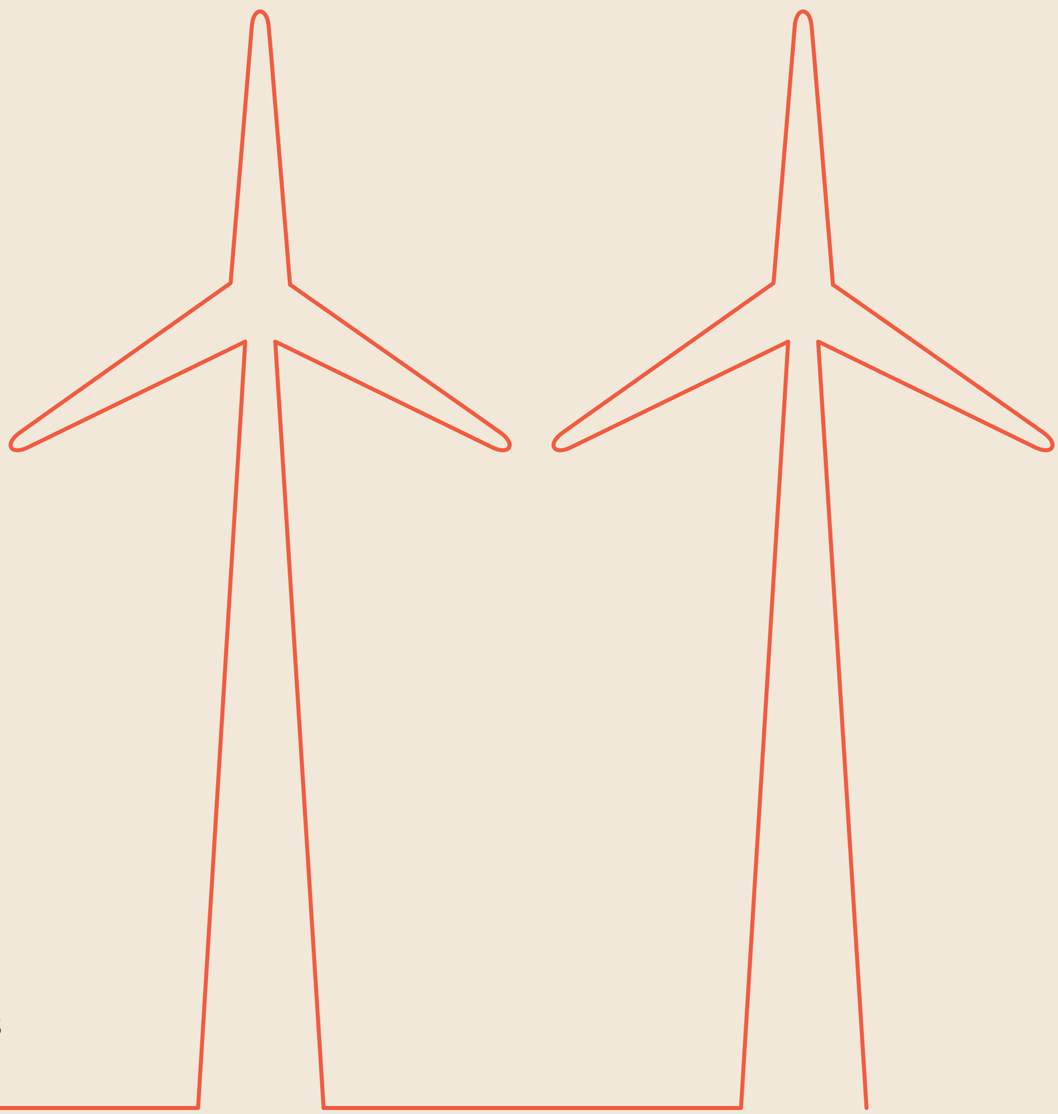
NERGICA
Renewable Energy Research and Innovation

Drone Solutions for Wind Turbine Inspections

Overview of Cutting-edge Solution for Wind Farm O&M Industry



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Summary

Over the past few decades, wind energy has enjoyed sustained growth in numerous regions around the world. Concerns over greenhouse gas reductions combined with the maturity of the technology and falling costs have led a number of countries to adopt this technology. Further, this trend suggests that wind energy in the 21st century will play an increasingly significant role in the energy strategies of many jurisdictions, including Canada.

