RENEWABLES 101 - WIND POWER

The race to scale

An introduction to and overview of wind turbine power generation systems and developments in their size and scale

Crawford®

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Race to scale - an introduction

In recent years wind turbines have grown in size and capacity, featuring larger rotor diameters and taller towers to capture more wind energy. This improvement has resulted in increased energy production and generally greater cost-effectiveness.

Offshore wind turbines in particular surpass their onshore counterparts in size and power due to fewer space constraints. These offshore turbines have significantly increased in size and scale, boasting larger blades and more substantial towers.

These developments aim to harness stronger and more consistent winds at sea, ultimately leading to higher energy output. Throughout these advancements the priorities and evaluations of manufacturing and insurance companies regarding large wind turbines have become integral to the race to scale.

From examining technical and insurance considerations we can deduce that the race to scale presents risks and challenges, posing difficulties for both developers and the insurance market. However, this competition can be overcome through technological developments and standardisation as advancements in technology, design, and engineering play crucial roles in the evolution of larger and more efficient wind turbines.

This report delves into the technical and insurance aspects associated with using larger blades, serving as a potential guide for future developers. We explore the historical progress of wind turbines and the underlying theory behind the pursuit of larger turbines. We also address potential risks, issues and insurance considerations related to the use of larger wind turbines.

Wind power – a brief history

Developments in onshore and offshore wind turbines reflect a steady increase in both swept area and hub height, significantly enhancing their energy output and efficiency over the years.

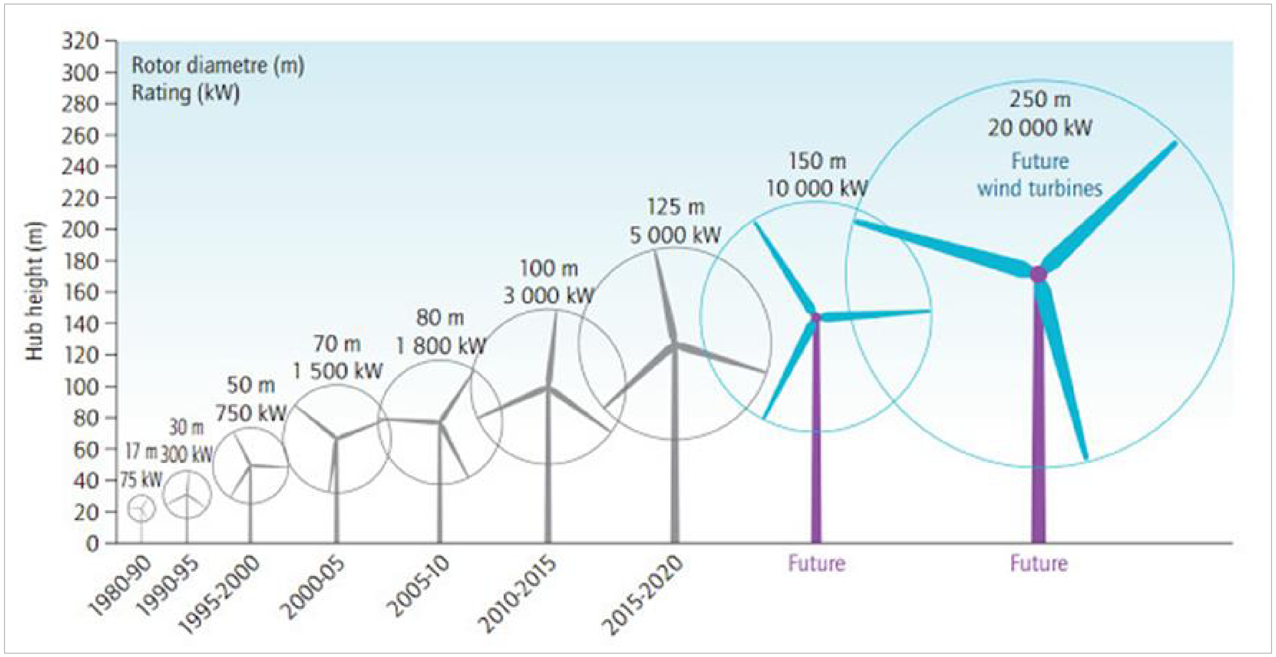

FIG 01 - Size and scale of WTG development courtesy of EWEA

Wind power - a brief history (cont.)

