Risk Management Of Work At Height In Higher Capacity Wind Turbines

Prem Kumar R[1], R. Saravanan[2], R. Bharathiraja[3], C. S. Rathnasabapathy[4]

[1]Research Scholar, Department of Chemical Engineering, Annamalai University, Annamalai Nagar, Chidambaram, Tamil Nadu, India

[2]Professor, Department of Chemical Engineering, Annamalai University, Annamalai Nagar, Chidambaram, Tamil Nadu, India

[3]Professor, Department of Chemical Engineering, Veltech High Tech Dr.Rangarajan Dr.Sakunthala Engineering College, Avadi, Chennai, Tamil Nadu, India

[4]Associate Professor, Department of Chemical Engineering, Annamalai University, Annamalai Nagar, Chidambaram, Tamil Nadu, India

Abstract

The evolution of higher capacity wind turbines has been a remarkable journey marked by technological advancements, engineering innovation, and increased efficiency. Over the years, wind turbine technology has continuously evolved to harness stronger winds, generate more electricity, and meet the growing demand for clean and renewable energy. The global average onshore turbine size, in terms of capacity, increased from 1.64 MW in 2010 to 3.68 MW in 2021 due to improved efficiency and yield of large turbines. Offshore installations usually have significantly larger turbine sizes than onshore installations. While most offshore turbines are larger than 2 MW, some offshore sites have installed turbines larger than 7 MW. The global average offshore wind turbine size in 2021 was 5.88 MW. This capacity enhancement per wind turbine brings increased tower heights, longer blades and increased rotor size resulting in increased generation of wind power. Increase in the size of the wind turbines and its components bring new challenges in transport, construction, operation, maintenance, de-commissioning of turbine and its components.

Wind turbine industry for more than four decades faces the issue of people falling from height leading to injuries of very serious in nature and leading to many fatalities till date. This study discusses the safety management considerations for working at heights and measures that are needed on the wind turbine to manage the work at height risks during its lifetime using innovative technologies which are new and best in the industry.

Keywords: Wind turbine, Risk assessment, Work at heights, GWO training, Safe transportation tools and AI safety gear technology.

Introduction

Wind turbine manufacturers produce large wind turbines for several reasons, each of which contribute to maximizing the efficiency, energy production, and economic viability of wind power generation. Some key reasons include the following

Higher Energy Output: Larger wind turbines generally have larger rotor diameters and taller towers, allowing them to capture more wind energy. The larger the rotor sweep area, the more wind the turbine can intercept, leading to higher energy production. This is particularly important as wind energy generation is directly proportional to the cube of the wind speed.

Economies of Scale: Manufacturing larger turbines can lead to economies of scale, where the cost per megawatt of capacity decreases as the size of the turbine increases. This means that, while the upfront cost may be higher for a large turbine, the cost per unit of energy produced is often lower.

Reduced Installation and Maintenance Costs: Large turbines with higher hub heights can access stronger and more consistent winds at higher altitudes. This can lead to more stable energy generation, reducing the need for maintenance and enhancing the overall reliability of the turbine.

Improved Cost Competitiveness: As wind energy competes with other forms of energy generation, manufacturers strive to make wind power more cost competitive. Larger turbines help achieve this goal by producing more energy per turbine, which can offset the initial investment and operational costs.

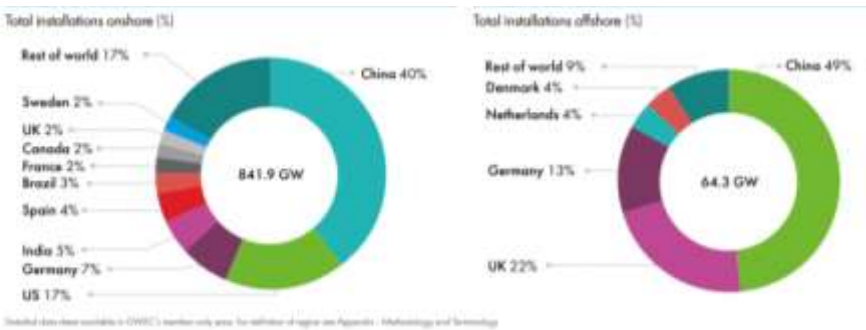
Land Use Efficiency: Large turbines can produce more energy while utilizing the same land area as smaller turbines. This is particularly beneficial in areas with limited available land for wind farms, making the most efficient use of the space.

Environmental Impact: Producing more energy per turbine reduces the need to install and maintain a larger number of smaller turbines, potentially minimizing the overall environmental footprint of wind farms.

With above benefits, working at height hence now becomes an integral and challenging aspect of the wind energy industry, particularly in the context of wind turbine maintenance, installation, and inspection. Wind turbines are complex structures, often reaching towering heights, and require specialized skills, equipment, and safety measures to ensure the well-being of workers and the successful execution of tasks. This introduction provides an overview of the significance, challenges, and safety considerations associated with working at height in wind turbines. Wind turbines harness the power of the wind to generate clean and renewable energy. However, their towering structures, often exceeding **120 meters** in height, necessitate frequent maintenance, repair, and inspection to ensure optimal performance and safety. These tasks are carried out by skilled technicians and workers who operate at significant heights, making working at height a critical component of the wind energy industry.

Every year [1], the wind sector grows more and more. This indicates that more people are being hired each year for various positions within the wind energy industry. Many workers are exposed to dangers that could cause them to get hurt, suffer long-term harm, or even die. When possible, dangers should be totally removed. Preventive steps should be attempted to lessen the risk if this is not practicable. The increasing trend of the percentage of onshore and offshore installations of wind turbines across the globe in the year 2022 are given in Fig. 1.

Fig. 1. Total onshore and offshore installations as of 2022



1.1 Continued Challenges in Working at Height

Working at height in wind turbine industry presents a unique set of challenges that require risk management consideration in the design or product, work process/methods, storage and transportation tools, specialized training in area of work at heights, documented procedures, and instructions with necessary precautions. Every effort should be made to avoid working at heights and the exposure to a fall risk whenever possible. Although, there is a long history of successfully managing dangers related to working at height, still the incidents are repeatedly happening. In this article, the work at height situations, their current design and their challenges are discussed with the measures required to bring down the risk.

