fire Alarm Systems 2021 Edition
- EN 50308: Wind Turbines – Protective Measures 2004 Edition

German, Federal Maritime and Hydrographic Agency Standard Design (BSH)

- BSH SD: Minimum requirements concerning the constructive design of offshore structures within the Exclusive Economic Zone (EEZ) 2015 Edition

Code of Federal Regulations (CFR)

- 46 CFR: Shipping 2020 Edition

Confederation of Fire Protection Associations Europe (CFPA-E)

- No. 22: Wind Turbines – Fire Protection Guideline 2012 Edition

Det Norske Veritas (DNV)

- DNV-ST-0145: Offshore Substations 2020 Edition
- DNV-SE-0077: Certification of Fire Protection Systems for Wind Turbines 2015 Edition

UK Civil Aviation Authority (CAA)

- CAP 437: Standards for Offshore Helicopter Landing Areas 2021 Edition

8.2 List of Acronyms

ACP - American Clean Power Association
AFFF - aqueous film forming foam
AHJ - authority having jurisdiction
API - American Petroleum Institute
ASTM - American Society for Testing and Materials

BMP - Best Management Practice
BOEM - Bureau of Ocean Energy Management
BSEE - Bureau of Safety and Environmental Enforcement
BSH SD - German Federal Maritime and Hydrographic Agency Standard Design

°C - degrees Celsius
CAA - Civil Aviation Authority
CFPA-E - Confederation of Fire Protection Associations in Europe
CFR - Code of Federal Regulations
CMS - central monitoring system
CO_2 - carbon dioxide
CPN - cost priority number
CTL - certified test laboratory

DBD - design basis document
DIFFS - deck integrated fire fighting system
DNV - Det Norske Veritas
DOI - US Department of the Interior

EFTA – European Free Trade Association
EN - European Standards
EU - European Union

°F - degrees Fahrenheit
FACP - fire alarm control panel
FERA - fire explosion risk analysis
FM - Factory Mutual
FMEA - failure mode and effects analysis
ft^2 - square feet
FT - fixed temperature
FTA - fault tree analysis

GIS – gas-insulated switchgear
gpm - gallons per minute
GRP - glass-reinforced plastics

HAWT - horizontal axis wind turbine
HAZID - hazard identification study
HAZOP – hazard and operability study
HV - high voltage
HVAC - heating, ventilation, air conditioning

IEC - International Electrotechnical Commission

IEEE - Institute of Electrical and Electronics Engineers
IMO - International Maritime Organization
IR - infrared
ISO - International Organization for Standardization
ITM - inspection, testing, maintenance

kW - kilowatt

LPCB - Loss Prevention Certification Board
LPL - lightning protection level
LV - low voltage

MMS - Minerals Management Services
MODU - mobile offshore drilling units
MRA – Mutual Recognition Agreements
MW - megawatt

NEC – National Electrical Code
NFPA - National Fire Protection Association
NREL - National Renewable Energy Laboratory
NUI - normally unattended installation

OCS - Outer Continental Shelf
ORCP - Offshore Compliance Recommended Practices

PBD - performance-based design
PFAS - perfluoroalkyl and polyfluoroalkyl substances
PFP - passive fire protection
PLC - programmable logic controller
PS - polystyrene
PUR - polyurethane

ROR - rate-of-rise
rpm - rotations per minute
RTU - remote terminal unit

SCADA - supervisory control and data acquisition
SF_6 - sulfur hexafluoride
SOLAS - Safety of Life at Sea
SPIC - State Power Investment Corporation
STT - standard time-temperature

UK – United Kingdom
UL - Underwriters Laboratories
UPS - uninterruptible power supply
USCG - US Coast Guard
UV - ultraviolet