Onshore wind turbines:

- **1980s-90s:** Initial onshore wind turbines had small rotor diameters, often 20 - 30m, and hub heights between 20 - 50m.
- **Early 2000s:** Turbines began to increase in size, with rotor diameters reaching 70m and hub heights around 80m.
- **2010s:** Swept areas grew to approximately 10-12,000m2 with rotor diameters around 120m and hub heights in the range of 100-150m.
- **Late 2010s-2020s:** Continual advancements led to larger turbines, with rotor diameters surpassing 150m and hub heights reaching 160-200m, increasing the swept area to around 18-21,000m2.

Offshore wind turbines:

- **Early 2000s:** Offshore turbines started with rotor diameters around 60-80m and hub heights of 60-80m, with smaller-scale projects close to shore.
- **2010s:** Advances in offshore technology led to larger turbines with rotor diameters of 120-150m and hub heights ranging between 90-120m, increasing the swept area significantly.
- **Late 2010s-2020s:** As offshore wind farms moved further out to sea, rotor diameters expanded further, often reaching 180-220m, and hub heights increased substantially, often 150-200m. This led to much larger swept areas of approximately 25-35,000m2.

Wind power theory

Introducing swept area:

Today's wind turbines are 20-40% efficient at converting wind energy into electricity. Although this efficiency depends on many variables, one of the critical factors in efficiency is the size of the rotor diameter and swept area.

Increasing the swept area through the rotor diameter and length of the blades will potentially increase the energy conversion efficiency of wind turbines as it has a direct square relationship to the power captured from the wind (P). This means that if you double the size of the swept area, you quadruple the potential power output of the turbine (assuming all other factors remain constant).