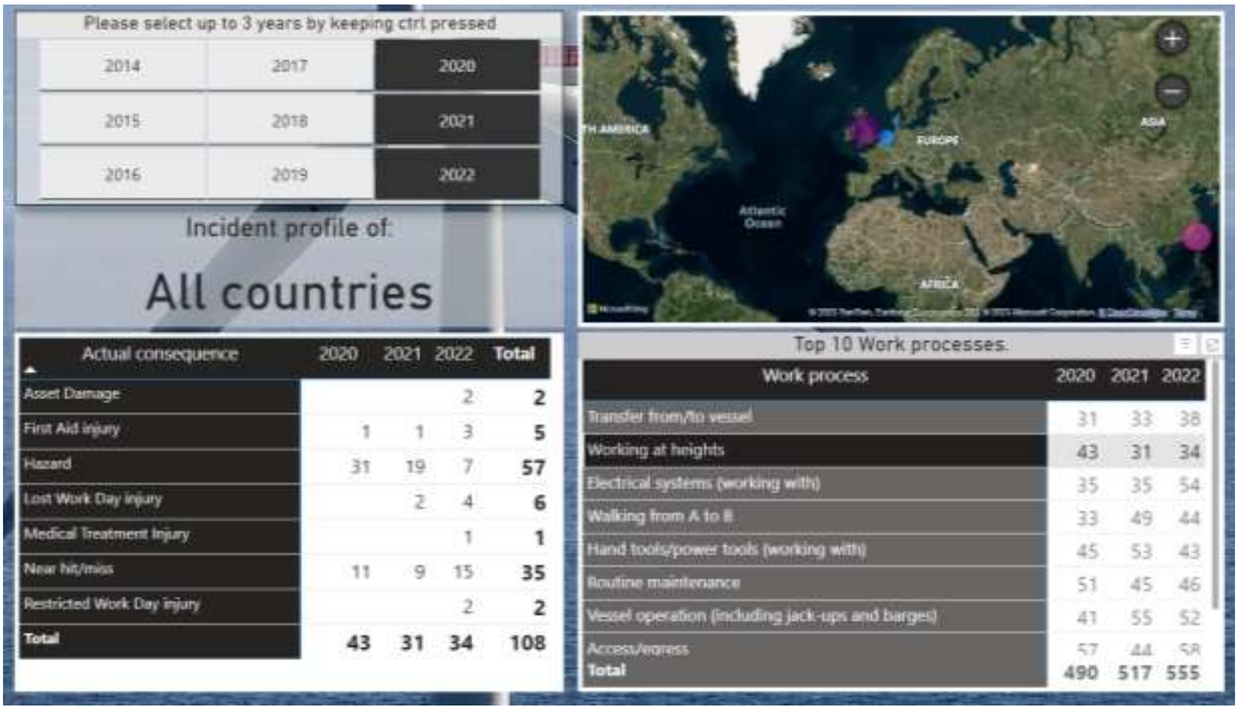
1.2 Accidents scenario of working at height.

Working at height in a wind turbine refers to the tasks and activities performed by technicians and workers while situated above the ground, typically at significant heights within a wind turbine structure. These wind turbines are tall structures designed to harness wind energy and convert it into electricity. These turbines consist of various components, including the tower, nacelle (housing the generator and other machinery) and rotor blades. Workers who engage in work at height in wind turbines are often referred to as wind turbine technicians, installation and commissioning technician, service technicians, or wind techs. Their primary responsibilities include inspection, maintenance, repair, and installation of various components within the wind turbine. This can involve tasks such as installation of wind turbine or its components, checking the condition of rotor blades, performing electrical repairs, conducting routine inspections of the turbine's systems and repair and replacement of components. Everyday wind turbine technicians need to access heights within the turbine structure to carry out their tasks. This requires climbing the tower through internal ladders, staircases or even external climbing systems. Depending on the turbine's size and design, technicians may need to ascend several tens to over a hundred meters above the ground.

Safety is of paramount concern when working at height in wind turbines due to the inherent risks associated with elevated work. A better infrastructure and climbing facility are provided for last two decades by all wind turbine manufacturers like approved ladders, availability of service lifts and availability of climb assist system. Technicians are trained and are mandated to wear appropriate personal protective equipment (PPE), such as safety harnesses, helmets, and safety lines. These measures have improved the working environment to prevent and reduce falls and ensure the well-being of workers.

Despite of the above measures, the industry is repeated witnessing fatal accidents related to work at height every year since 1980 till date as per the sources reported. The number of incidents [2] in offshore for the year 2020-2022 is presented in Table 1 which shows a total number of 108 incidents including hazardous observation related to work at height in all countries.

Table 1. Incidents reported in offshore from 2020 to 2022 related to work at height.



Actual consequence	2020	2021	2022	Total
Asset Damage			2	2
First Aid injury	1	1	3	5
Hazard	31	19	7	57
Lost Work Day injury		2	4	6
Medical Treatment Injury			1	1
Near hit/miss	11	9	15	35
Restricted Work Day injury			2	2
Total	43	31	34	108

Work process	2020	2021	2022
Transfer from/to vessel	31	33	38
Working at heights	43	31	34
Electrical systems (working with)	35	35	54
Walking from A to B	33	49	44
Hand tools/power tools (working with)	45	53	43
Routine maintenance	51	45	46
Vessel operation (including jack-ups and barges)	41	55	52
Access/egress	57	44	58
Total	490	517	555

Similarly, the incidents on onshore is also studied for the period the year 2020-2022. At least 3 fatal accidents are reported from different parts of the world. Details of accidents are listed in Table 2.

Table 2: Fatal accidents related to work at heights as per the reported sources from the year 2020 to 2022.