At a time when wind power is rapidly expanding, blade inspections are becoming an important maintenance activity. Although a number of inspection methods currently exist, the emergence of advanced technologies such as drones is showing great promise.

According to IHS Markit [1], annual wind turbine O&M costs amount to approximately $50,000 per megawatt.

Indeed, drone inspections offer undeniable advantages. In fact, studies conducted together with various industrial players have demonstrated that remote drone-based inspections proved to be approximately five times faster than those in which rope-access techniques were used. Besides this advantage, drones can be used to quickly and economically obtain an idea of the magnitude of defects and their distribution throughout a given wind farm.

Certain technical and legislative factors must be taken into account, however, to guarantee the effectiveness of the inspection and the validity of the data gathered at the time thereof. Such factors notably include the selection of sensors and a camera capable of providing satisfactory resolution, optimization of the flight plan, the expertise in composites necessary to identify and prioritize defects and, lastly, use of a software or expert system capable of producing diagnostic reports that will help operators make informed O&M decisions with regard to their turbines.

Recent technological advances are now allowing operators to entertain the prospect of increasingly complete automation of inspections and diagnostics as a solution for the future. However, automation raises a number of questions in terms of both technologies and legislation. Each of these questions in turn translates into a challenge that helps drive the applied research sector.

Nergica excels in the field of wind farm optimization and is a leading player in the research, validation and commercialization of innovations related to wind turbine inspection and O&M. Owner and operator of a full-scale outdoor research site, Nergica works together with a broad diversity of players in the wind sector to develop solutions that will ultimately allow renewables to be better integrated into the energy portfolio of countries.

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Introduction

The rationale for this study is rooted in the clear interest expressed by operators for the use of drones to carry out inspections of turbines and wind farms. The report attempts to answer – at least partially – the numerous requests for information that have been addressed to Nergica with regard to using drones to inspect operational turbines.

Though not exhaustive in nature, this study does provide an overview of the inspection market and the needs of the sector. It presents existing as well as up-and-coming solutions such as drone-based inspections and the automation of the various stages of inspection and diagnostics.

In the context of the energy transition that is gaining momentum across the country and around the world, new drone-based technologies are increasingly attractive and could very well revolutionize the field of inspection and maintenance of large infrastructures such as wind turbines in the foreseeable future.

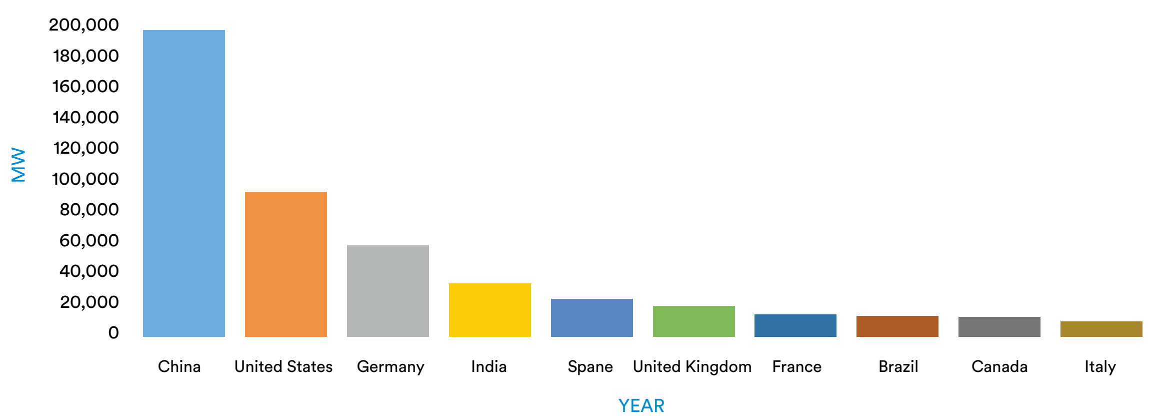
Photo credit : MagBag

Wind Power: Energy in the Air!