VAWT - vertical axis wind turbine
VdS - VdS Schadenverhütung GmbH

8.3 Survey Questionnaires and Answers Data

#	Question	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5	Respondent 6
Q1b_1	1. Please select which company you work for: - First Letter of Company	T - W	T - W	A - E	A - E	N - S	N - S
Q1b_2	1. Please select which company you work for: - Company Name	Wood	Wood	DNV	DNV	PSEG	Orsted
Q1a	If your company's name is not listed, please enter it here;						
Q2	2. Which title most closely aligns with your role? (Select one): - Selected Choice	Supervisor	Supervisor	Engineer	Supervisor	Project Manager	Engineer
Q2_6_TEXT	2. Which title most closely aligns with your role? (Select one): - Other; please specify - Text						
Q3	3. Can you provide information on fire detection, protection, suppression and explosion protection systems ("fire safety systems") available for the offshore wind industry? (Select one):	Yes	Yes	Yes	Yes	No	Yes
Q3a	Can you provide a contact or contacts within your organization that can provide this information? (Select one):						

“THE FINDINGS AND CONCLUSIONS IN THIS REPORT HAVE NOT BEEN FORMALLY DISSEMINATED BY BSEE AND SHOULD NOT BE CONSTRUED TO REPRESENT ANY AGENCY DETERMINATION OR POLICY.”

#	Question	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5	Respondent 6
Q3b_1	If yes, please provide the following information: - Name:						
Q3b_2	If yes, please provide the following information: - Email Address:						
Q4	4. What international, national, regional, and/or industry fire protection standards do you follow for fire protection of offshore wind turbines and offshore substations?	NFPA, DNV offshore wind standards, API (a good reference for industry best practice), and CFRs.	DNV Offshore Wind Standards, NFPA, CFRs, FM, UL, and API.	NFPA 11, 13, 14, 15, 17, 20, 30, 72, 850, 2001 VdS CEA4001, VdS 2095, VdS 2108, VdS 2109, VdS 2380, EN54 series DNVGL-ST-0145	NFPA-11, 13, 15, 20, 25, 30, 72, 850, 2001, 2010 VdS- CEA4001, 2095, 2108, 2109, 2380, 2496 EN-54 series DNVGL-ST-0145 MODU, SOLAS, IMO		DNV GL-ST-0145 EN 54 NFPA 11, 16, 2001
Q5	5. Do you have internal fire protection standards for protection of offshore wind turbine generators and offshore substations?	No	No	No	No		Yes
Q5b_Id	Please upload a PDF copy of your internal fire protection standard document for protection of offshore wind turbine generators and offshore substations. - Id						
Q5b_Name	Please upload a PDF copy of your internal fire protection standard document for protection of offshore wind turbine generators and offshore substations. - Name						

#	Question	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5	Respondent 6
Q5b_ Size	Please upload a PDF copy of your internal fire protection standard document for protection of offshore wind turbine generators and offshore substations. - Size						
Q5b_ Type	Please upload a PDF copy of your internal fire protection standard document for protection of offshore wind turbine generators and offshore substations. - Type						
Q6	6. How would you characterize any differences between the internal fire protection standards and the other international, national, or regional standards used?				sometimes the differences are significant (between European and American requirements), especially when it comes to the design parameters of active fire protection (AFP) systems for the protection of oil filled equipment (transformers, shunt reactors etc.)		There might be more specific requirements in internal standard and requirements, e.g. rooms that are evaluated critical to asset have specific requirements.
Q7a	7. How important is fire protection in your design of offshore wind turbine generators and offshore substations?	Very important	Very important	Very important	Very important		Very important

#	Question	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5	Respondent 6
Q7b	Provide a basis for your selection above:	Assuming the substation is normally unmanned, fire protection should be provided for asset protection.	Asset protection, assuming an unmanned facility. Personnel protection for manned facilities.	I am responsible for design verification and commissioning in the field of technical safety/fire protection (passive and active fire protection, process safety etc.), evacuation etc.	My duties include verification of design documentation in terms of technical safety of installations (fire protection systems, process safety, evacuation, passive fire protection (PFP) etc.) and participation in the installation and commissioning phase.		Fire protection are evaluated very important to personal and asset, to ensure a safe and reliable operation.
Q8a	8. Do you have manned offshore renewable facilities?	No	No	Yes	Yes		No
Q8b	Do you have different fire protection engineering practices in place when comparing manned versus unmanned facilities?			Yes	Yes		
Q8c	Please briefly summarize the differences using examples:				- Helideck- DIFF system as an alternative to fixed monitor systems is recommended for unmanned substations - Public Address and General Alarms (PA/GA) - DNVGL-ST-0145 states that single-rack arrangement is acceptable for unmanned offshore substation.- Evacuation - a slightly different approach to evacuation measures for unmanned and manned substations.		