2702	WAH	Fatal	19/01/2020	Tonstad wind farm, Sirdal	Finland	"Finsk arbeider omkom i ulykke i Sirdal" (In Finnish - Finnish worker died in accident in Sirdal). Report of a fatality at Tonstad wind farm, Sirdal, Finland. The 40- year old male worker died as the result of a fall. Police are now investigating.	Reported by NRK Sorlandet on 19 Jan 2020
2778	WAH	Fatal	20/06/2020		Brazil	"Operário cai de torre eólica em que trabalhava e morre no RN" (In Portugese - Worker falls from the wind tower where he worked and dies in RN). Report of a fatality at a wind farm construction site in Rio Grande do Northe. The accident happened on Saturday morning, 06/20, when worker Gerson Alves da Silva, 21 years old, died when he fell 35m from one of the wind energy towers located in Vila Acre, in the city of Serra do Mel, far 37 km from Mossoró, in the western region of Rio Grande do Norte. Two other workers were left hanging and managed to escape.	Reported by CPG https://clickpetroleoegas.com.br/ on 22 June 2020
2832	WAH	Fatal	24/09/2020	Langford Wind power farm, Christoval, Texas	USA	"Big Spring man dies in fall from Tom Green County wind turbine". 39 year old Aaron Scott Johnson had been working on the turbine when he fell 80-100 feet. He had been working alone and his body was only discovered several hours later. He was pronounced dead at the scene.	Reported by sanangelolive.com and San Angelo Standard-Times on 24 September 2020
2998	WAH	Fatal	04/01/2021	Whitewater, California	USA	"Calexico man identified as victim of fatal 100-foot fall inside Whitewater turbine". Mario Contraras Jr, a 52- year old employee of Site Constructors Inc. was named as the victim of a fatal fall inside a wind turbine at Whitewater, California. An investigation is underway.	Reported by www.desertsun.com on 4 January 2021
3078	WAH	Fatal	03/06/2021	Tom Green County, Texas	USA	"Wrongful death lawsuit filed after man dies from fall at a wind turbine". Report of a fatality at a wind turbine in Tom Green County, Texas. A maintenance worker fell 80 feet. He had been left to work alone and court documents report that no guard rail was present at the third floor access hole, where he fell from.	Reported by sanangelolive.com on 3 June 2021
3190	WAH	Fatal	17/01/2022	Windpark Wilhelmshöhe 2, Uetze, Niedersachsen	Germany	"Uetze: Arbeiter stürzt im Windrad ab - und stirbt" (In German - Uetze: worker falls in wind turbine - and dies). Report of a fatal accident at Windpark Wilhelmshöhe 2, Uetze, in Niedersachsen. A 22-year old construction worker is reported to have fatally fallen 30-60 meters inside a wind turbine under construction.	Reported by NDR on 17 January 2022
3196	WAH	Fatal	24/01/2022	Potzneusiedl wind farm, Burgenland	Austria	"Probe after fatality at Austrian wind farm". Report of a fatal accident at a wind turbine under construction at the Potzneusiedl wind farm, Burgenland, in Austria. Enercon confirmed that the construction worker fell 100m inside one of the turbines under construction.	Reported by ReNews.biz on 24 January 2022
3275	WAH	Fatal	05/06/2022	Viking wind farm, Shetland, Scotland	UK	"Viking Shetland wind farm: Man dies at Upper Kergord construction site". Report of the fatality of a construction worker at the Upper Kergold construction site for Viking wind farm in Shetland. The 23-year old man died at the scene on Sunday 5 June. An investigation is underway by site operator BAM Nuttall	Reported by The Herald on 8 June 2022

Source: Wind Energy Global Incident statistics [3]

Many of fall from heights are reported at construction site during the phase of installing and commission wind turbines. These are primarily done by a developer company who are tier 2 or tier 3 to the wind turbine manufacturing companies or to the customer. Individuals in this work force they often change companies for a better renumeration. Hence training /refresher training to the large work force by the tier 2 or tier

3 is a continuous ongoing process. Sometimes this training process is compromised due to project timelines. Many administrative controls do fail in a project site as there could many be activities happening in parallel or peak project period where the workforce focus would shift on the high priority task and giving least priority to activities related to work at heights. This situation endangers the safety of the worker working at heights.

The study also reveals that many of the accident happened because of unsafe acts and few because of unsafe condition. Some most common behavioral factors are rushing due to sudden unexpected changes; unrealistic planning; the need to get home, and pressure from management to meet contractual agreements. The workforce also perceives the risk to be due to complacency; learnt behaviors/culture, and lack of impact from training [4,5].

Most common measures that have been implemented post incident are alerts and communication, Refresher Training, Posting Safety Signs and Poster, Changing the working company or the workforce, establishing new procedures, controlling the work with work permit. Challenge to this “Control of work” may not work because of remote location / operation. The above are least effective measures related to hierarchy of controls. Very rarely the design change will or may happen. Those are update to a better infrastructure with alternate arrangements, climbing facilities like approved ladders, availability of service lifts, availability of climb assist system etc.,

Work at heights is the most frequent activity happening across wind industry in all life cycle phase of wind turbine. All wind turbine manufacturers, associated organizations, customers have established various safety rules pertaining to their operations out of which the most common one is rule of working at heights. In spite to this rule still accidents resulting in fall from height are reported resulting average 3 fatalities per year (reported and non-reported sources) since 1981 till date. Hence, it is required to revisit the current measures based on the learnings, thorough a proper risk assessment technique, identify the gaps and improve the design measures, process measures related to work at heights. The industry needs to take it seriously as this activity is happening in all lifecycle phase of the machine or wind turbine.

Referring to the theory from Herbert Heinrich and Frank Bird [6], it is predicted that there are lot of unsafe acts related to work at heights which could have resulted in severe or fatality. This is illustrated in the Fig. 2. Most accidents could be predicted and prevented by acting on minor incidents and the behavior of employees. Hence, to reiterate the safe behavior on work at heights and address unsafe conditions in the work environment, every stakeholder such as manufacturer, service providers, owners, or customers had established many rules in line with their safety policy. The most common one is “Rule of Work at Heights” which say protect yourself against fall when working at heights great than 1.8 mts or always use fall protection when working at height.

Fig. 2. Safety Pyramid

1.3 Climbing facilities in wind turbine.

The infrastructure for climbing in wind turbines is a critical aspect of ensuring the safety of technicians and workers who need to access various parts of the turbine for maintenance, inspection, and repair. Climbing in wind turbines involves a combination of physical structures, safety equipment, and protocols to minimize risks and ensure efficient and safe access. Below are some of the components or infrastructure available in wind turbine for climbing in wind turbines:

It's important to note that the specific climbing infrastructure can vary based on the design and size of wind turbines, as well as local regulations and safety standards. The infrastructure is designed to minimize the risks associated with working at heights and to provide a safe environment for technicians to carry out their tasks effectively.