Over the past few decades, wind energy has enjoyed robust growth in numerous regions around the world. In fact, in 2015 wind energy showed a sharper increase in newly installed capacity than any other form of energy production [2].

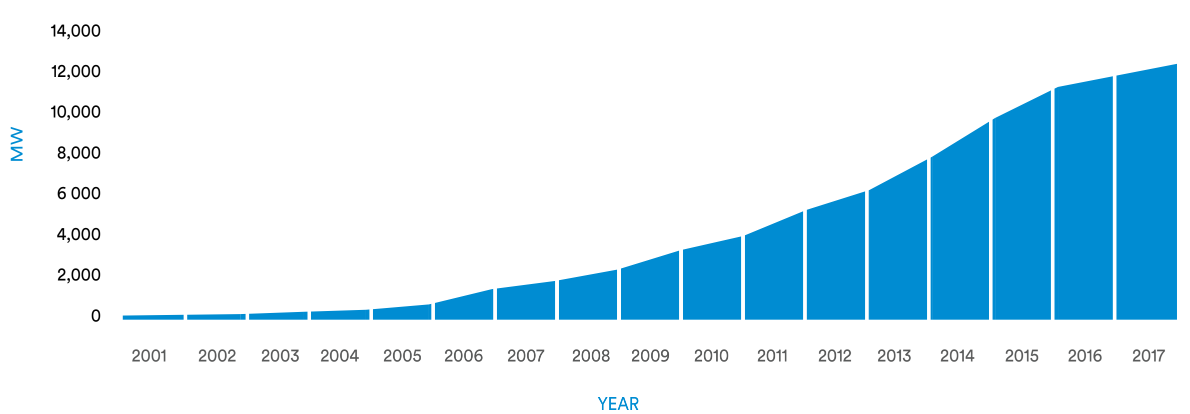
Of the 540 GW of wind power installed worldwide in 2017, ten countries accounted for 457 GW (Figure 1), with Canada placing ninth in the ranking [3].

Figure 1 Top 10 Countries for Installed Wind Power in 2017 [MW] [4]