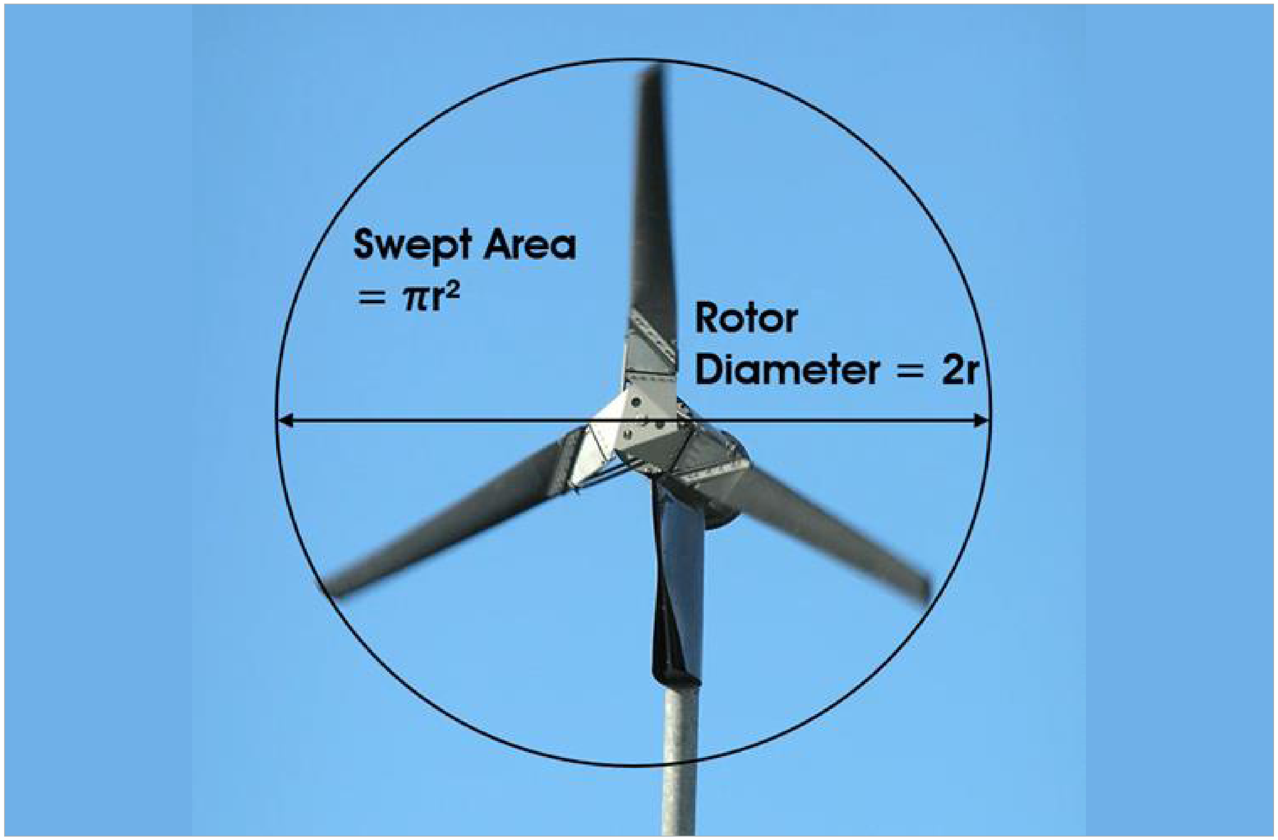

FIG 04 - Wind Turbine swept area and rotor diameter.

Wind power theory (cont.)

Average wind speed vs height / altitude:

Higher wind speeds are generated with taller wind turbines, which is called wind shear. According to the National Renewable Energy Laboratory (NREL) the wind shear formula is:

$$v_{(2)} = v_1 \left(\frac{z_2}{z_1}\right)^a$$

Where v1 and v2 are the velocities at height z1 and z2 respectively and a is the wind shear exponent.

Therefore both the square relationship between swept area and power capture, as well as the cubed relationship between wind speed and power generation, emphasise the importance of larger swept areas (achieved through bigger rotor diameters and taller turbines) and higher hub heights to maximise the power output and efficiency of wind turbines.

FIG 05 - Graph of Annual Mean Windspeed vs Height

Wind power theory (cont.)

Introducing hub height:

By placing turbines at greater hub heights where wind speeds tend to be stronger and more consistent, the potential energy available for capture by the turbines increases significantly. Even a small increase in wind speed at higher hub heights can result in a much larger increase in the power extracted from the wind due to the cube relationship.

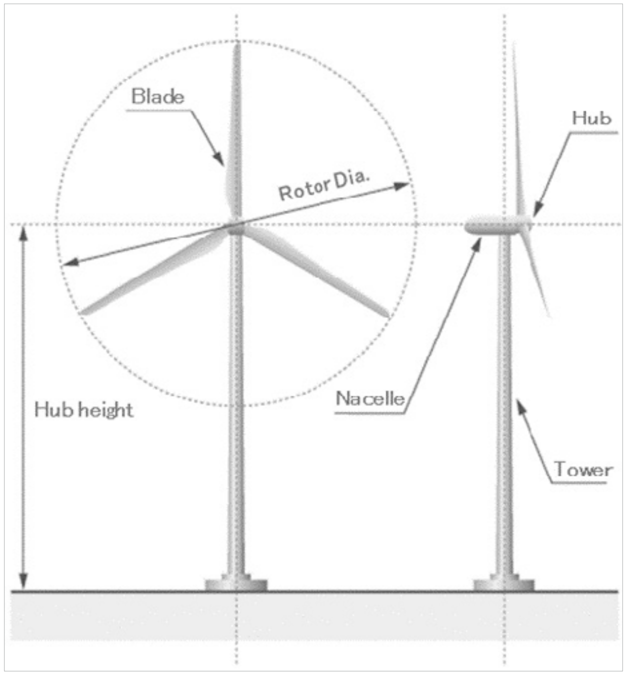

FIG 06 - Image representing rotor diameter and hub height

Wind power equation: P = ρ A V3 / 2

The power captured by a wind turbine is directly proportional to the swept area. This relationship is represented mathematically by the formula for the power in the wind, which is proportional to the area swept by the turbine blades.

