RENEWABLES 101 - WIND POWER

A comprehensive introduction to wind farms

A guide to onshore wind turbines and wind farms – their design, operation and risks

Crawford®

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Introduction

Wind farms are large-scale power generation installations composed of multiple wind turbines strategically placed to harness wind energy. These sites can be located onshore or offshore and contribute electricity directly to the power grid. Unlike small individual turbines, wind farms are designed for commercial electricity production

Typical components of a wind farm include:

- Wind turbines
- Rotor blades and nacelle
- Towers and foundations
- Yaw and pitch systems
- Substations and transformers
- Export cables and grid infrastructure

Wind turbines

Wind turbines capture kinetic energy from the wind and convert it into electrical power using a rotor, gearbox, generator, and power electronics.

Design & Operation:

- Rotor blades rotate when wind speeds exceed the cut-in threshold (~3 m/s)
- Mechanical rotation is transferred to a generator via a gearbox or direct-drive system
- Power electronics convert and condition the electricity for grid compatibility

Specifications:

- Capacity: 2 MW to 15+ MW per turbine
- Rotor diameter: 80 to 220 m
- Hub height: 80 to 160 m

Maintenance:

- Routine inspections, lubrication, sensor calibration
- Remote monitoring systems for predictive maintenance

Blades

Wind turbine blades are critical aerodynamic structures designed to extract kinetic energy from the wind and convert it into rotational energy which drives the turbine's generator. Typically made from composite materials, blades are among the most exposed and high-stress components of both onshore and offshore wind farms.

Design and Composition

Wind turbine blades are typically constructed from:

- **Glass-fibre-reinforced plastic (GFRP):** the most common material due to its balance of strength, weight and cost.
- **Carbon-fibre-reinforced plastic (CFRP):** used in premium or ultra-long blades to improve stiffness and reduce weight.
- **Epoxy or polyester resins:** bind the fibres and provide structural integrity.

Internally, blades may include:

- **Spar caps or shear webs:** stiffening elements that increase rigidity.
- **Lightning protection systems:** metal conductors embedded along the blade to divert strikes to ground.
- **Heating elements or coatings (in cold climates):** reduce icing.

Size and Specifications

- **Length:** typically 40–80 metres for modern onshore turbines; over 100 metres for offshore applications.
- **Weight:** ranges from 10 to 30 tonnes depending on materials and length.
- **Tip speed:** can exceed 300 km/h in operation.
- **Design life:** typically 20–25 years, though actual performance depends heavily on environmental conditions and maintenance.

Aerodynamic Function

- Blades operate using aerofoil principles:
  - Lift is generated on the curved upper surface of the blade.
  - Drag is minimised to improve efficiency.
- Blades are twisted along their length to optimise the angle of attack at varying radial positions.
- Blade pitch is actively controlled to maximise energy capture and protect against overload.
- The rotor, comprising multiple blades (usually three), spins the low-speed shaft, initiating the energy conversion process.

Blades (cont.)

Operation and Monitoring

- Pitch systems adjust the blade angle in response to wind speed to optimise performance and prevent overloading during gusts or storms.
- Supervisory control and data acquisition (SCADA) systems track blade performance metrics (e.g. vibration, pitch angle, power output).
- Some turbines use acoustic or visual sensors to detect damage or leading-edge erosion.

Maintenance and Inspection

Blades must be regularly inspected and maintained:

- Visual inspections via rope access or drones identify surface damage or wear
- Thermographic imaging may be used to detect internal defects
- Ultrasound or tap testing helps locate delamination or bonding failures
- Leading edge protection systems (coatings or tape) reduce erosion caused by rain, hail or airborne particles

Inspections are especially important following:

- Lightning strikes
- Severe storms
- Prolonged periods of high wind or icing

Risks and Failure Modes of Blades

Common risks include:

- **Lightning damage:** Despite lightning protection, extreme strikes can puncture the blade, cause delamination or ignite fires.
- **Delamination and cracking:** From fatigue, temperature cycles or poor-quality manufacture/repair.
- **Blade icing:** Adds weight, reduces aerodynamic performance and can cause dangerous shedding of ice.
- **Leading edge erosion:** From windborne particles or rain; reduces efficiency and leads to structural damage.
- **Foreign object impact:** Birds, hail or dropped tools during maintenance.
- **Transportation and handling damage:** Blades are vulnerable during shipping, especially for offshore installations.
- **Catastrophic failure:** In rare cases blades may shear off completely, causing rotor imbalance and structural collapse

Blades (cont.)

Mitigation Strategies

- **Condition monitoring systems:** Vibration and strain sensors detect early signs of failure.
- **Blade heating or anti-icing coatings:** Reduce ice-related shutdowns in cold climates.
- **Lightning protection systems:** Must be inspected and maintained to function correctly.
- **Regular maintenance schedules:** Include cleaning, repair of erosion, and blade balancing.
- **Factory quality assurance:** Crucial to prevent latent defects from resin-rich or fibre-poor regions within blade laminates.

Yaw and pitch systems

Yaw control

A wind turbine yaw system helps to align the rotor of the wind turbine with the wind direction. The aim is to keep the rotor blades facing into the wind which maximises the power output and improves the efficiency of the turbine.

› Design

The yaw system typically consists of a yaw drive, a yaw motor, a yaw brake, a yaw controller, and a yaw position sensor. The yaw drive is the mechanical component that rotates the rotor while the yaw motor provides the power to rotate the yaw drive. The yaw brake is used to lock the rotor in place during maintenance or in the event of a wind turbine shut down. The yaw controller is responsible for controlling the yaw motor based on the wind direction, and the yaw position sensor provides feedback on the position of the rotor.

› Specification

The specifications for a wind turbine yaw system can vary depending on the size and type of the wind turbine. However the following are typical specifications:

- **Yaw drive:** made of a high-strength material such as cast iron, steel or aluminium, with a diameter of 1-2m and a weight of several tons.
- **Yaw motor:** typically a direct current or an alternating current motor with a power output of several kW.
- **Yaw brake:** hydraulic or mechanical with a braking force of several hundred kN.
- **Yaw controller:** microprocessor-based with a software program to control the yaw motor based on the wind direction.
- **Yaw position sensor:** typically a potentiometer or a rotary encoder with an accuracy of 0.1-1 degree.

› Operation

The yaw system operates by turning the rotor so that it faces into the wind. The yaw position sensor detects the wind direction and the yaw controller uses this information to control the yaw motor, which rotates the yaw drive and aligns the rotor with the wind. The yaw brake is used to lock the rotor in place during maintenance or in the event of a wind turbine shut down.

The wind turbine yaw system is operated by the yaw controller which uses data from the yaw position sensor to determine the direction of the wind.

Yaw and pitch systems (cont.)