#	Question	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5	Respondent 6
Q9	9. What are your fire protection engineering practice design requirements for offshore wind turbines and offshore substations? (Select all that apply)	Passive compartmentalization (i.e., fire resistant/noncombustible construction, fire barriers, and smoke barriers), Active fire protection systems (i.e., suppression, detection), Other fire risk management procedures (i.e., fire response team, fuel management, power disconnect, etc.)	Passive compartmentalization (i.e., fire resistant/noncombustible construction, fire barriers, and smoke barriers), Active fire protection systems (i.e., suppression, detection), Other fire risk management procedures (i.e., fire response team, fuel management, power disconnect, etc.)	Passive compartmentalization (i.e., fire resistant/noncombustible construction, fire barriers, and smoke barriers), Active fire protection systems (i.e., suppression, detection), Other fire risk management procedures (i.e., fire response team, fuel management, power disconnect, etc.)	Passive compartmentalization (i.e., fire resistant/noncombustible construction, fire barriers, and smoke barriers), Active fire protection systems (i.e., suppression, detection), No fire protection requirements, Other fire risk management procedures (i.e., fire response team, fuel management, power disconnect, etc.)	Passive compartmentalization (i.e., fire resistant/noncombustible construction, fire barriers, and smoke barriers), Active fire protection systems (i.e., suppression, detection), Other fire risk management procedures (i.e., fire response team, fuel management, power disconnect, etc.)	
Q9b_1	Based on your previous responses, please provide descriptions for: - Passive compartmentalization - briefly summarize	Fire rated bulkheads based on contents of room.	Fire rated bulkheads based on the type of occupancy.		Segregation of areas- The substation shall be divided into different areas according to the type of activities that will be carried out and the associated hazard potential. Areas of high risk potential shall be segregated from areas of low risk potential, and from areas containing important safety functions. Incident escalation between areas shall be avoided. Accommodation spaces, service spaces, control stations as well as spaces containing equipment, sudden failure of which may result in hazardous situations (e.g. fire pumps, emergency sources of power, and other operational or safety systems), should not be located adjacent to hazardous areas.	Fire integrity of walls and decks, penetrations	

#	Question	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5	Respondent 6
Q9b_2	Based on your previous responses, please provide descriptions for: - Active fire protection systems - briefly summarize	Compressed Air Foam System for transformer rooms. Inergen system for battery rooms.	Compressed Air Foam System and gaseous extinguishing system (Inergen)		The objectives of active fire protection systems are to: extinguish fires, provide efficient control of fires, limit damage to structures and equipment.A range of active fire protection systems shall be provided in the substation. The system(s) selected should be suitable for the intended use and environment. When selecting a system, consideration should be given to the impact of its discharge on the equipment.	FAS, FES (Inert gas system, Foam system, Deluge Spray system, DIFF system)	
Q9b_3	Based on your previous responses, please provide descriptions for: - No fire protection requirements - briefly summarize				In some cases the assessment of the need for e.g. active fire protection is carried out on the basis of a risk assessment. An example would be the use of coolants other than oil for transformers, such as MIDEL.		
Q9b_4	Based on your previous responses, please provide descriptions for: - Other fire risk management procedures - briefly summarize	Shunt trip all power sources upon H2 detection in battery room.	Shunt trip of electrical sources upon H2 detection in the battery room(s).			Performing FERA, HAZID/HAZOP	
Q10	10. What types of passive fire protection are used? (Select all that apply)	1-hour fire rated construction	1-hour fire rated construction		1-hour fire rated construction, Other	Smoke partitions / smoke barriers,1-hour fire rated construction,2-hour fire rated construction	