Ladders - Wind turbines are equipped with internal and external ladders that allow technicians to ascend and descend the tower safely. The industry, in the recent upgrade of turbine development, moved to approved ladders conforming to standards which fall under the machinery safety regulations. The primary standard relevant to the safety of ladders in wind turbines is:

EN ISO 14122 - Safety of Machinery: Permanent Means of Access to Machinery. This standard, part of the ISO 14122 series i.e. Part 1-4, provides guidelines and requirements for the design, construction, and installation of permanent means of access, including ladders, stairs, and walkways, for various types of machinery, including wind turbines. The standard aims to ensure the safety of personnel accessing machinery for operation, maintenance, inspection, and other tasks.

These standards specify requirements for dimensions, clearances, access points, guardrails, handrails, steps, rungs, load-bearing capacities, and other safety-related aspects of permanent means of access. They aim to ensure that ladders and other access systems are designed to prevent falls and provide safe access for maintenance and other activities.

Fixed ladders equipped with cages or enclosures provide additional fall protection for workers accessing rooftops or other elevated areas. Platforms can be installed at various levels to provide rest areas.

Fixed personal fall protection system - A fixed fall protection system is a permanent safety solution designed to prevent falls from heights in various industrial and commercial settings. These systems are installed on structures such as rooftops, walkways, platforms, and other elevated areas where fall hazards exist. Fixed fall protection systems offer continuous protection for workers who need to access elevated areas as part of their job duties. Here are some common types of fixed fall protection systems.

a. Guardrails and Handrails: Guardrails and handrails are physical barriers that provide edge protection to prevent workers from accidentally falling off elevated surfaces. They are designed to meet specific height and load requirements.

b. Horizontal Lifeline Systems: Horizontal lifeline systems consist of an anchored cable that spans across a work area, allowing workers to attach themselves to the lifeline and move horizontally while remaining connected. This is given in Fig.3.

Fig. 3 Horizontal Lifeline Systems

c. Vertical Lifeline Systems: Vertical lifeline systems include a rope or cable that runs vertically, often along ladders or fixed structures. Workers can attach themselves to the lifeline using a fall protection harness and move up or down while secured. EN 363 PFPE Personal fall protection equipment - Personal fall protection system.

d. Fall Arrest Rail Systems: These are rail-based systems installed along walkways, platforms, or edges of elevated areas. Workers can attach themselves to the rail system with a lanyard or self-retracting lifeline.

e. Anchor Points: Fixed anchor points are installed on structures to provide secure attachment points for personal fall protection equipment. These points are strategically located to allow workers to connect while performing tasks at heights.

ISO 14567, Personal protective equipment for protection against falls from height. Single point anchor points

Service Lifts or Elevators - Many of the larger wind turbines have service lifts or elevators that provide a more convenient and efficient way to access higher parts of the turbine. Service lifts, also known as elevators or hoists, play a crucial role in ensuring safe and efficient access for technicians and maintenance personnel within wind turbines. These lifts are designed to transport individuals and equipment vertically through the height of the turbine, providing a convenient and secure means of reaching different levels for maintenance, inspections, repairs, and other tasks. These service lifts are customized for wind turbines which are designed and manufactured according to relevant local legislations, standard and guidelines as below.

Although many of the turbines are equipped with this special purpose or service lift, still people need to climb turbine because of design complexity in top tower section or bottom tower sections in case of hybrid towers.

Staircases and platforms - In addition to ladders, some turbines incorporate staircases, especially in areas where frequent access is required. The wind turbine has also Platforms and rest areas, such as service platforms which are horizontal resting areas installed at various heights on the tower. They provide a safe space for technicians to take breaks and regroup during their ascent or descent. Also, few turbines because of their design complexity they also have Transition Platforms which are located at the transition points between tower sections and provide a secure place to change from one ladder to another. Some turbines have safety cages around ladders to prevent workers from accidentally falling off the ladder.

Access areas in wind turbine with the above climbing facilities have suitable fall arrest systems, approved anchor points which are verified and validated during the design and development or product. These systems demand every technician to use their own Personnel Protective Equipment such as full body safety harnesses, twin tail lanyards, work positioning rope, fall restraints, fall arrester and anchor points that protect technicians in case of a fall. They allow workers to be attached to a secure anchor point while climbing.

Access doors and hatches - Wind turbine towers are designed with access doors and hatches at different levels to allow technicians to enter and exit safely. These doors are equipped with locking mechanisms to prevent unauthorized access. The hatches are also designed with self-closing mechanism i.e., with gas dampers. In addition to that all the climbing facilities so have adequate illumination with emergency backup. This adequate lighting becomes essential to ensure visibility for technicians climbing within the tower, especially in low-light conditions or carrying out maintenance during nights. The manufacturer or the operators also provides a head torch lamp to the individual who access wind turbine for their work routines.

Safety Signage and Route marking: Clear and standardized signage helps workers identify the correct routes and access points. Auto glow signage are also available in the wind turbine to move safely within turbine during normal access and in case of emergency that might lead to escape or evacuate.

Some hazardous situations from the industry involving workers working at height is shown in the Fig. 4. which represents presence of person on the nacelle roof for drive train installation, presence of two person on the nacelle for hub installation and presence of persons on the nacelle for crane less component exchange in maintenance.

Fig. 4 Work at height activities drive train installation, hub installation, generator replacement.

Materials and Methods

To improve health and safety conditions at workplace risk assessment becomes an integral tool to identify risks and opportunities in the product design and development process. The risk assessment is performed to ensure the safety of the people working in wind turbine. The main requirements for the identification of HSE risks is derived from directive 89/391/EEC article 9 in the EU (Measures to encourage improvements in the safety and health of workers at work), the ISO 14001 (4.3.1 Environmental aspects), and ISO 45001 (6.1 Action to address risks and opportunities).