› Maintenance

Maintenance of the wind turbine yaw system is important to ensure proper operation and to minimise the risk of failure. Maintenance tasks include:

- The yaw motor should be regularly lubricated to reduce friction and wear.
- The yaw brake should be inspected regularly for signs of wear or damage and repairs should be made as needed.
- The bolts on the yaw drive should be checked and tightened regularly to ensure that the components are properly secured.
- The yaw position sensor should be inspected regularly for accuracy and proper function.
- The software program used to control the yaw motor should be updated as needed to ensure that it is functioning properly.
- Dirt, debris and other contaminants can build up on the components of the yaw system over time, reducing their efficiency and lifespan. Regular cleaning can help to maintain the performance and longevity of the system.

› Potential problems

There are several risks associated with the operation of a wind turbine yaw system. These include:

- **Failure of the yaw motor or drive:** If the yaw motor or drive fails the rotor may not align properly with the wind, resulting in a reduction in power output.
- **Malfunction of the yaw controller:** If the yaw controller fails it may not properly control the yaw motor, leading to incorrect alignment of the rotor with the wind.
- **Wear and tear on the yaw brake:** Over time the yaw brake may wear out or become damaged, reducing its ability to hold the rotor in place during maintenance or in the event of a wind turbine shut down.
- **Corrosion:** The yaw system is exposed to the elements and can be susceptible to corrosion which can reduce its reliability and lifespan.

Yaw and pitch systems (cont.)

Wind turbine blade pitch control

A wind turbine blade pitch control system is designed to adjust the angle of the blades to optimise power generation and protect the turbine from high wind loads. The pitch control system typically consists of pitch actuators, pitch sensors, a pitch controller, and a pitch angle feedback system.

The pitch actuators are responsible for adjusting the pitch angle of the blades to maintain a constant rotational speed and ensure efficient operation. They are typically hydraulic or electric motors that rotate the blade through a series of gears, changing the blade's angle of attack.

The pitch sensors measure the angle of the blade and the rotational speed of the rotor and provide feedback to the pitch controller. The pitch controller then compares the desired pitch angle with the actual pitch angle and adjusts the pitch actuator accordingly.

The design of the pitch control system varies depending on the size and type of the wind turbine. Small turbines may use a simple on/off control system while larger turbines may use a more complex closed-loop control system.

Regular maintenance is essential to ensure the proper functioning of the pitch control system. This includes checking for leaks in hydraulic systems, verifying the accuracy of sensors and inspecting the pitch actuators for damage. Failure to properly maintain the pitch control system can result in reduced power output, downtime and potential damage to the turbine.

Notable risks associated with the pitch control system include blade overspeed which can occur if the system fails to adjust the pitch angle correctly. This can lead to damage to the turbine or even catastrophic failure. Mechanical failure of the pitch actuators or sensors can also cause problems such as uncontrolled blade movements or complete loss of power generation.

Regular maintenance including lubrication and checking component alignment is essential to prevent these failures. To enhance reliability redundancy is often built into pitch control systems, ensuring continued operation even if one component fails.

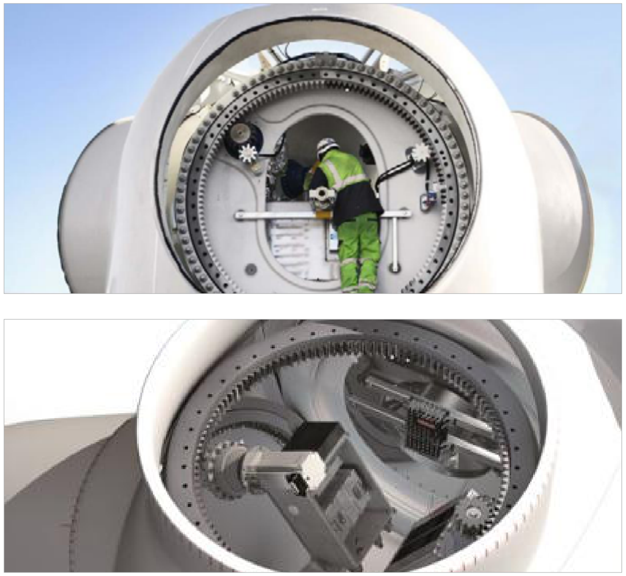


FIG 01 & 02 - Illustration of Blade pitch in wind turbine

The Nacelle

The wind turbine nacelle is the part of the wind turbine that houses components such as the generator and the gearbox. Its main function is to convert the kinetic energy of the wind into electrical energy.

Wind turbine nacelle components and functions include:

1. **Generator:** Converts mechanical energy into electrical energy
2. **Gearbox:** Increases the rotational speed of the rotor to the speed required by the generator
3. **Rotor shaft and main bearing:** Transmits the rotational energy from the rotor blades to the gearbox
4. **Brakes:** Used to stop the rotor in emergency situations or during maintenance
5. **Yaw system:** Enables the nacelle to turn and face the wind
6. **Pitch system:** Controls the angle of the rotor blades to optimise their efficiency
7. **Control system and protection:** Monitors the performance of the turbine and controls its various systems to optimise performance and protect the turbine from damage

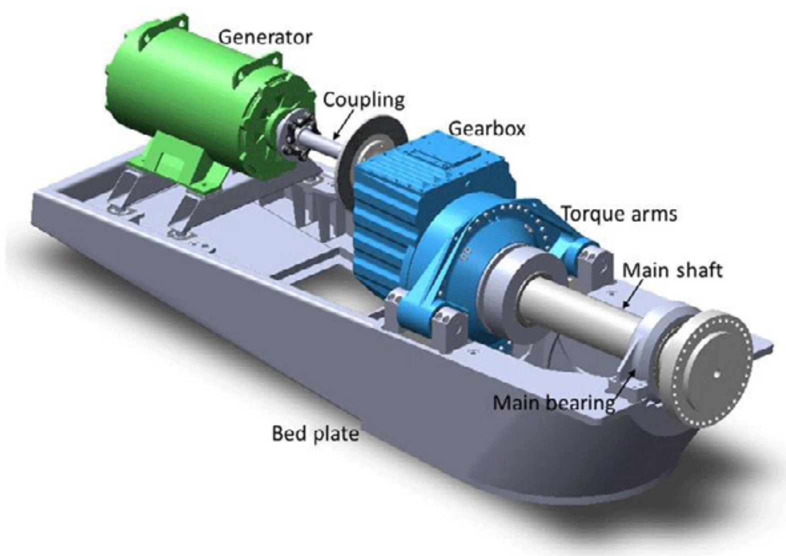


FIG 03 - Illustration of wind turbine nacelle (Source: WES)

The Nacelle (cont.)

Generator

A wind turbine generator is a device that converts kinetic energy from wind into electrical energy that can be used for power generation. The three blades drive the shaft which is connected to the generator located inside the nacelle. The tower supports the rotor and nacelle and helps to place the rotor at a sufficient height to take advantage of strong and consistent winds.