The formula is P = ½.ρ.A.V3, where:

- P is the power extracted from the wind
- ρ is the air density
- A is the area swept by the blades
- V is the wind speed

We referred earlier to the cube relationship with wind speed when discussing hub height. The power in the wind (P) is proportional to the cube of the wind speed (V3). This cube relationship means that small increases in wind speed can lead to significant increases in the power available from the wind.

Wind power theory (cont.)

Let us consider two specific wind turbine models, the GE 2.3-116 and the GE Haliade-X, to highlight the impact of increased swept area and hub height on power output.

Example 1 - GE 2.3-116

- Rotor diameter (D1): 116 m
- Hub height (H1): 94m

Using the formula P = ½ ρ A V3 and assuming a constant air density (ρ) and focusing on the impact of the increased rotor diameter on the power output:

- Let us assume the initial wind speed (V1) is 10 meters per second (m/s)
- Swept area (A1): π r2 = π (58)2= 10,569 m2 (to nearest whole number for simplicity)
- Power output (P1): P = ½ ρ A1 V13 = ½ ρ 10,569 103 = 528,450 ρ watts

NOTE: *We left the final answer in terms of since if the turbines were next to each other the value would not change and has no effect on our answers in this case. For reference, a typical value might be 1.2 kg/m3)*

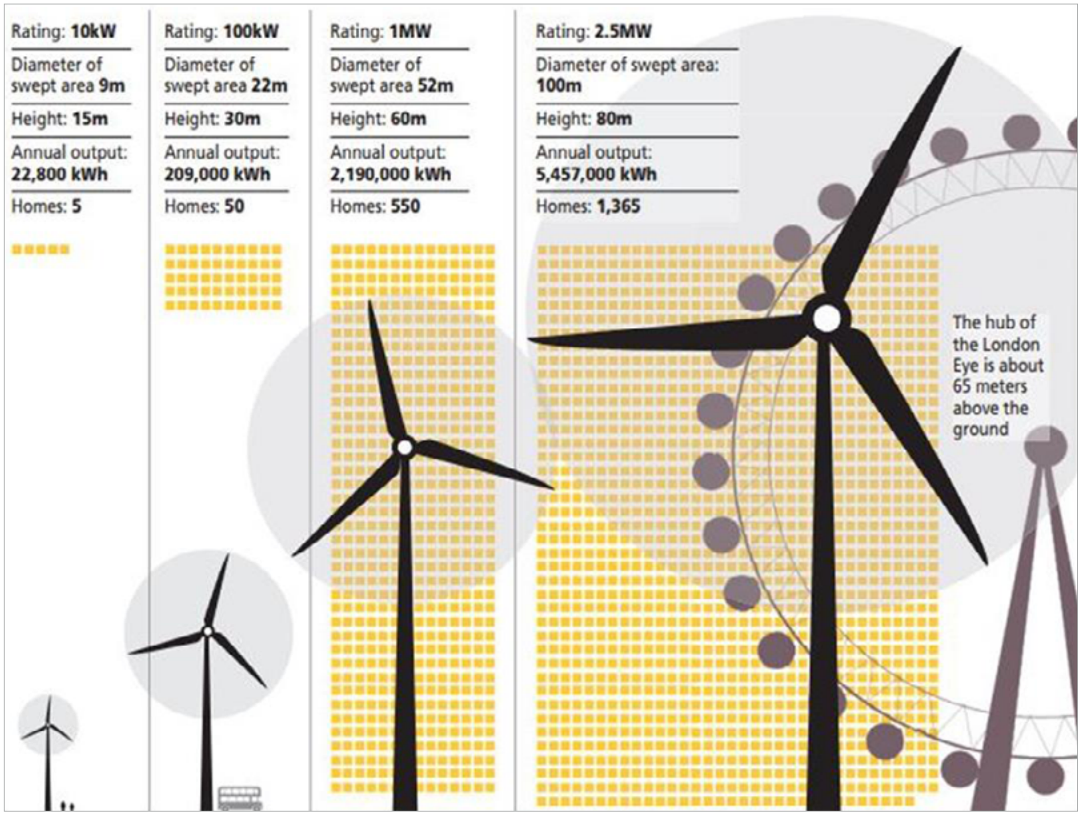

FIG 07 - Hub heights and WTG Output - Image courtesy of cse.org.uk

Wind power theory (cont.)