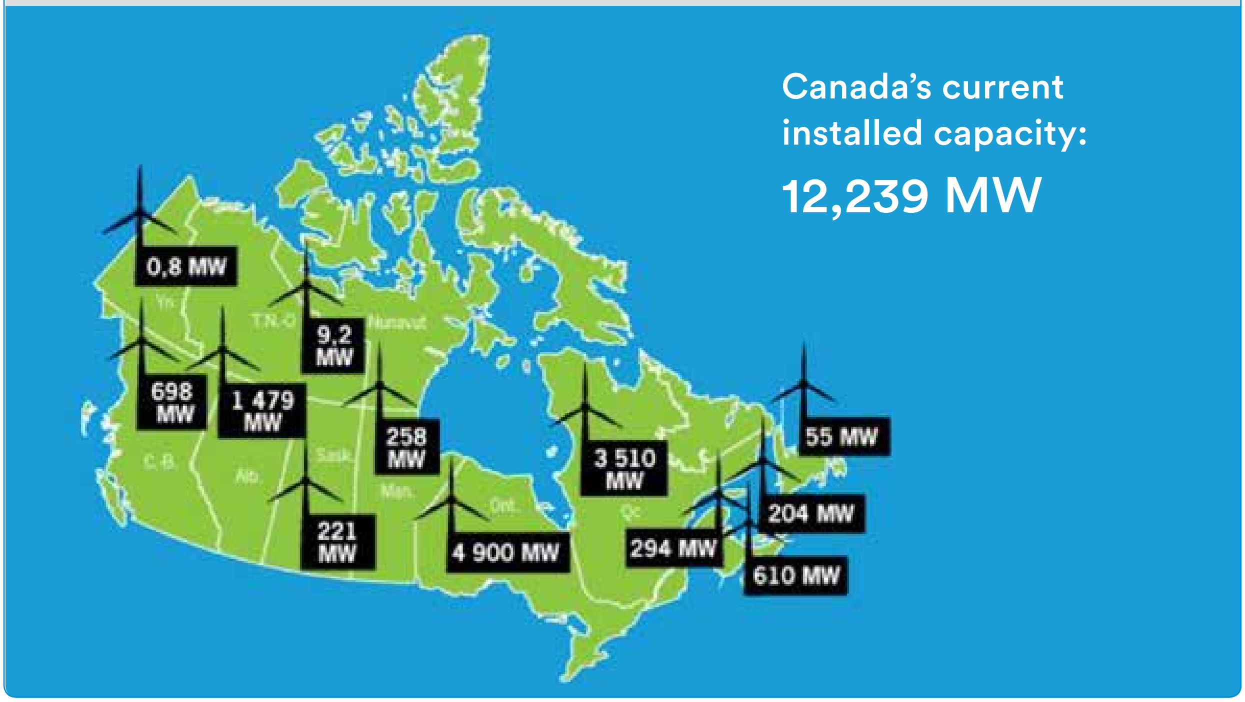
In fact, between 2001 and 2017, Canada registered a remarkable uptick in the adoption of wind energy (Figure 2).

Figure 2 Evolution of Installed Wind Energy Capacity in Canada [MW] – 2001 to 2017 [3, 4]



More precisely, Ontario, Quebec and Alberta account for 4,900 MW, 3,510 MW and 1,479 MW, respectively, of the country's installed capacity, which totalled over 12,000 MW in 2017 (Figure 3). This 12,239 MW of installed capacity alone represents 6,409 wind turbines that require regular inspection and maintenance. [4].

Figure 3 Cumulative Installed Capacity in Canada per Province as of December 2017 [6]



Although installed wind capacity is increasing in many regions throughout the world, the most rapidly-expanding markets are those of the European Union and Asia, especially China (Figure 4) (Figure 5). Closer to home, since 2009 the North American market has also witnessed constant progression in its installed wind capacity (Figure 6), which, as of 2016, stood at 82,184 MW represented by 52,343 turbines across the continent.

Figure 4 Evolution of Installed Wind Energy Capacity in European Union [MW] – 2001 to 2017 [3, 4]

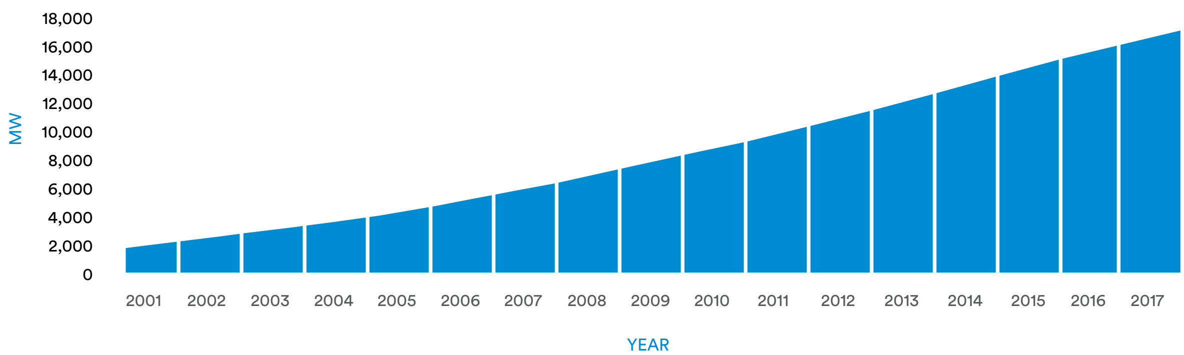


Figure 5 Evolution of Installed Wind Energy Capacity in India and China [MW] – 2001 to 2017 [3, 4]