The rotor diameter, the size of the generator and the height of the tower all contribute to the overall power output of the turbine. The generator itself can be either a synchronous generator or an asynchronous generator with the choice depending on the specific requirements of the system.

The turning of the generator creates a flow of electricity that is either used on-site or fed into the power grid. Some wind turbine generators are equipped with a control system that adjusts the pitch of the blades to optimise the output of the generator in changing wind conditions.

FIG 04 - Illustration of Direct-drive turbine (Source: ENERCON)

The Nacelle (cont.)

› Standard drive vs direct drive

A wind turbine generator can be either a standard generator or a direct drive generator. The main difference between the two types lies in the way they transfer energy from the rotor to the generator.

A standard generator, also known as a geared generator, uses a gearbox to increase the speed of the rotor before it reaches the generator. This is necessary because the rotor typically turns at a relatively slow speed while the generator requires a higher speed to produce electricity efficiently. The gearbox enables the required increase in speed.

A direct drive generator, as the name suggests, has no gearbox. Instead the rotor is directly connected to the generator which results in a more efficient transfer of energy. The lack of a gearbox also means that there are fewer moving parts which reduces the risk of mechanical failure and improves reliability. Direct drive generators are typically quieter and have a longer lifespan than standard generators.

In terms of power output direct drive generators are typically more efficient as there is less energy loss between the rotor and the generator. However direct drive generators are also larger and more expensive than standard generators, which can make them less practical for smaller wind turbine systems.

Direct drive generators, due to their high torque output, are generally bulkier and heavier. They demand more permanent magnets and rare earth elements along with sturdier mechanical frameworks – complicating design, logistics, production, and installation for OEMs.

Direct drive generators typically exhibit lower power density compared to their geared counterparts due to their operation at low rotational speeds, to produce higher torque for the same power output.

The Nacelle (cont.)

Since:

$$P = T \times \omega$$

(where P is the power, T is the torque and ω is the angular velocity)

When the angular velocity (ω) is low (as in direct drive systems where the generator spins at the slow speed of the prime mover), the torque (T) must increase proportionally to maintain the desired power. Producing higher torque requires a generator with a larger diameter and greater mass to provide the necessary mechanical leverage and magnetic flux capacity.

This leads to an increase in the physical size and weight of the generator which in turn lowers the power density defined as power output per unit volume or mass.

One promising approach involves the use of superconducting generators which are capable of producing higher magnetic shear stress and so greater power density.

The choice between the two boils down to the specific requirements of the wind turbine system including size, power output, reliability and cost.

Direct drive generators, like all wind turbine components, are susceptible to certain risks and failures that can affect their performance and reliability. Some of the most common risks include:

- **Magnetic saturation:** Direct drive generators use permanent magnets to generate electricity and excessive magnetic saturation can occur when the magnetic field becomes too strong. This can cause the generator to overheat and fail.
- **Mechanical stress:** Direct drive generators are exposed to high mechanical stress due to the direct connection between the rotor and the generator. This can cause fatigue in the generator components and lead to failure.
- **Controller failure:** The controller regulates the generator's operation. If it malfunctions it can result in the generator overloading and failing.

In many cases significant parts, or even the entire generator, in direct drive generators may need to be replaced leading to longer downtime and higher expenses. In contrast geared generators consist of a smaller, high-speed generator coupled with a gearbox. Failures can occur in either the generator or the gearbox but because these components are more modular parts like gears, bearings or the generator itself can often be replaced separately. This modularity allows for more flexible and potentially less expensive repairs as well as easier maintenance, although the gearbox adds mechanical complexity and requires routine care.

The Nacelle (cont.)

Gearbox

A wind turbine gearbox is a mechanical component that is crucial for the operation of a wind turbine. It is responsible for increasing the rotational speed of the low-speed rotor to the high-speed shaft that drives the generator which produces electricity.

› Design

Wind turbine gearboxes are typically designed as a planetary gear system with three stages of gears that provide a high gear ratio in a compact package. The gearbox housing is typically made of cast iron or steel while the gears are made of high-strength materials such as steel or titanium to withstand the high loads and stresses imposed on them. They are also designed with precise tolerances to ensure smooth operation and to minimise noise and vibration.

› Specifications

Wind turbine gearboxes are designed to meet specific performance specifications including maximum torque and rotational speed, operating temperature range, and noise and vibration levels. These specifications vary depending on the size and capacity of the wind turbine and the gearbox must be designed and manufactured to meet these specific requirements.

› Operation

The wind turbine gearbox operates by receiving the low-speed rotor input and transmitting the high-speed shaft output to the generator. The planetary gear system within the gearbox increases the rotational speed of the input allowing the generator to produce electricity at the appropriate frequency. The gearbox is lubricated with oil to reduce friction and wear and the oil must be changed periodically to maintain proper operation.

› Maintenance

Proper maintenance is crucial for the longevity and performance of a wind turbine gearbox. This includes regular oil changes, inspections, and monitoring of the gearbox for signs of wear or damage. It is also important to monitor the gearbox for any abnormal noise or vibration which can indicate a potential problem. Regular maintenance can help to extend the life of the gearbox and reduce the risk of unscheduled downtime.

› Risks and potential problems

Wind turbine gearboxes are subjected to high loads and stresses which can result in wear and damage over time. Some of the common problems that can occur include gear wear, bearing failure, oil leaks and gearbox overload. If not addressed these issues can result in unscheduled downtime, reduced energy production and increased maintenance costs. In some cases they can also result in a complete gearbox failure, which can cause significant damage to the wind turbine and require costly repairs. To minimise these risks it is important to follow a regular maintenance schedule and to monitor the gearbox for any signs of wear or damage.

The Nacelle (cont.)

› Gearbox inspections and testing

Diagnostic tests and inspections are important components of best practice operation and maintenance for wind turbine gearboxes.
They include:

- **Visual inspections:** Regular visual inspections of the gearbox can help to identify any signs of wear or damage such as oil leaks, cracks or deformations.
- **Oil analysis:** Regular analysis of the gearbox oil can help to determine if the oil is contaminated or if there are signs of wear or damage in the gears or bearings.
- **Vibration analysis:** Vibration analysis is used to detect any abnormal vibrations in the gearbox which can indicate a potential problem with the gears or bearings.
- **Acoustic analysis:** Acoustic analysis involves listening for any unusual noises in the gearbox which can also indicate a problem with the gears or bearings.
- **Thermal imaging:** Thermal imaging can be used to identify any hotspots in the gearbox which can indicate high levels of friction or wear.
- **Load testing:** Load testing involves applying load to the gearbox and measuring the response which can help to identify any issues with the gear mesh, bearings or oil system.
- **Gear mesh analysis:** Gear mesh analysis involves measuring the tooth contact patterns of the gears which can help to identify issues such as misalignment or wear.
- **Bearing analysis:** Bearing analysis involves measuring the health of the bearings which can help to identify any issues with the bearings such as excessive wear or damage.