#	Question	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5	Respondent 6
Q10_1	Based on your previous responses, please provide descriptions for: - Smoke partitions / smoke barriers - briefly describe					Separation of areas	
Q10_2	Based on your previous responses, please provide descriptions for: - 1-hour fire rated construction - briefly describe	A-60 rated bulkheads around the transformer rooms.	Fire rated bulkhead around the transformer rooms.		fire partitions of class A-0, 15, 60	Wall/deck fire rating	
Q10_3	Based on your previous responses, please provide descriptions for: - 2-hour fire rated construction - briefly describe					Wall/deck fire rating	
Q10_4	Based on your previous responses, please provide descriptions for: - 3-hour fire rated construction - briefly describe						
Q10_5	Based on your previous responses, please provide descriptions for: - Other - briefly describe				fire dampers		
Q11	11. For offshore wind turbine generators, what types of fire protection systems are used? (Select all that apply)	Automatic clean agent / gaseous systems, Fire extinguishers	Automatic clean agent / gaseous systems, Fire extinguishers		Automatic clean agent / gaseous systems, Fire extinguishers		

#	Question	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5	Respondent 6
11b_1	Based on your previous responses, please provide descriptions for: - Hydrants and hoses - describe the protected equipment and access to firefighting PPE such as SCBA:						
11b_2	Based on your previous responses, please provide descriptions for: - Monitors - describe the protected equipment and access to firefighting PPE such as SCBA:						
11b_3	Based on your previous responses, please provide descriptions for: - Automatic wet-pipe sprinkler and spray systems - describe the protected equipment:						
11b_4	Based on your previous responses, please provide descriptions for: - Automatic deluge spray systems - describe the protected equipment:						
11b_5	Based on your previous responses, please provide descriptions for: - Automatic clean agent / gaseous systems - describe the protected equipment:	For the enclosure, clean agent or water mist shall be used. Water mist is the best option.	While it is not a gaseous extinguishing system, water mist is the best option for turbine enclosures		NOVEC 12390, FM200, water mist		

#	Question	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5	Respondent 6
11b_6	Based on your previous responses, please provide descriptions for: - Automatic foam-solution sprinkler system - describe the protected equipment:	CAFS system for transformer rooms.					
11b_7	Based on your previous responses, please provide descriptions for: - Fire extinguishers - describe the protected equipment and access to firefighting PPE such as SCBA:	Located throughout the facility in accordance with NFPA 10.	CO2 and dry chemical extinguishers are located as per NFPA 10 and USCG CFR requirements.		NacelleThe need for automatic fixed fire protection within the nacelle of a wind turbine generator should be based on the Fire Protection Design Basis and associated Fire Risk Evaluation. An AFP should cover electrical enclosures and cabinets within the nacelle and tower. Likewise, a local application extinguishing system might be appropriate for the gearbox lubrication system or hydraulic control system. If used, fire suppression capability should be provided for oil piping or any area where oil can flow, accumulate, or spray. Fire extinguishing systems, where provided for hydraulic control equipment, should include protection of reservoirs, pumps, accumulators, piping, and actuating systems.		
11b_8	Based on your previous responses, please provide descriptions for: - Other - describe the protected equipment:						

#	Question	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5	Respondent 6
Q12	12. For offshore substations, what types of fire protection systems are used? (Select all that apply)	Automatic clean agent / gaseous systems, Automatic foam-solution sprinkler system, Fire extinguishers	Automatic clean agent / gaseous systems, Automatic foam-solution sprinkler system, Fire extinguishers		Hydrants and hoses, Monitors, Automatic wet-pipe sprinkler and spray systems, Automatic deluge spray systems, Automatic clean agent / gaseous systems, Automatic foam-solution sprinkler system, Fire extinguishers	Automatic wet-pipe sprinkler and spray systems, Automatic deluge spray systems, Automatic clean agent / gaseous systems, Automatic foam-solution sprinkler system, Fire extinguishers	
12b_1	Based on your previous responses, please provide descriptions for: - Hydrants and hoses - describe the protected equipment and access to firefighting PPE such as SCBA:				for manned substations		
12b_2	Based on your previous responses, please provide descriptions for: - Monitors - describe the protected equipment and access to firefighting PPE such as SCBA:				helideck		
12b_3	Based on your previous responses, please provide descriptions for: - Automatic wet-pipe sprinkler and spray systems - describe the protected equipment:				living quarters, diesel generator rooms	Heli deck DIFFS	