Safety risk assessments can take various forms depending on the context, scope, and industry. Some of the common types of safety risk assessments include Hazard and Operability Study (HAZOP), Job Safety Analysis (JSA) or Job Hazard Analysis (JHA), Hazard Identification (HAZID), Failure Modes and Effects Analysis (FMEA): Bowtie Analysis Event Tree Analysis (ETA): Fault Tree Analysis (FTA), Quantitative and qualitative Risk Assessment (QRA) etc., In these methods each one has its own advantages and limitations.

To reduce the complexity, a Qualitative Risk Assessment methodology is carried out which involves using numerical data and constructing a 5 x 5 matrix with the probability or likelihood and consequence or severity [6] to assess risks through cross functional team approach. This specific assessment method is chosen considering based on the needs of the situation such as the nature of the risk, the goals of the assessment, and the industry or context in which it is applied. [8]. The Table 3 explains the various ratings for the probability and severity with a scale of 1 to5.

Table 3: Risk assessment matrix – Probability 1-5 scale, Severity 1-5 scale

RISK MATRIX				Consequence or Severity Score [How Severe could outomes be if the risk event occurred]				
			Severity	**Illness causing Non-disability.**Injury resulting in First Aid, or no treatment at all. No need for formal medical treatment by registered medical professionals before returning to work. No Lost Time Injury.	**Illness causing temporarily disability Injury** resulting in Medical Treatment by a physician or registered professional, or Restricted Work. (able to return to same work sooner)Injury or illness resulting in Medical Treatment by a physician or registered professional, or Restricted Work. (able to return to same job)	**Illness causing partial disability.** Injury resulting in Lost Time Injury. (able to return to same work at later point)	Illness causing permanent disability or reduction in normal life expectancy Serious Injury, or injury preventing staff from returning to work at OEM. (unable to return to same work)	**Fatal injury or Permanent disabling injury** or illness (unable to return to any work)
				1. Insignificant	2. Minor	3. Medium	4. Major	5. Catastrophic
Probability Score / Chance of Occurance	**Likelihood**							
	Unusual sequence / coincidence can occur but is hard to imagine.	5.Very Likely		Medium (5)	High (10)	Very High (15)	Very High(20)	Very High (25)
	Can occur but similar events are not common.	4.Likely		Medium (4)	Medium (8)	High (12)	Very High(16)	Very High (20)
	Similar events have occurred.	3.Possible		Low (3)	Medium (6)	Medium (9)	High (12)	High (15)
	Could happen any timetime..	2.Unlikely		Very Low(2)	Medium (4)	Meduim (6)	Medium (8)	Medium (10)
	Almost certain, happens as a regular occurrence.	1.Very unlikely		Very Low(1)	Very Low(2)	Low (3)	Meduim (4)	Meduim (5)

During the early phase of wind turbine design, need to identify, analyze, and manage the risks related to the health and safety of people, following the principles of ISO12100 (Safety of machinery – General principles for design – Risk assessment and risk reduction) [9]. Following the standard helps the designer in designing a safer product by applying the hierarchy of control and document the design process, ensuring compliance with the Machinery Directive and/or other applicable legislation.

The risk assessment for the activities involving work at height in the wind turbine are taken and analyzed in Fig.7.7. The initial risk score is 20.

Figure 7: Work at height -Assessment of Risks using 5 X 5 – Probability, consequence matrix.

Hazard Type / Hazard Group	Activity / Work in the Wind farm site	Hazard outcome / Risk	Severity	Likelihood	Initial Risk Score	Risk Mitigation Plan	Residual Hazard outcome / Risk	Severity	Likelihood	Residual Risk	Risk Statement	Phase of WTG
Mechanical Hazard	Working at height in the tower. (From tower ladder, service lift, Yaw deck Nacelle, Nacelle roof, Hub & locations allowing for fast rescue).	Risk of falls from height resulting in severe injury or death.	5	4	20	**Design Mitigations** • Design required climbing facilities as per risk assessment in reference to Machinery directive 2006/EC/42 & ISO 12100 • Provide ladders & access means which are in reference to EN ISO 14122 11.3.1EU. "EN 795Personal fall protection equipment - Anchor devices 11.3.2ISO 14567Personal protective equipment for protection against falls from a height — Single-point anchor devices • Provide approved anchor point in the point of use /work vicinity • Make sure that all platform hatches are automatically closed when they are not in use. • Design AI safety gear detection technology in the towers, platforms, service crane hatch & Nacelle to ensure compliance with personal protective equipment (PPE) regulations and safeguard the workforce. **Process Mitigations** • Ensure the work force is trainined & qualified as per GWO requirments • Make sure that all platform hatches are closed when they are not in use. • Make sure that there are no persons in the areas where overhead work is done • Design tools such as Protable Safety Railings, Customised Cover plates, Protable anchor units such as tripod etc., • Obey the rules for work at height. Refer to local requirements. • Use work positioning rope and fall arrest lanyard in combination to restrict movement. • Use the necessary PPE for working at height. The PPE must be attached to approved anchor points, slides, or cables. • Use the Vertical and or horizontal lifelines based on task specific arrangement. • Use AI safety gear detection technology to ensure compliance generates which can raise alarms & alerts for non-compliance, allowing immediate attenation to prompt corrective actions.	Risk of a fall from height with properly worn personal fall arrest equipment causing suspension trauma resulting in injuries.	4	2	8	Risk of fall from height.	Construction, Commissioning, Maintenance, De-Commissioning

From the above risk assessment [10], the below are the three important measures suggested discussed based on the case studies, incident reported so far with an aim to reduce the risk of work at heights. This requires immediate attention by the industry or manufacturers, operators of the windfarm, customers and or wind farm owners.

P-Plan, D-Do, C-Check, A-Act approach – Fig.8. Responsibilities of Designer and User on Risk management for work at heights [11,12,13]

Figure 8: Risk Management by designer and user [13,14,15,16]

Measure 1: Design and use AI safety gear detection technology in the towers, platforms and nacelle to ensure compliance with personal protective equipment (PPE) regulations and safeguard your workforce.[17]

AI-PPE detection refers to the use of artificial intelligence (AI) technology to identify and recognize personal protective equipment (PPE) worn by individuals. This technology plays a crucial role in ensuring workplace safety, compliance with safety regulations, and monitoring adherence to PPE requirements in various industries. AI-PPE detection systems use computer vision and machine learning algorithms to analyze visual data and determine whether individuals are wearing the necessary PPE.[18].