It is important to note that the specific diagnostics and tests used will depend on the size and type of the wind turbine gearbox as well as its age and operating conditions. The results of these tests can help to determine the condition of the gearbox and inform the maintenance schedule, allowing for any necessary repairs or replacement components to be installed in a timely manner.

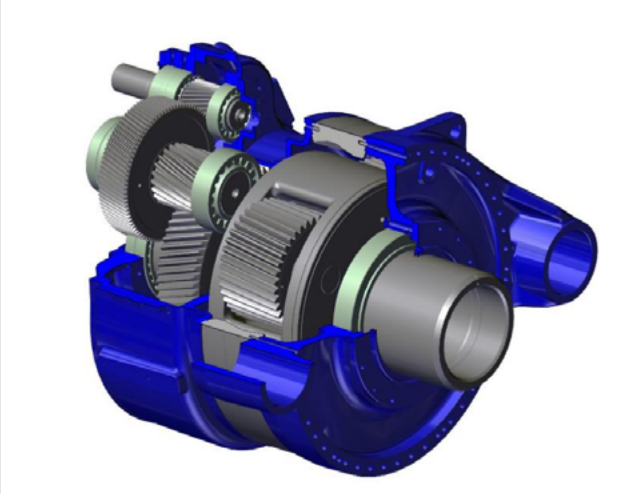


FIG 05 - Illustration of Gearbox

The Nacelle (cont.)

Rotor shaft and main bearing

› Rotor shaft

A wind turbine rotor shaft, also known as the main shaft, is a critical component that connects the rotor hub to the gearbox and generator. The design and specifications of the main shaft are determined by the size and power output of the wind turbine.

The main shaft typically consists of a high-strength steel alloy that can withstand the stresses and loads imposed by the rotating blades. The shaft is usually a hollow cylinder with a large diameter to accommodate the rotor hub and bearings at one end and the gearbox and generator at the other end.

During operation the rotor blades are driven by the wind and turn the rotor hub, which in turn rotates the main shaft. The main shaft transfers the rotational energy to the gearbox which increases the rotational speed and torque before sending it to the generator to produce electricity.

Regular maintenance is essential to ensure the proper operation of the main shaft and the entire wind turbine. Maintenance activities include lubricating the bearings, inspecting the shaft for any signs of wear or damage and replacing bearings or other components as needed.

Notable risks associated with the main shaft include fatigue failure, which can be caused by factors such as cyclic loading and vibrations. Cracks or other defects in the shaft can lead to catastrophic failure which can result in severe damage to the wind turbine and/or injury to personnel. Proper design, material selection and regular maintenance are critical to minimise the risk of failure and to ensure the safe and reliable operation of the wind turbine.

FIG 06 - Illustration of Main shaft and bearing (Source: SKF)

The Nacelle (cont.)

Various sensors and systems can monitor the condition of the wind turbine rotor shaft. These include:

- **Vibration sensors:** These sensors detect any excessive vibrations in the rotor shaft and other components of the wind turbine. By monitoring the vibration levels maintenance personnel can identify potential issues and take corrective action before they lead to a failure.
- **Temperature sensors:** Can be used to monitor the temperature of the rotor shaft and bearings. High temperatures can indicate a problem with lubrication or other issues that can lead to premature wear or failure.
- **Strain gauges:** Can be attached to the rotor shaft to measure the stress levels and bending forces experienced by the shaft. This data can be used to identify any areas of the shaft that are under excessive stress and to adjust the design or operation of the wind turbine accordingly.
- **Oil condition monitoring:** Wind turbines use lubricating oil to protect the bearings and other components of the turbine. By monitoring the condition of the oil maintenance personnel can identify any issues with lubrication, such as contamination or degradation, and take corrective action to prevent damage to the rotor shaft and other components.
- **Shaft displacement sensors:** These sensors can measure the displacement of the rotor shaft which can provide information on the alignment of the shaft and bearings. Misalignment can cause excessive wear on the shaft and bearings and can lead to premature failure if not corrected.

The Nacelle (cont.)

› Main bearing

A wind turbine main bearing is a critical component that supports the rotating blades and rotor assembly of a wind turbine. It allows the rotor assembly to turn around a fixed axis and transfer the torque generated by the wind to the generator. The main bearing is typically a large rolling element bearing designed to handle both radial and axial loads.

The main bearing design and specification depend on the size and type of the wind turbine. The bearing must be able to withstand high loads, resist fatigue and wear, and operate under harsh environmental conditions. The main bearing is usually mounted on a stationary structure and consists of an inner and outer ring, rolling elements, and a cage. The rolling elements can be balls or rollers and the cage holds the rolling elements in place.

During operation the wind turbine main bearing rotates at a slow speed and under high loads.

As a result it requires regular maintenance to prevent damage such as wear and corrosion. Maintenance activities may include lubrication, inspection of rolling elements and replacement of damaged components.

Several risks are associated with wind turbine main bearings. One notable risk is the potential for bearing failure which can result in costly repairs and downtime. This can be caused by factors such as inadequate lubrication, fatigue and wear. Regular maintenance and monitoring can help reduce the risk of bearing failure.

The Nacelle (cont.)

Wind turbine brakes

A wind turbine rotor brake is a mechanical device that is used to stop the rotation of the wind turbine rotor. It is typically located near the hub of the turbine and can be either an active or passive system.

› Design

Rotor brakes can be either mechanical or hydraulic. Mechanical brakes consist of a disc or drum that is mounted on the rotor shaft and a set of brake pads or shoes that are clamped onto the disc or drum. Hydraulic brakes use hydraulic fluid to apply pressure to the brake pads or shoes, which then clamp onto the disc or drum.

› Specification

The design of the rotor brake will depend on the size and type of the wind turbine. The brake must be able to withstand the rotational forces of the rotor, which can be significant, and must also be able to stop the rotor quickly in the event of an emergency. The brake must be able to operate reliably in a wide range of weather conditions.

› Operation

Rotor brakes are typically controlled by a system that monitors the turbine's performance and adjusts the speed of the rotor accordingly. If the turbine needs to be shut down, either for maintenance or in an emergency, the brake will be engaged to stop the rotation of the rotor.

› Maintenance

Rotor brakes require periodic maintenance to ensure they are operating properly. This may include inspection of the brake pads or shoes, replacement of worn parts and testing of the brake's performance.

Possible issues:

- If the rotor brake fails to engage properly it can lead to serious damage to the wind turbine and pose a risk to people and property nearby.
- Overheating of the brake pads or shoes can cause them to fail so proper maintenance and monitoring is important.
- If the hydraulic system fails the brake may not be able to engage, thus backup systems are essential.

The Nacelle (cont.)