#	Question	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5	Respondent 6
12b_4	Based on your previous responses, please provide descriptions for: - Automatic deluge spray systems - describe the protected equipment:				oil filled devices: Shunt reactor rooms, main/auxiliary transformer rooms, diesel generator rooms, rooms containing gas bottles filled with flammable gas, fire water pump rooms etc.	Heli fuel Units	
12b_5	Based on your previous responses, please provide descriptions for: - Automatic clean agent / gaseous systems - describe the protected equipment:	Inergen for the battery rooms	Inergen for battery rooms.		control rooms, switchgear rooms, battery rooms, HVAC rooms, UPS rooms, electrically driven crane engine rooms, LV and HV rooms, telecommunication or public address rooms etc.	Control /Electrical / SCADA panels	
12b_6	Based on your previous responses, please provide descriptions for: - Automatic foam-solution sprinkler system - describe the protected equipment:	CAFS for the transformer rooms	Compressed air foam system for transformer rooms.		diesel generator rooms, diesel tank area etc.	Transformers	
12b_7	Based on your previous responses, please provide descriptions for: - Fire extinguishers - describe the protected equipment and access to firefighting PPE such as SCBA:	Located in accordance with NFPA 10	CO2 and Dry chem are located as per USCG CFRs and NFPA 10.		All	Electrical and oil equipment	
12b_8	Based on your previous responses, please provide descriptions for: - Other - describe the protected equipment:						

#	Question	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5	Respondent 6
Q13	13. Do you have a current inspection, testing, and maintenance program for fire alarm and fire suppression system for offshore wind turbines and substations?	No	Yes		Yes	Yes	
Q13a	Briefly describe testing method and frequency:		Testing method and frequency is as per NFPA requirements.		It depends on the operator's requirements, applicable standards (NFPA, VdS, etc.), manufacturer's recommendations for a given system, etc. The program is developed as a resultant of all these requirements.	Testing according to Manufacture recommendations min. yearly inspection / test	
Q13b	Does the program follow an industry or corporate inspection and testing program? - Selected Choice		Industry		Industry	Corporate	
Q13b_3_TEXT	Does the program follow an industry or corporate inspection and testing program? - Other - please describe: - Text						
Q14	14. What is the water supply for the water-based fire protection system? - Selected Choice				On-site fresh-water storage tank	On-site fresh-water storage tank	
Q14_4_TEXT	14. What is the water supply for the water-based fire protection system? - Other - please describe: - Text						

#	Question	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5	Respondent 6
Q15	15. For offshore wind turbine generators, what types of fire detection systems are used? (Select all that apply)	Smoke detection, Heat detection, Visual flame detection	Smoke detection, Heat detection, Visual flame detection		Smoke detection, Heat detection, Linear detection, Aspirating smoke detection		
15b_1	Based on your previous responses, please provide descriptions for: - Smoke detection - describe protected equipment	Inside the turbine enclosure and located in accordance with NFPA 72.	Smoke detection is provided as per NFPA 72.		Electrical Equipment		
15b_2	Based on your previous responses, please provide descriptions for: - Heat detection - describe protected equipment	Inside the turbine enclosure and located in accordance with NFPA 72.	Heat detection is provided as per NFPA 72.		gearbox lubrication system, hydraulic control system, transformers,		
15b_3	Based on your previous responses, please provide descriptions for: - Linear detection - describe protected equipment				gearbox lubrication system, hydraulic control system, transformers		
15b_4	Based on your previous responses, please provide descriptions for: - Aspirating smoke detection - describe protected equipment				Electrical Equipment		
15b_5	Based on your previous responses, please provide descriptions for: - Visual flame detection - describe protected equipment	Flame detection inside the enclosure.	Flame detection provided based on industry best practice.				