Here's how AI-PPE detection typically works:

1. Data Collection:

- Cameras or other visual sensors are strategically placed in the workplace to capture images or video footage of individuals.

2. Data Preprocessing:

- The captured visual data is preprocessed to enhance image quality, reduce noise, and prepare it for analysis.

3. Object Detection:

- Object detection algorithms, often based on deep learning frameworks like convolutional neural networks (CNNs), are applied to the data. These algorithms identify and locate objects of interest within the images, such as helmets, safety vests, gloves, goggles, and masks.

4. PPE Recognition:

- The AI system uses the detected objects to recognize specific types of PPE. This recognition is based on patterns learned from training data that include various images of people wearing different types of PPE.**Fig.9** Shows the detection of missing PPE with persons working in construction site using AI system.

Figure 9: PPE Recognition using AI system.

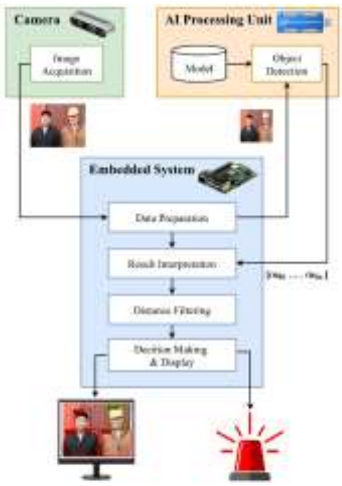
5. Alerts and Reporting:

- If the AI system detects that an individual is not wearing the required PPE, it can trigger alerts to notify relevant personnel or supervisors. This can also immediately raise alarm in the work vicinity allowing worker to immediately correct the situation and follow safe procedures.

6. Integration:

- AI-PPE detection systems can be integrated with existing safety and security systems, access control systems, or other monitoring tools to ensure a comprehensive approach to workplace safety and enter or climb wind turbine. Fig.10 shows the integration of Camera & AI processing unit to detect, monitor & report PPE compliance.

Figure 10: Architecture of PPE detection system



Implementation or Key Benefits of AI-PPE Detection are Enhanced Safety where AI-PPE detection helps ensure that workers are adequately protected by identifying instances where PPE is not worn. This supports in Regulatory Compliance. AI-PPE detection assists in meeting these compliance requirements. In addition to this, this system supports Real-Time Monitoring. The technology provides real-time monitoring, allowing immediate corrective actions to be taken if non-compliance is detected. This also helps in getting Data Insights which can be used to identify trends, areas of improvement, and training needs. This helps in reduced workload and increased control which does not allow people to reach heights for supervision and control. AI-PPE detection automates the process of PPE compliance checking, reducing the need for manual inspections.

Implementation of this technology's effectiveness depends on factors such as lighting conditions, camera placement, and the variety of PPE used in the workplace.

Measure 2: Design tools such as Portable Safety Railings, Customized Cover plates, Portable anchor units such as tripod etc., or use safety nets.

Cover plates, also known as floor or access whole covers, are safety devices used to mitigate the risk of falling into holes or openings in floors, walkways, or platforms. They are essential for preventing accidents and ensuring the safety of workers where there is a risk of fall. Use or need of cover plates shall be identified in the risk assessment and are to be customized according to the wind turbine design where there is a potential hazard of falling through openings [18]. These cover plates when placed over openings such as floor holes or service access points to create a secure and stable surface. This prevents individuals from accidentally stepping into these openings.

Situation 1: Working in Hub during maintenance and repair – Blade replacement process. Fig.11.represents the hazardous fall situation upon removing the blade through crane less solutions.

Figure 11: Fall situations during maintenance – Component replacement

Solution 1: Customized cover plate designed to cover the opening so that it is easy to install and use. Fig.12.represents the designer cover plates/ tool to manage hazardous / potential fall situation & prevent fall upon removing the blade through crane less solutions.

Figure 12: Cover Plate to Prevent fall during component replacement.

Cover plates are typically made from durable materials such as steel, aluminum, or fiberglass. The choice of material depends on the intended use and load requirements of the area. The cover plate's load capacity is crucial to ensure it can support the weight of people and equipment that might be passing over it. Some cover plates feature locking mechanisms to prevent unauthorized access or removal. This enhances safety by ensuring that the cover remains in place.

Some of the types of cover plates are.

a) Solid Covers: These are flat, non-slip plates that fully cover the opening. They provide a safe walking surface and prevent objects or individuals from falling through.

b) Grated Covers: Grated or perforated cover plates allow visibility of the area below while still providing a walking surface. They are commonly used in areas where light or ventilation is required.

According to the application the particular type to be selected considering the ergonomic aspects to mount, dismount and use it.

Situation 2: Hazardous / potential fall situations when using the service hoist in the nacelle. Fig.13.shown a wind turbine nacelle compartment where the preparation is done to use service hoist.

Figure 13: Fall Situation: Opening of service hatch in the nacelle rear end.

Solution 2: Portable safety railings are temporary barriers designed to prevent falls and provide edge protection in various work environments. They are versatile safety solutions that can be easily moved and set up in areas where there is a risk of falling, such as construction sites, maintenance projects, events, and temporary work platforms. Portable safety railings help ensure the safety of workers, other employees and equipment by creating a barrier between people and potential fall hazards. In addition to that AI-system can also be used to monitor, detect, raise alarm to correct and comply with PPE adherence.

The primary design consideration for portable safety railings is the ease of installation. Portable safety railings are designed for easy and quick setup without the need for extensive tools or permanent fixtures. This makes them suitable for temporary work areas. This should be designed to be stable and durable to withstand inclement weather conditions. In order to achieve primary purpose to prevent falls by creating a physical barrier, it is important to choose portable safety railings that are specifically designed for the intended application and that meet safety standards and regulations. When using portable safety railings, it's also crucial to ensure proper setup and installation to maintain their effectiveness in preventing falls and ensuring the safety of workers and others in the area.