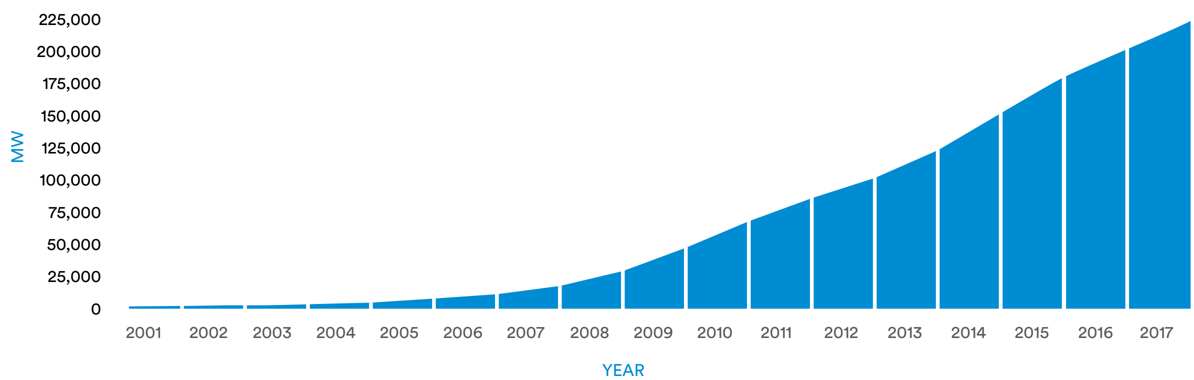
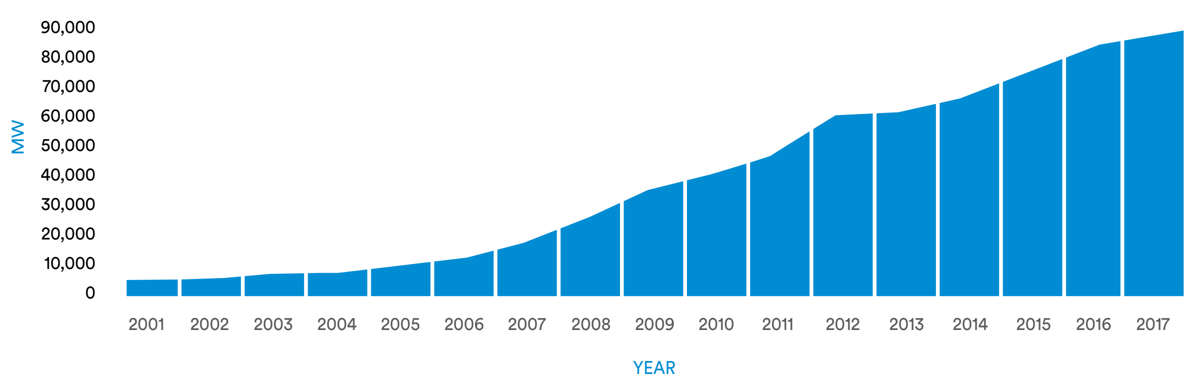


Figure 6 Evolution of Installed Wind Energy Capacity in United States [MW] – 2001 to 2017 [3, 4]



Wind Energy: Driver of the Energy Transition

Phasing out diesel consumption in favour of renewables is becoming urgent, notably in the context of the challenges associated with the climate accords ratified by numerous nations following the United Nations Climate Change Conference (COP21) negotiations.