Example 2 - GE Haliade-X

- Rotor diameter (D2): 220m
- Hub height (H2): 150m

To calculate the potential power output of the Haliade-X model we must consider the larger rotor diameter and hub height. Assuming the same wind speed (V2) of 10 m/s and constant air density (ρ) as for example 1 above:

- Swept area (A2): π (D2/2)2 = π (110)2 = 38,484m2 (to nearest whole number for simplicity)
- Power output (P2): P = ½ ρ A2 V23 = 0.5 ρ 38,484 103 = 1,924,200 ρ watts

Comparing the power output of the GE 2.3-116 and the GE Haliade-X turbines operating at the same wind speed:

The GE Haliade-X, with its significantly larger swept area due to the increased rotor diameter, has a potential power output approximately 3.64 times greater than the GE 2.3-116 model.

This exemplifies how the increase in swept area, achieved through larger rotor diameters and hub heights, significantly impacts the power output of wind turbines, highlighting the drive to grow longer blades and raise hub heights further still.

Scaling – wind turbines today

Here is a comparison between onshore and offshore wind turbines:

Onshore wind turbines:

- **Largest turbines:** The largest onshore wind turbines have power ratings ranging from 4MW to 5MW with rotor diameters usually between 100-130m. These larger onshore turbines are designed for areas with favourable wind conditions and are more commonly found in specific onshore locations where wind speeds are adequate enough to justify their installation.
- **Frequently occurring size:** The most frequently occurring onshore wind turbines typically have power ratings in the range of 2MW - 3.5MW with rotor diameters between 80 - 100m. These turbines are more adaptable to a wider range of wind conditions and geographical locations, making them the most common choice for onshore wind farms globally.

Offshore wind turbines:

- **Largest turbines:** Offshore wind turbines boast significantly higher power ratings, often ranging from 10-14MW, and have massive rotor diameters exceeding 150m. These turbines are designed for offshore environments with more consistent and stronger wind speeds allowing for substantial energy production.
- **Frequently occurring size:** The more common offshore wind turbines typically have power ratings in the range of 6-8MW with rotor diameters around 120-150m. These turbines are commonly used in various offshore wind farms and are favoured for their balance between size, power output and ease of installation in different offshore conditions.

This split illustrates the power ratings and rotor diameter ranges for both the largest, less frequently occurring turbines and the more commonly found turbines in both onshore and offshore wind energy installations.

World's largest blades:

The world's largest blades - with a length of 123m - are on the MySE 16-260 wind turbine designed by Ming Yang Power Group. They have also recently announced a new turbine with 140m long blades.

This is followed by MySE 16.0-242 wind turbine with blade lengths of 118m.

Vestas V236-15.0 MW™ offshore wind turbine features blades of 115.5m.

B115 blades, with a length of 115m, are fitted to the SG 14-236 DD.

From today to 2030 – and beyond

In the coming decade wind turbine development is poised to undergo significant advancements, potentially setting turbines in 2030 apart from current commercial models. Envisaged innovations include:

- **Increased size and power output:**

Turbines in 2030 are expected to surpass current capacities, featuring even larger rotor diameters and higher power ratings potentially exceeding 15-20 MW. Turbines of this size have been announced but are not yet widely deployed. These enhancements could significantly boost energy output.

- **Technological innovations:**

Anticipated advancements in materials, aerodynamics and manufacturing processes are expected to result in more efficient and durable turbines. Lighter yet stronger composites may enable larger blade designs without compromising structural integrity, enhancing energy capture and efficiency.