Fall Safety nets: Fall safety net and border rope combo (System S) for use in wind turbines that complies with EN 1263-1. Additionally, the heavy, air-permeable woven cloth in combination with it shields employees inside from falling objects and equipment. The load-bearing fall safety net receives weights that are evenly distributed thanks to the woven tarp. Although the applicability is currently limited, it can be investigated.

Figure 14: Safety Net

Measure 3: Ensure the work force is trained and qualified as per GWO requirements on "Work at Height". [19]

Training the workforce as per Global Wind Organization (GWO) [19] is crucial for ensuring safety and competency in the wind energy industry. This also includes a refresher training to gain the necessary skill and competency for working at heights. GWO is an internationally recognized organization that establishes standardized safety training for workers in the industry.

Below is the data as on Q1’2023 from GWO, which shows a standard training gap on “WAH - Work at Heights” for the workforce across regions. There are around 450 training providers across globe and the training providers are increasing substantially every year to cater the needs of the industry.

Figure 15: Statistics from GWO on Training status across Global as in Q1’2023

Select Standards and Modules: bst (Group) + WAH (Code (Simplified))

Select Geography: All

Total Addressable Market Data by Region

Region	Total Addressable Market	Active Participants	Market Gap	Market Share
Europe	134145	91,313	30662	68.1 %
South America	20869	12,211	8471	58.5 %
Oceania	9920	2,807	7019	28.3 %
North America	69602	16,963	50884	24.4 %
Africa	9665	1,685	7931	17.4 %
Central America	450	53	396	11.8 %
Asia	318635	20,558	295392	6.5 %
Middle East	5435	239	5193	4.4 %
Total	**568721**	**145,619**	**405948**	**25.6 %**

GWO training covers various aspects of working in wind turbines such as work at heights, first aid, fire awareness, and manual handling. Below are the necessary steps to be followed for “Work at Heights” as a general guide on how to train the workforce according to GWO requirements:

1. **Identify Training Needs [20]:** Determine which GWO training modules are required based on the job roles and tasks performed by the workforce. Common modules include Basic Safety Training (BST), Work at Heights, Advanced Rescue Training (ART), and Enhanced First Aid (EFA).

2. **Select Approved Training Providers:** GWO-approved training providers offer training programs that adhere to GWO standards. Verify that the training provider you choose is GWO-accredited for the specific modules you need.

3. **Enroll Employees:** Enroll employees in the appropriate GWO training modules based on their roles and responsibilities. Ensure that they meet any prerequisites for specific courses.

4. **Attend Training:** Employees attend GWO training sessions conducted by certified instructors. Training is often a combination of theoretical lessons and practical exercises.

5. **Assessment and Certification:** Participants are assessed through written exams and practical assessments to ensure they have acquired the necessary knowledge and skills. Successful participants receive GWO certificates.

6. **Refresher Training:** GWO certificates are valid for a specific period (usually two years). It's essential to keep track of expiration dates and schedule retraining as required GWO recommends refresher training before the certificates expire to maintain competence. Refresher training ensures that employees are up to date with the latest safety practices and regulations.

   GWO training is not a one-time event. Wind industry safety is continually evolving, so ongoing training and education are essential to ensure a safe work environment. By following GWO training requirements, you're investing in the safety and competence of your workforce. This, in turn, contributes to better operational efficiency, reduced accidents, and improved overall safety culture within your organization.

Conclusion

Performing risk assessment before design the wind turbine, start of the task and continuously reviewing the risk assessment from time-to-time basis helps in identifying the pertinent gaps in a timely manner. This triggers to explore the best technologies in the market and implementing them in work site or product. The wind turbine safety manuals and work instructions (WI) related to manufacturing, installation, commissioning, service, maintenance, replacement, and decommissioning must clearly show the HSE risks identified in each process step and ensure that the people performing the work are informed about the HSE risks. It is critical to keep in mind that employers and employees both share responsibility for safety. Employees must be willing to work safely, use the resources that are available, and adhere to established processes, while employers must provide the appropriate infrastructure, resources, training, and support. Employers and employees can cooperate to achieve the shared objective of preserving a secure workplace and guaranteeing the welfare of all employees. Employers can contribute to the safe and effective completion of wind-turbine construction projects and maintenance by adopting a proactive attitude to safety.

Measures listed below, based on current risk assessment, help the industry to make “Zero accident” condition possible with respect to work at heights.

1. Conduct a thorough risk assessment.

An extensive risk assessment must be done before starting any work on wind turbines, including installation, commissioning, maintenance, and dismantling. The likelihood and severity of the injury or harm should be identified, analyzed and evaluated to determine the the potential risks associated with falls and working at heights. As a result, the risks will be prioritized, and a safety strategy will be worked out. Thus, the safety of the workforce will be improved by taking action to eliminate or reduce the hazards. It is also essential to keep the risk assessment up to date in order to spot and address new threats as quickly as feasible.

2. Access and Implement fall protection in the Design.

During the design and development phase of the product, 3D reviews or virtual reality session can help the designer as a cross function team approach to assess the situation and provide necessary measures such as selection of correct horizontal or vertical fall arrest system as per requirement or design needs, make the approved anchor or rescue points available at the point of use. Guardrails, safety nets, and other fall protection measures ought to be put in at heights where falls can occur. Employers must keep employees safe and lower the risk of harm by putting in place appropriate fall protection.

Utilization technologies such as AI for detection of PPE which can trigger for alarm and attract immediate focus in remote locations at heights. Also implementing cover plates and other measures required will come in handy. Continuous risk assessment provides an up-to-date understanding of the current risks that the organization or project is facing. This awareness allows for timely responses to emerging threats or changes in risk factors.

3. Train workers on the Work at Height Hazards / Situations.

All workers involved in wind-turbine construction and demolition should be trained on the hazards related to work at heights, correct selection and use of PPE including fall protection. Before assigning people to a task, this training should be given, and then, in accordance with industry requirements, refresher training should be given at least once every two years to keep employees informed of the most recent safety practices and recommendations. Employers may guarantee workers have the knowledge and abilities to perform safely and that they are aware of the hazards involved with their employment by offering training. By doing this, the probability of accidents and injuries can be decreased. Workers should also receive training on how to maintain and wear PPE properly. Employers can contribute to lower the risk of falls and fall-related injuries by providing workers with fall prevention training and by putting in place fall protection measures. The industry can utilize the services from GWO approved training providers as a One-stop solution which will cover all the above and will comply with Height Safety training standards. As on Q1'2023 the training gap from the available data for the industry in work at height is huge.[21] This requires immediate prioritization and plan to close the same by the workforce organizations.