Nacelle risk example

› Nacelle fire

Several factors feed into the fire risk borne by wind turbine nacelles. These include:

- **Mechanical failure:** Components such as gearboxes and generators can fail causing friction and heat that can start a fire.
- **Electrical malfunction:** The electrical components inside the nacelle can generate heat which can lead to a fire if components malfunction or are not properly maintained.
- **Flammable materials:** The use of flammable materials, such as hydraulic fluid or lubricating oil, can create a fire hazard if they come into contact with a spark or high temperatures.
- **Lightning strikes:** Wind turbines are often located in areas with high lightning activity which can cause electrical surges and potential sparks, leading to a fire.
- **Human error:** Accidents during maintenance, repair or installation work can also lead to increased fire risks.

To mitigate these risks, wind turbine manufacturers and operators have implemented safety measures such as fire detection and (in some cases) suppression systems, regular maintenance and inspection programmes and the use of non-flammable materials where possible.

The electrical equipment inside the nacelle of a wind turbine is typically the most at risk of fire. This includes components such as transformers, generators, and switchgear which can all generate heat and sparks during operation. In particular electrical arcing can occur due to insulation failure (Partial Discharge) or loose connections, which can ignite a fire.

FIG 07 - Nacelle fire in wind turbine

Control systems and protection

Control systems - SCADA and RMS

Supervisory control and data acquisition (SCADA) systems and remote monitoring systems (RMS) are critical components of modern wind farms. They allow operators to remotely monitor and control wind turbines to ensure their safe and efficient operation.

Below is a brief overview of SCADA and RMS systems in wind farms and how they help ensure safe operation:

- **SCADA System**: A centralised control system that allows operators to monitor and control wind turbines remotely. SCADA systems use sensors and other devices to collect data on wind speed, power output, temperature and other parameters. This data is transmitted to a central hub where operators analyse it and make decisions to optimise performance.
- **RMS:** In addition to the SCADA system, RMS are often installed on individual wind turbines. These systems allow operators to monitor the condition of individual components such as the gearbox, generator, and rotor blades. By tracking the performance of individual components operators can detect early signs of wear or damage and take action to prevent failures.

Typical SCADA and RMS signals/alarms:

- **Wind speed:** Alerts operators to high wind speeds which could damage the turbine or cause safety risks.
- **Power output:** Allows operators to monitor the amount of electricity being produced by the wind turbine and detect any drops in power output that could indicate a fault.
- **Temperature:** Monitors the temperature of key components such as the gearbox and generator to detect any overheating that could cause damage to the turbine.
- **Vibration:** Detects abnormal levels of vibration in the turbine which could indicate a fault or misalignment.
- **Oil pressure:** Monitors the oil pressure in the gearbox to ensure that it remains within safe limits.
- **Fault codes:** The turbine's control system will typically generate fault codes if any issues arise such as overspeed, low oil pressure or if temperature limits are exceeded.

Control systems and protection (cont.)

Protection systems (non-LPS)

Wind turbines typically have several protective systems to ensure safe and reliable operation. Some of these protective systems and their functions include:

- **Overspeed protection:** This system monitors the rotational speed of the wind turbine and activates the braking system when the turbine exceeds its maximum safe operating speed. This helps prevent damage to the turbine and the generator.
- **Blade pitch control:** This system adjusts the angle of the turbine blades to optimise power output and prevent damage in high winds. In case of excessive wind speeds the system can pitch the blades out of the wind to reduce the load on the turbine.
- **Yaw control:** This system controls the orientation of the turbine to ensure that the blades are always facing the wind. It helps prevent damage to the turbine structure due to wind loads.
- **Emergency stop system:** This system enables the wind turbine to shut down in case of a fault or emergency. It can be triggered by various factors such as overspeed, high wind speeds or low oil pressure.
- **Temperature monitoring:** The temperature of key components such as the gearbox and generator is monitored to prevent overheating which can cause damage to the turbine.
- **Grid protection:** Where wind turbines are connected to the electrical grid, protective systems are in place to ensure that the turbine does not supply power to the grid during faults or voltage disturbances. This protects the turbine and the grid from damage.

In summary these protective systems work together to ensure the safe and reliable operation of wind turbines while also maximising power output and minimising downtime.

Tower and foundations

Turbine towers play a crucial role in wind energy systems by supporting the nacelle and blades at heights that allow them to capture stronger and more consistent winds. These towers are primarily made from steel tubes, valued for their strength and flexibility, though sometimes concrete hybrids are used to reduce costs or enhance stability.

Foundations vary by location:

Onshore:

- Gravity foundations: depend on their own mass to remain stable.
- Piled foundations: secured by long piles driven deep into the ground to hold the structure firmly.

Offshore:

- Monopile foundations: consist of large steel cylinders embedded into the seabed.
- Jacket structures: lattice-style frameworks anchored to the sea floor.
- Floating platforms: designed for deep-water locations where anchoring is not possible.