Current studies focus on improving wind turbine performance by increasing blade radius and decreasing weight through the exploration of novel materials and modifications to blade inner structures. The investigation of lighter materials for larger rotor diameters is crucial for enhancing wind turbine performance.

- **Enhanced offshore capabilities:**

Offshore wind turbines are likely to advance, catering to deeper waters and harsher environments. More advanced floating turbine designs may emerge, expanding possibilities for offshore wind energy production in previously inaccessible locations.

- **Smart and integrated systems:**

Turbines in 2030 might feature advanced digital technologies enabling predictive maintenance and improved efficiency through real-time data analysis and grid integration. These smart systems could optimise energy production and ensure better grid stability.

- **Reduced cost and environmental impact:**

Ongoing advancements are expected to lower the levelised cost of energy (LCOE) for wind power. Innovations in design, construction and maintenance may reduce the environmental impact of turbine manufacturing and operation, contributing to a more sustainable energy sector.

Continued efforts to drive down the LCOE underscore the commitment to making wind energy more economically viable and environmentally friendly, establishing it as a major contributor to the global energy landscape in 2030.

Scaling - limiting factors, risk and issues

The theoretical maximum size of a wind turbine is constrained by various factors encompassing engineering limitations, materials technology and logistical challenges. While there is no universally agreed maximum limit at present, certain constraints imply that extremely large wind turbines would encounter practical and physical limitations.

Key factors restricting the maximum size include:

› **Materials and structural integrity:**

Wind turbine components such as blades and towers must maintain structural integrity. As turbines increase in size so material stresses rise, potentially leading to structural and mechanical issues. The challenge lies in identifying materials that can withstand these forces while remaining lightweight and cost-effective.

The pursuit of materials capable of handling increased stresses in larger turbines is crucial for ensuring the structural soundness and performance of wind turbines.

› **Transportation and installation:**

Components like oversized blades and heavier tower sections in extremely large turbines pose significant transportation and logistical challenges. Specialised equipment and infrastructure for delivering and installing these massive parts could become costly and increasingly difficult to locate.

Flexible blades with controlled flap-wise bending present a feasible approach for blades up to 100m, addressing challenges in transportation and installation.

› **Manufacturing limitations:**

The production process for extremely large turbine components may require specialised facilities and technologies that are not yet fully developed or cost-effective on a large scale.

3D concrete printing (3DCP) may emerge as a useful manufacturing technology, enabling on-site blade moulds and ultra-tall wind turbine towers, potentially improving the overall efficiency of wind turbines.

FIG 07 - GE's 3D Printed WT Tower.

Scaling - limiting factors, risk and issues

› Environmental and site constraints:

Onshore turbines face limitations related to land space and zoning regulations while offshore turbines need to consider water depth, foundation types and logistical challenges in deep waters.

Ongoing exploration of advanced manufacturing technologies, like 3D concrete printing, demonstrates the industry's commitment to overcoming environmental and site constraints in pursuit of larger and more efficient wind turbines.

While current wind turbines are growing in size, engineers and researchers continue pushing boundaries, exploring new designs and materials to create more powerful and efficient turbines. The theoretical maximum size remains uncertain with the practical limit hinging on a balance between technical, logistical and economic constraints as technology evolves.

Risks and issues

› Supply chain:

The increased size of wind turbines in recent years poses challenges for supply chains struggling to keep pace with technical risks, particularly in aerodynamic structure, due to a lack of standardisation. Manufacturing capacity falls short for larger models, necessitating component redesign, and manufacturing companies face difficulties in delivering high-quality products amid the competitive race among developers.

The threat of unfulfilled contracts and the challenge of risk assessment during operation and maintenance arise from low-quality, non-standardised models. Larger blade sizes exceed material capabilities and flexibility, complicating replacements and spare part availability. The shortage of skilled workers in the supply chain exacerbates engineering challenges associated with larger machines.