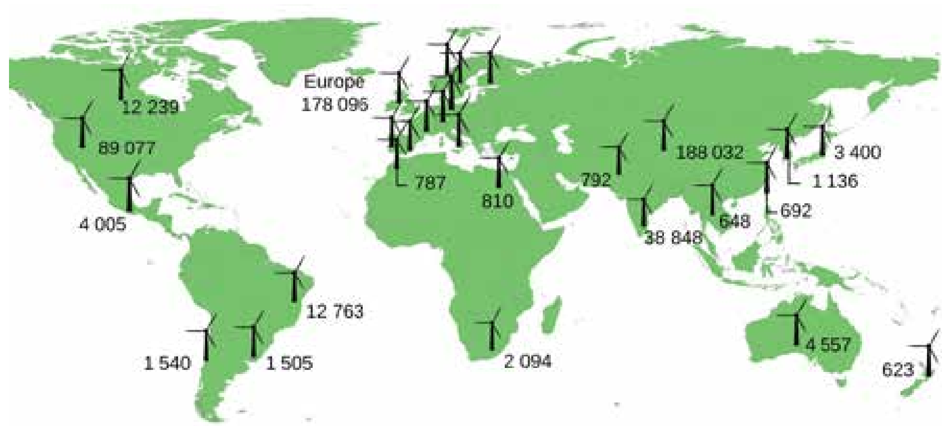
In the wake of this agreement and at a time when signatory nations are embarking on a major energy transition, the wind sector is receiving more attention than ever. The maturity of the technology and falling costs have inspired a number of countries to embrace this technology (Figure 7) and suggest that wind power in the 21st century will account for an increasingly significant portion of the energy portfolio of many nations, including Canada.

The Government of Canada has set an objective of supplying 90% of its electricity production from renewable and non-polluting sources by 2030 [8]. In November 2015, the Government of Alberta followed suit with the announcement of its energy strategy calling for the progressive replacement of two-thirds of the 6,300 MW of coal-fired electricity with renewable sources by 2030. A promise that in all likelihood will be kept, as in December 2017, the Government of Alberta officially announced Phase I for 600 MW of wind power, followed a few months later by Phases II and III for an additional 700 MW.

Closer to home, in Quebec, the commissioning of the most recently announced wind projects will help the Government of Quebec meet its objective of installing 4,000 MW of wind in the province [9]. This ultimately represents nearly 2,000 wind turbines.

Although the province's 2030 Energy Policy does not call for any new supply [9], the demand for turbine component replacements is expected to keep Quebec-based manufacturers busy through approximately 2024-2025 [10]. In the meantime, manufacturing companies have been actively developing their export markets while operators are showing increased interest in O&M issues in an effort to optimize the performance and service lives of their wind turbines.

Figure 7 Distribution of Global Wind Energy Capacity [MW] for Countries Totalling over 500 MW as of 2017 [4], [7]



Inspection Market

In a context where wind farms are proliferating and wind power is playing an increasingly significant role in countries' energy strategies, blade inspection is becoming a key maintenance activity.

In this regard, a study conducted in 2015 by Complete Wind, a company specializing in blade inspections and repair, reveals that in a sample of 4,860 blades installed on turbines of various makes and sizes, 85% showed defects, with an average of 10 defects per blade [11].

Consequently, wind farm operators are seeking tools that provide accurate and efficient diagnostics that will help them save time and money. Although a number of inspection techniques have been tested and employed – including visual inspections, video cameras, rope access, cherry pickers and telescopes – it must be recognized that blade inspection remains an arduous and costly exercise. The emergence of new, more advanced technologies such as drone-based inspection can help revolutionize this market in which certain companies are slowly beginning to carve out a niche for themselves.

For an operator, a useful inspection is one that helps prioritize maintenance tasks and evaluate the resources needed to remedy each issue.

Photo credit : Nergica

Photo credit : MagBag

Market Needs

In its report "Drones for Wind Turbine Inspection" [12], which contained market forecasts for drone-based turbine inspections, Navigant Research predicted that by 2024, global revenue for drone sales and drone-based inspection services in the wind sector would rise to nearly $6 billion.