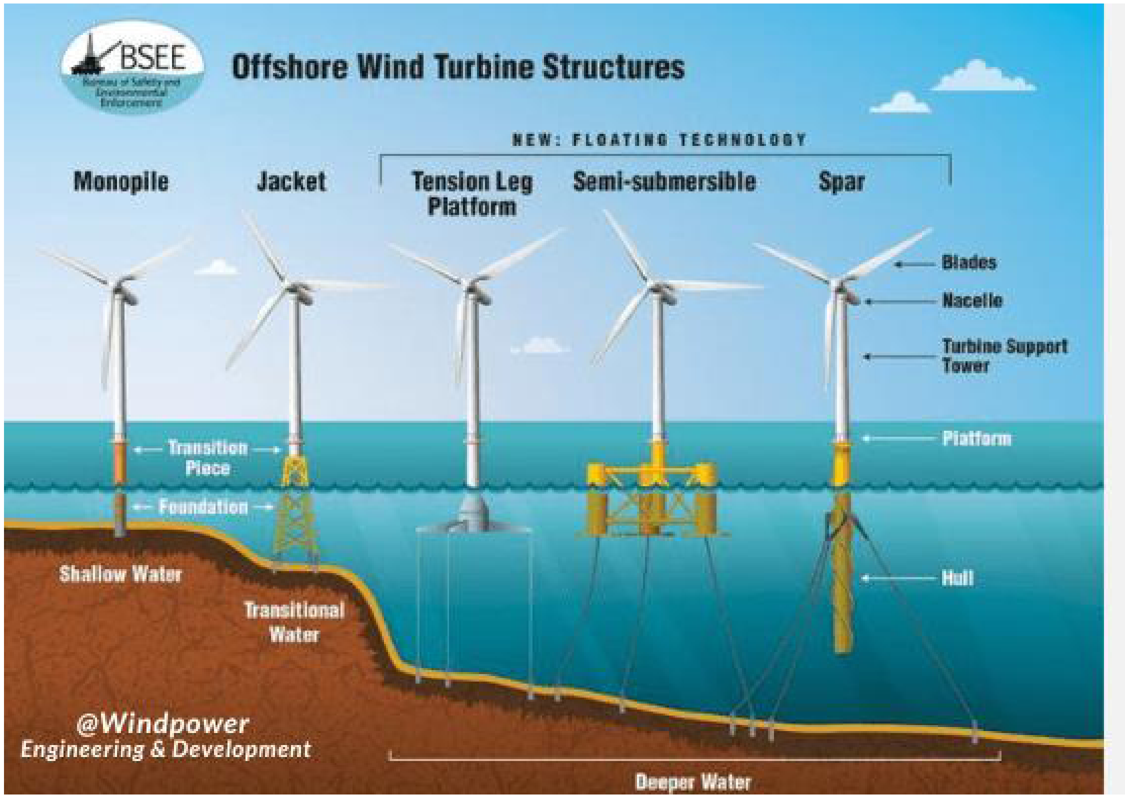


FIG 08 - Types of Offshore Wind Foundations

Tower and foundations (cont.)

Risks:

Turbine towers are exposed to various risks that can impact their structural integrity and operational lifespan. One major concern is **corrosion** – especially for offshore towers that are constantly exposed to saltwater, humidity and harsh marine conditions which accelerate the degradation of metal components.

Another significant risk is **fatigue failure** caused by the continuous and fluctuating stresses from wind loads and turbine operation and which can lead to cracks and weakening of materials over time.

Scour also poses a serious threat to offshore foundations: this is the process where strong water currents erode the seabed around the foundation, potentially undermining its stability and increasing the risk of structural failure.

These factors require careful monitoring and proactive maintenance to ensure the safety and longevity of turbine towers.

Maintenance:

To address these challenges regular maintenance is essential, involving thorough structural inspections and the application of anti-corrosion coatings along with cathodic protection to prevent material degradation and ensure long-term durability.

Substations and transformers

Substations and transformers play a critical role in wind farm infrastructure by converting and controlling the electrical power generated by turbines for safe and efficient transmission to the electrical grid. While individual turbines generate medium-voltage (MV) power (typically 0.69 kV to 33 kV), this must be stepped up to higher voltages (e.g., 132 kV or 400 kV) for efficient long-distance transmission.

Both onshore and offshore wind farms utilise one or more substations with offshore facilities often requiring bespoke offshore substation platforms.

Functions

Wind farm substations and transformers serve the following key functions:

- Voltage step-up: Raise turbine-generated power from MV to high voltage (HV) suitable for grid export.
- System protection: Houses protection relays, circuit breakers, and switchgear to isolate faults and manage loads.
- Reactive power management: Provide voltage regulation through reactive compensation (capacitor banks or STATCOMs).
- Control and communication hub: Interfaces with SCADA and communication systems for monitoring and controlling the full wind farm.

Components

› Step-up transformers

Step-up transformers play a critical role at wind farms by increasing the voltage of the electricity generated by wind turbines for efficient transmission. These transformers are typically found in two main locations: near individual wind turbines and at the wind farm's main substation.

At the turbine level, pad-mounted transformers are commonly used. These are compact units installed close to or integrated within the base of each turbine. Their primary function is to step up the low voltage generated by the turbine, usually around 0.69 kV, to a medium voltage level, typically between 11 kV and 33 kV. This intermediate voltage is more suitable for transmission across the internal collector network of the wind farm.

At the substation level, a larger and more powerful main transformer is used to further increase the voltage to high transmission levels, commonly 132 kV, 275 kV or 400 kV, depending on the grid requirements. This step is significant for minimizing energy losses during transmission over long distances to the grid connection points.

Most step-up transformers used in wind energy systems are three-phase units which provide balanced power and efficient operation.

Oil-immersed type transformers are the most prevalent due to their enhanced cooling and insulating properties, making them well-suited for outdoor and high-capacity applications.

Dry-type transformers which use air or solid insulation instead of oil and typically have lower power ratings and less efficient heat dissipation compared to oil-immersed models.

Substations and transformers (cont.)

The core and coil assemblies are enclosed within a sealed tank filled with mineral or synthetic insulating oil which serves to dissipate heat and insulate the internal components.

Protection and monitoring:

Transformers are equipped with several critical features. Buchholz relays are installed to detect gas accumulation and internal faults providing early warning of potential failures.

Oil temperature sensors are used to monitor thermal conditions and prevent overheating, while pressure relief devices ensure safe venting of gases in case of internal pressure buildup.

Together these components ensure the reliable, safe and efficient operation of the transformer system.

› Substation infrastructure

Substations are critical in wind power projects, serving as the interface between the medium voltage (MV) generated by turbines and the high voltage (HV) transmission network.

Key components are as following:

Switchgear systems

- **Gas-Insulated Switchgear (GIS):** Utilises pressurised SF_6 gas to insulate and extinguish arcs within a compact enclosure. GIS is preferred in environments with space constraints, harsh weather conditions (such as offshore or coastal locations) or where pollution and corrosion are concerns.
- **Air-Insulated Switchgear (AIS):** Employs ambient air for insulation and typically requires larger physical space. AIS is cost-effective and easier to maintain but is more vulnerable to environmental factors such as humidity and pollution. It is commonly used in onshore substations with ample space.

Protection relays

- **Overcurrent protection:** Protects equipment from excessive currents due to faults.
- **Earth fault protection:** Detects ground faults and isolates affected circuits.
- **Differential protection:** Compares current entering and leaving equipment (e.g., transformers) to detect internal faults.
- **Distance protection:** Measures impedance to detect and isolate faults along transmission lines.

Control building

- **SCADA:** Allows real-time monitoring and control of the substation and wind farm operations.
- **Communication equipment:** Facilitates data transfer between local devices and central control centres via fibre optics or wireless links.
- **Battery banks:** Provide uninterruptible power supply (UPS) for protection and control systems during outages.
- **Auxiliary power systems:** Includes backup diesel generators or connection to a station service supply to ensure continued operation of substation auxiliaries.

Substations and transformers (cont.)

Fire detection and suppression systems

These systems are essential for high-risk areas such as transformer bays and cable basements:

- Heat and smoke detectors; for early fault detection.
- Automatic fire suppression systems; using inert gases or water mist to extinguish fires with minimal damage to electrical equipment.
- Alarm systems; connected to SCADA for real-time alerts.

Substation operation process

The operational process typically follows these steps:

1. Power collection

- Each wind turbine generates electricity at MV (typically 33–66 kV).
- Power is transmitted via underground (onshore) or subsea (offshore) collection cables to the substation.

2. Voltage step-up

- A main power transformer at the substation steps up MV to HV (typically 132–400 kV) to match grid transmission levels.
- This reduces current and minimizes losses over long-distance transmission.