› Obsolescence:

The rapid adoption of larger wind turbines contributes to the accumulation of obsolete equipment which then presents serious environmental concerns, especially considering the non-recyclable nature of current fibreglass blades. Strategies involving R&D attempts to repurpose wasted fiberglass components for materials like cement are under way, emphasizing the need to develop a recycling supply chain.

Addressing the obsolescence issue involves finding sustainable solutions for decommissioned turbines to mitigate environmental impact and establish an economically viable recycling supply chain.

Quality analysis and standards

› **Quality analysis and testing:**

Quality analysis and testing pose challenges for blades beyond 100m as longer blades require specific instruments, making test replication difficult. Full-scale structural analysis and testing become particularly challenging with larger-sized blades.

The industry faces the need to develop advanced testing methodologies and instruments to ensure the quality and structural integrity of blades beyond the 100m mark.

› **Developing standards and guidelines:**

Several standards and guidelines play a crucial role in addressing challenges associated with larger wind turbines:

- **ISO/IEC 17025:** Provides general requirements for testing and calibration laboratories.
- **DNVGL-ST-0376, IEC 61400-5:** Pertains to the design and manufacturing of blades, encompassing requirements for repair, testing, materials, operation, transportation and installation.
- **IEC 61400-24:** Defines lightning protection system design for blades.
- **IEC 61400-23:2014 and ANSI/AWEA 61400-23:** Outline requirements for full-scale structural testing of wind turbine blades, including interpretation and evaluation of results, providing insights into the probability of the full-scale blade meeting design assumptions.

Adherence to these standards and continuous development of new guidelines are essential to ensure the quality, safety and reliability of larger wind turbines, fostering innovation and sustainability in the industry.

FIG 08 - World's largest wind turbine - Goldwind GWH252-16MW – Fujian Province, China

Insurance considerations

› **Installed capacity/constructability issues (size and scale of operations):**

The type and size of wind turbines impact insurance premiums with advanced technology installations leading to lower rates, due to the perceived reduced risk of failure.

Transportation challenges and complex installation processes with larger turbines increase risks and premiums. On-site construction such as 3D printing could eliminate transportation issues and reduce costs. Embracing advanced construction methods can mitigate insurance risks associated with large wind turbines, enhancing cost-effectiveness.

› **Record and operating history:**

Insurance rates are influenced by the claims history of wind farm developers/operators. A substandard operating history can result in increased insurance costs due to heightened risks. Limited records for larger wind turbines pose challenges for insurers in risk assessment. Establishing a comprehensive record and operating history for larger wind turbines is crucial for accurate risk assessment and competitive insurance rates.

› **Portfolio size and geographical location:**

Experience and safety assessments related to the operation of large wind turbines impact insurance premiums. An experienced insured benefits from better rates and geographical location is important in assessing NatCat risks, with higher risks leading to higher premiums. Strategic planning and risk mitigation in diverse geographical locations can influence insurance rates for large wind turbines.

› **Warranties:**

Defect warranties tend to cover turbine damage and servicing but exclusions for issues such as cracking due to faulty materials exist. For large blades bending stiffness becomes critical and reliable technology and design are recommended for extended warranties. Investing in reliable technology and design for large blades can enhance warranty offerings, providing confidence to insurers and lowering premiums.

Insurance considerations

› **Operation & maintenance (O&M):**

Big turbines and blades pose complexity in construction and O&M, impacting insurance costs. Inspection, repair, lubrication and cleaning are more challenging, requiring advanced management strategies. Larger turbine components necessitate advanced software solutions for operation. Implementing advanced O&M strategies and software solutions is vital to managing insurance costs and ensuring the longevity of wind turbines.

› **Supply chain and spare parts:**

Supply chain complexities and spare parts for large turbines require specific arrangements, leading to higher premiums. Manufacturing and logistics for large wind turbines and their blades involve novel materials, operational and transportation considerations. Developing efficient supply chain strategies for large turbines is essential.

› **Availability of specialist labour, trained technicians and equipment:**

Large turbines and blades require specialised handling, emphasising the need for trained labour and equipment, thereby impacting insurance costs. Safety and technical training reduce the risk of failure, ultimately lowering premiums.