4. Proper maintenance of equipment.

It is critical that all fall arrest systems are adequately inspected and maintained and are only operated within design limits. All the fall protection system, ladders, anchor points, self-closing hatches, other hatches, rails, etc., shall be regularly inspected and are properly maintained. Regular equipment inspections, testing, and maintenance can help to find any problems early on and solve them. This will help to guarantee that the equipment is safe. Employers should create protocols for the secure use and upkeep of height safety arrangements and or equipment's and make sure that work force are trained in the inspection and maintenance protocols. By this way, the chance of equipment failure be lowered, which can result in reduction of severe accidents and injuries.

5. Provide adequate PPE

Workers must be protected against falling by personal protective equipment (PPE). Workers should be given proper PPE, such as hard helmets, safety goggles, harnesses, and fall protection equipment, by employers, developers, or service providers. Additionally, workers should receive training on how to maintain and wear PPE. Employers can contribute to lowering the risk of workplace accidents and injuries by providing workers with proper PPE and instruction on how to use it.

6. Regularly review safety procedures.

Employers should regularly evaluate procedures, perform inspection and audits, hold safety meetings to identify hazards and implement any necessary improvements. Employers may assist in identifying and removing hazards and guarantee that workers are protected from damage by routinely examining and updating safety manuals and instructions.

To conclude, work at heights and wind-turbine cannot be separated in all lifecycle phase of wind turbines. This requires a high level of safety and caution. The design should prevent the unsafe behavior related to work at heights. Individual behavior plays a crucial role. This should be carefully assessed, and necessary measures shall be brought into the product. From time to time with respect to various activities such as major component replacement, crane less solutions etc, should be risk assessed and above discussed measures such as cover plates, portable railing or anchorage system, fish nets et, shall be established prior to start of work to ensure safe execution. Necessary considerations to monitor and facilitate the activity shall be established through the design and use of AI safety gear detection technology critical areas such as climbing towers, working on platforms, opening the service hatch in the nacelle, many more situation etc., to ensure compliance with personal protective equipment (PPE) regulations, written procedures and to safeguard the workforce in addition to GWO Work at height trainings.

Bibliography

1. GWEC | GLOBAL WIND REPORT 2023, Global Wind Energy Council, Rue de Commerce 31 1000 Brussels, Belgium. Lead Authors Mark Hutchinson, Feng Zhao. Published 27 April 2023
2. G+ is the global health and safety organization. https://www.gplusoff shorewind.com/work-programme/workstreams/statistics
3. Wind Energy Global Incident statistics https://scotlandagainstspin.org/ wpcontent/uploads/2023/07/Detailed-incidents-to-30-June-2023.pdf
4. R. A. Haslam, S. A. Hide, A. G. F. Gibb, D. E. Gyi, T. Pavitt, S. Atkinson, and A. R. Duff, ``Contributing factors in construction accidents,'' Appl. Ergonom., vol. 36, no. 4, pp. 401_415, 2005.
5. S. Rowlinson, Construction Safety Management Systems. Evanston, IL, USA: Routledge, 2004.
6. Herbert Heinrich and Frank Bird Theory, https://inunison.io/stay-safe/stay-safe/near-miss-reporting-the-safety-pyramid-part-1/

7. An occupational risk assessment approach for construction and operation period of wind turbines by M. Gul, A.F. Guneri , M. Baskan
8. Occupational risk for an onshore wind farm, Author, O.N. Aneziris a, I.A. Papazoglou a, A. Psinias b
9. EN/ISO 12100: Safety of Machinery – General Principle of Design- Risk Assessment and Risk Reduction
10. An integrated model using SWOT analysis and Hesitant fuzzy linguistic term set for evaluation occupational safety risks in life cycle of wind turbine. Adem, A.; Çolak, A.; Dağdeviren, M., (2018). Saf. Sci., 106, 184-190
11. Development of quality, environment, health, and safety (QEHS) management system and its integration in operation and maintenance (O and M) of onshore wind energy industries Waqar Hussain, Sadia Khan, Ather Hussain Mover
12. Wind Turbine Accidents: A Data Mining Study, By Sobhan Asian, Gurdal Ertek, Cagri Haksoz, Sena Pakter, Soner Ulun
13. Text mining analysis of wind turbine accidents: An ontology-based framework Gurdal, Ertek, Xu Chi, Allan N. Zhang, Sobhan Asian
14. Safety Support Guidebook from KEYENCE, leading supplier of automation and industrial system
15. Energy Institute (EI) publisher of a wide range of technical guidance documents, research papers and standards to support the energy industry https://publishing.energyinst.org/my-profile
16. Newsletter for wind industry https://www.windsystemsmag.com/wind-turbine-construction-safety-tips/
17. A Smart System for Personal Protective Equipment Detection in Industrial Environments Based on Deep Learning at the Edge GIONATAN GALLO , FRANCESCO DI RIENZO , FEDERICO GARZELLI, PIETRO DUCANGE , AND CARLO VALLATI , (Member, IEEE)
18. Study and development of a methodology for the estimation of the risk and harm to persons from wind turbines CME Robinson PhD CEng MIMech ES Paramasivam PhD EA Taylor PhD MInstP MRAeS AJT Morrison BEng CEng MICE MIStruct ED Sanderson MA CEng MIMechE
19. a Safer and Product Work force, GWO Basic Safety Training standard: https://www.globalwindsafety.org/trainingstandards/trainingstandards
20. Safety and Health in Wind Energy Strategies for Small Wind Energy Businesses Targeted Topic Training, developed by the University of Wisconsin Oshkosh, Center for Career Development and Employability Training
21. GWO training data : https://www.globalwindsafety.org/statistics/global-wind-workforce-forecast-2021-2025.