3. High voltage switching and control

- Isolate circuits for maintenance or fault repair
- Reroute power flow based on operational requirements
- Respond to faults or abnormal grid events by disconnecting affected sections
- Remote control of breakers and isolators is integrated with the SCADA system

4. Power transmission

- The stepped-up HV electricity is exported to a grid connection point or a larger grid substation
- Export is via overhead transmission lines (onshore wind farm) or HV subsea export cables (offshore wind farms)

5. Remote monitoring and automation

- Continuous monitoring of voltage, current, breaker status, fault conditions and environmental variables.
- Remote operation of all switchgear and control systems.
- Data logging for performance analytics and predictive maintenance.

Substations and transformers (cont.)

Maintenance

Substation and transformer maintenance is critical to wind farm uptime. Activities include:

- **Thermal imaging:** Detects hotspots in connections or components.
- **DGA (dissolved gas analysis):** Oil testing in transformers to identify developing faults.
- **Oil level and quality monitoring:** For dielectric strength and contamination.
- **Relay and breaker testing:** Verifies correct operation of protection systems.
- **Cleaning and inspection:** Particularly for AIS and insulators prone to contamination. Especially in offshore substations exposed to salt spray.

Remote condition monitoring is increasingly used to detect anomalies before failure occurs.

Risks and failure modes

- **Transformer Failure:** Caused by overloading, insulation breakdown, oil leaks, moisture ingress, or winding short circuits.
- **Switchgear Failure:** Mechanical seizure, contact wear, or arc flash due to switching faults.
- **Oil Fires or Explosions:** Resulting from internal arcing in oil-filled transformers.
- **Lightning Damage:** Especially if surge arrestors or earthing are inadequate.
- **Water Ingress:** In cable terminations or substation enclosures, particularly offshore.
- **SCADA Cybersecurity Breach:** Substation systems are vulnerable to targeted attacks.
- **Export Cable Overload or Fault:** If protection settings or load forecasting are inadequate.

Failures can result in total generation loss, expensive component replacement, and months of downtime.

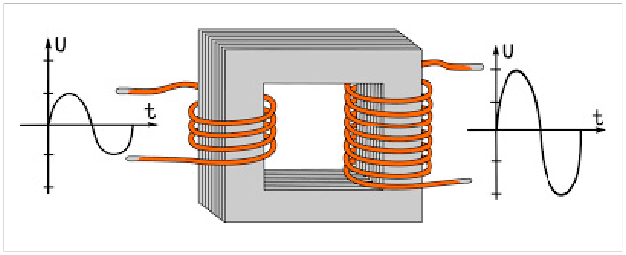


FIG 09 AND 10 - Overview of Step-up Transformer (Sources: Velatron Technologies & Arrow Electronics

Substations and transformers (cont.)

Risk mitigation strategies

- **Protective relay coordination:** Ensures faults are isolated quickly with minimal impact.
- **Transformer monitoring systems:** For real-time diagnostics of internal conditions.
- **Surge protection devices:** Divert lightning strikes or switching surges safely to ground.
- **Fire suppression systems:** In transformer bays and control rooms.
- **Redundancy in substation design:** N+1 transformer configurations reduce single-point failure risk.
- **Routine preventative maintenance:** Scheduled testing, inspection and servicing.

Insurance considerations

Losses involving substations and transformers can represent a significant portion of wind farm insurance claims due particularly to:

- High repair or replacement costs
- Long lead times for transformer manufacture
- Extensive grid outage implications
- Environmental liabilities from oil leaks or fires

Understanding component ratings, protection schemes and historical failure data is essential for underwriting and risk assessment.

Grid connection

In both offshore and onshore wind energy projects power generated by turbines is transmitted to the main grid through high-voltage cables which are critical to the reliable delivery of electricity.

Offshore projects use subsea cables while onshore projects rely on underground or overhead cables. Both environments present distinct risks.

- Offshore: cable joint failures, often caused by installation challenges or operational stress, are a significant concern. Additional offshore risks include anchor drag from ships, fishing activities, and seabed movement due to natural currents or sediment shifts, all of which can expose or damage cables.
- Onshore: cables are vulnerable to damage from rodents, accidental impacts during construction or excavation and natural ground movement.

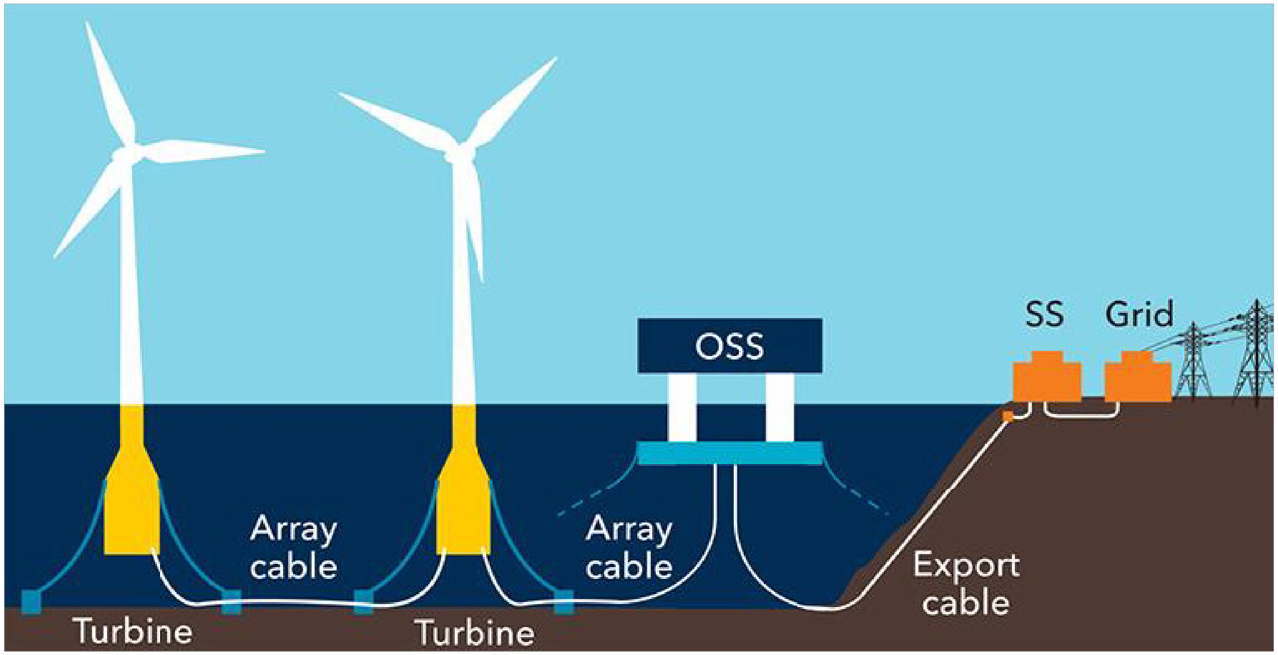


FIG 11 - Overview of Grid connection in floating windfarm (Source: DNV)

Grid connection (cont.)