Conclusions and summary

This document provides insights into the technical and insurance aspects associated with large wind turbine, aiming to enhance overall efficiency.

- **Technical perspective:**

Bigger turbines offer the potential for increased wind power but R&D companies must prioritise the development of novel technology and strategies for manufacturing, testing and full-scale analysis of ultra-long blades. Standardisation is crucial for advancing the technical aspects of larger turbines.

- **Insurance perspective:**

Addressing challenges in the supply chain, manufacturing, quality analysis, spare parts availability, operation and maintenance, and transportation is essential for the insurance market to accurately assess risks and set appropriate premiums.

The complexities associated with large turbines, including warranty disputes and underestimated downtime and business interruption costs, highlight the need for comprehensive risk management in the insurance sector.

- **Race to scale impact:**

The race to scale is adversely affected by: warranty disputes; challenges related to downtime and business interruption due to quality issues; insufficient spare parts inventory; and a shortage of skilled labour. Balancing the race to scale with quality control and risk management measures is critical to avoid warranty disputes and ensure the reliability of large wind turbines.

- **Development trajectories:**

Anticipating the development of even larger blades, collaborative advancements in technology and insurance practices are crucial for realising the full potential of wind turbines, fostering sustainable energy production.

- **Summary:**

In conclusion, the synergy between continuous technological innovation and robust risk management practices in the insurance sector is essential for the successful integration of larger turbines into the wind energy landscape. As development trajectories unfold these advancements are poised to solidify wind turbines with larger profiles as a key player in the global energy sector.

Appendix – OEM turbine development

Specific turbine models developed by major Original Equipment Manufacturers (OEMs) such as GE, Siemens Gamesa, Vestas and other key players have highlighted the evolution in size and scale. Below are some turbine models currently in service around the globe:

› **GE (General Electric) renewable energy:**

- GE 2.X Series: This includes models like the GE 2.3-116, which has a rotor diameter of 116m and a hub height of 94m, and the newer GE 2.X-127 with a rotor diameter of 127m.
- GE 5.X (Cypress) platform: This includes models with power ratings between 4.8-6.3 MW with rotor diameters up to 164m and hub heights up to 161m.
- GE Haliade-X: This model is among the largest offshore turbines with a massive rotor diameter of 220m and a hub height of 150m. It is considered one of the most powerful turbines available.

› **Siemens Gamesa renewable energy:**

- Siemens Gamesa SG 5.X Series: This includes models such as the SG 5.8-155 with a rotor diameter of 155m and the SG 5.8-170 with an increased rotor diameter of 170m.
- Siemens Gamesa SG 14-222 DD: This is a giant offshore turbine with a rotor diameter of 222m and is designed for high energy production in offshore wind farms.

› **Vestas Wind energy systems:**

- Vestas V150-4.2 MW: This model features a rotor diameter of 150m and a hub height of up to 166m, optimising energy capture and efficiency.
- Vestas V236-15.0 MW: Among the largest models this turbine boasts a rotor diameter of 236m and is designed for offshore applications, emphasising high power output.
- These models represent a selection of the turbine series developed by these prominent manufacturers, showcasing the trend toward larger rotor diameters and taller hub heights to improve energy generation and efficiency in both onshore and offshore wind energy.

› **A typical onshore WTG in 2023:**

- GE 5.X Series: General Electric's 5.X series turbines are among the largest onshore models. The GE 5.X turbines, such as the GE 5.3-158 and GE 5.5-158, have rotor diameters of up to 158m, GE-164 having rotor diameters of up to 164m aiming to optimise energy production and efficiency for onshore wind farms.

› **A typical offshore WTG in 2023:**

- GE Haliade-X: The GE Haliade-X is currently one of the largest offshore wind turbines. It features a massive rotor diameter of 220m and a hub height of 150m. The Haliade-X is designed to harness strong offshore winds, maximising energy generation in offshore wind farms. GE Haliade-X offshore turbine features a blade length of 107m.

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