#	Question	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5	Respondent 6
15b_6	Based on your previous responses, please provide descriptions for: - Manual activation - describe location						
15b_7	Based on your previous responses, please provide descriptions for: - Other						
Q16	16. For offshore substations, what types of fire detection systems are used? (Select all that apply)	Smoke detection, Heat detection, Visual flame detection, Manual activation	Smoke detection, Heat detection, Visual flame detection		Smoke detection, Heat detection, Linear detection, Aspirating smoke detection, Visual flame detection, Manual activation	Smoke detection, Heat detection, Aspirating smoke detection, Visual flame detection, Manual activation	
16b_1	Based on your previous responses, please provide descriptions for: - Smoke detection - describe protected equipment	Located in accordance with NFPA 72.	Smoke detection is provided as per NFPA 72.		Mechanically ventilated utility spaces, control rooms, switchgear rooms, HV capacitor rooms, battery rooms, instrument rooms, local equipment rooms, telecommunication or public address rooms, HVAC rooms, electrically driven crane engine rooms, UPS room, LV and HV rooms, Diesel generator or generator rooms, Firewater pump rooms, Accommodation: cabins, corridors, staircases, public rooms, radio room, laundry	Electrical, transformer, HVA/C, Generator storage rooms	

#	Question	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5	Respondent 6
16b_2	Based on your previous responses, please provide descriptions for: - Heat detection - describe protected equipment	Located in accordance with NFPA 72.	Heat detection is provided as per NFPA 72.		Main transformer/reactor rooms, auxiliary transformer rooms (units filled with mineral oil, synthetic ester or dry insulated), Storage area, workshops, Paint store	workshops	
16b_3	Based on your previous responses, please provide descriptions for: - Linear detection - describe protected equipment				Main transformer/reactor rooms, auxiliary transformer rooms (units filled with mineral oil, synthetic ester or dry insulated)		
16b_4	Based on your previous responses, please provide descriptions for: - Aspirating smoke detection - describe protected equipment				rooms with electrical equipment	Valve halls	
16b_5	Based on your previous responses, please provide descriptions for: - Visual flame detection - describe protected equipment	Supplementary coverage for fire protection system activation.	Flame detection provided based on industry best practice.		Main transformer/reactor rooms, auxiliary transformer rooms (units filled with mineral oil, synthetic ester or dry insulated), Diesel generator or generator rooms, Fuel oil storage, diesel engine room, Open decks and areas subject to high air speeds	Generator, open decks, oil storage area	
16b_6	Based on your previous responses, please provide descriptions for: - Manual activation - describe location	Manual alarm call points spaced in accordance with API guidelines.			at the entrance to rooms with active fire protection systems	Outside all protected rooms, further SCS activation	
16b_7	Based on your previous responses, please provide						

#	Question	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5	Respondent 6
	descriptions for: - Other						
Q17	17. Do you provide smoke ventilation systems for wind turbine generators or offshore substations?	No	No		No	No	
Q17b _1	If yes, - What are they protecting?						
Q17b _2	If yes, - Are they controlled/interlocked by the fire alarm system?						
Q18	18. Is the fire alarm system centralized and monitored with a SCADA system? - Selected Choice	Yes, please describe the system:	Yes, please describe the system:		Yes, please describe the system:	Yes, please describe the system:	
Q18_ 1_ TEXT	18. Is the fire alarm system centralized and monitored with a SCADA system? - Yes, please describe the system: - Text		NFPA 72 based Fire Alarm Control Panel with feed into DCS/SCADA.			Fire Alarm System with panel and signals to SCADA	
Q18_ 2_TE XT	18. Is the fire alarm system centralized and monitored with a SCADA system? - No, please describe other monitoring system: - Text						
Q19	19. What do you see as the primary fire risk for the unmanned wind turbine generators and/or offshore substations?	Transformer fires.	Asset protection / business interruption. It seems like most are unmanned with periodic occupancy, so the risk to personnel is reduced.		oil filled equipment (Shunt reactor rooms, main/auxiliary transformer rooms)	Rotating equipment running warm and loose electrical connections	

#	Question	Respondent 1	Respondent 2	Respondent 3	Respondent 4	Respondent 5	Respondent 6
Q20	20. Have you experienced a fire loss in an offshore wind turbine generator or offshore substation?	No	No		No	No	
Q20b	Briefly describe the fire event:						