To mitigate these risks developers use a combination of physical protection and strategic planning. Burial protection involves laying cables below the seabed or ground surface to protect them from external impacts.

Armouring or reinforcing cables with steel or other materials adds an extra layer of defence.

In both offshore and onshore settings detailed route planning is essential to avoid high-risk areas such as shipping lanes, fishing zones, or construction-heavy regions. These combined measures help ensure long-term operational integrity and reduce the likelihood of outages or costly repairs.

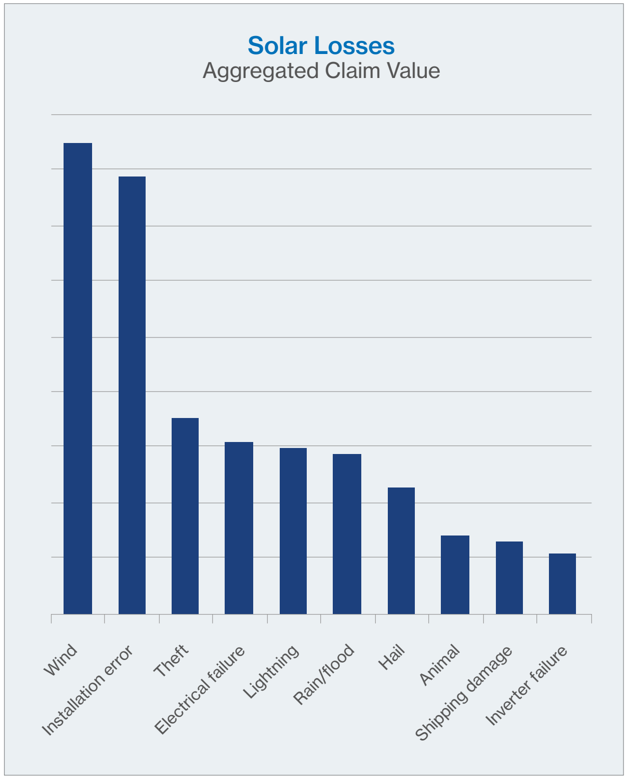
Crawford renewable energy loss database

The Crawford renewable energy loss database captures over 3,000 major losses on renewable energy projects. This database provides valuable insights into the causes and factors contributing to losses in the renewable energy sector, allowing insurers, risk managers and renewable energy project owners to improve their risk management practices.

By leveraging the insights from this loss database you can gain a better understanding of the risks associated with renewable energy projects, identify potential sources of risk and implement effective risk mitigation strategies. This can ultimately lead to more accurate pricing, better claims management and improved industry performance.

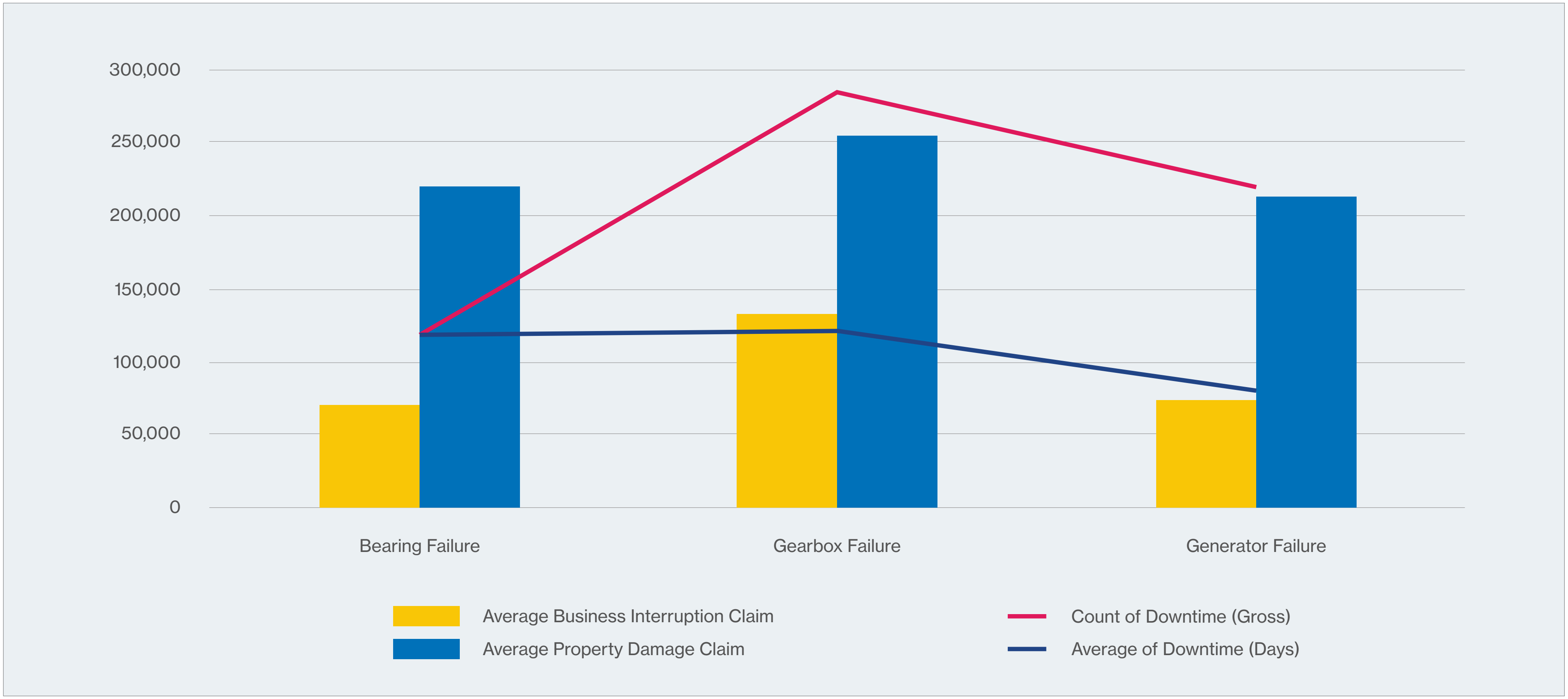
Our database provides detailed information on the causes and factors contributing to losses including equipment failures, weather-related events and operational errors. By analysing this data it is possible to identify common patterns and trends and to develop strategies to mitigate these risks and reduce the likelihood of future losses.

Whether you are an insurer looking to improve your underwriting discipline, a risk manager seeking to enhance your risk assessment processes or a renewable energy project owner looking to improve the performance and sustainability of your project, the Crawford renewable energy loss database is a valuable resource.



Crawford renewable energy loss database (cont.)

Example nacelle insights



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