In Canada, the 12,239 MW of installed capacity is composed of 295 wind farms that contain a total of 19,227 blades that must be regularly inspected (Table I) [7]. Inspecting these blades would represent an annual workload of approximately 600 working days for companies using drones throughout the country. In Quebec alone, inspecting the blades of 1,879 turbines would represent a market of approximately 176 working days a year[1].

Although operators generally seek to benefit from inspection services that are timely, reliable and the least costly possible, the needs of the market in terms of inspection and maintenance vary considerably depending on a number of factors. These include the number of wind farms in operation, installed capacity, age of the facilities and the climate conditions to which the infrastructures are exposed. However, notwithstanding specific conditions, blades are generally inspected approximately every five years for the duration of the manufacturer's warranty period, after which they are expected every other year [13].

In the Canadian wind industry, drone sales and turbine inspection services represent a $120 million market, $36 million of which is concentrated in Quebec.

Table I Number of Turbines and Blades by Canadian Province [7]

Province	Number of Turbines	Number of Blades
British Columbia	288	864
Alberta	901	2,703
Saskatchewan	143	429
Manitoba	133	399
Quebec	1,879	5,637
Ontario	2,515	7,545
Atlantic provinces	550	1,650
TOTAL	6,409	19,227

1 This estimate was obtained using the following calculation, which assumes that each blade is inspected every other year: number of working days per year = (1,879 turbines x 1.5 h/turbine) / (2 years x 8 h/day).

Inspection Methods

Initial inspection of turbine blades is generally carried out at the plant at the time of manufacture and quality control. Other inspections may also be conducted after the blades have been commissioned; in these cases, inspection is performed in the field at the end of the warranty period or on a recurrent basis in order to avoid major failures and ensure the aerodynamic performance of the blades. Blade inspection is performed in order to take advantage of the manufacturer's warranty, if any.

Of all the inspection methods currently available, many are only applicable at the place of manufacture or have only been tested on turbine blades in a laboratory environment. Inspection methods used in manufacturing plants and those employed in the field differ tremendously in terms of complexity. For example, on the premises of the manufacturing plant, it is quite straightforward to perform a comprehensive inspection, i.e. on and under the blade surface, whereas this same type of inspection is much more challenging to carry out in the field. Of the handful of methods that are suitable for installed blades, some are only applicable for evaluating the surface, while others can be used to assess the structure at variable depths below the surface. These are non-destructive methods.

Photo credit : Nergica/Microdrones

The criteria used to evaluate the performance of an inspection method are [14]:

- Sensitivity;
- Accuracy;
- Repeatability;
- Speed; and
- Ease of deploying the equipment.

Once the defects have been identified by the camera or any other method, they must be located (wind farm, turbine, blade, distance from blade root, GPS coordinates) and categorized, whether automatically, via image processing or manually by a technician. Various georeferencing methods are currently available on the market including laser rangefinders, sonars and GPS-enabled drones. Although a number of publications address this topic, automated detection of defects based on blade images is a technique that continues to evolve.

Surface Inspection

Evaluating the blade surface can help detect external defects such as cracks, erosion, lightning damage and debonding of the adhesive at the leading or trailing edge. On the other hand, surface inspection methods are inadequate for identifying internal defects, despite the fact that some of these flaws occasionally manifest themselves at the surface [14].

Surface inspection methods include visual inspection by workers, whether using rope-access techniques, working on a platform suspended from the nacelle [14], or an elevated platform [15]; visual inspection from the ground using binoculars or a telescope; and visual inspection with a ground-based or drone-mounted camera. The latter method may be used with or without automated image processing and with or without automated detection of defects. Evidently, each of these methods comes with its share of advantages and disadvantages (Table II).

Table II Performance of Various Visual Inspection Techniques for Turbine Blades [15]

Inspection Method	Low Cost	Possibility of *in situ* Repair	Not Dependent on Meteorological Conditions	Simplicity	Quality of Results	Speed
Rope access	Passable	Passable	Passable	Passable	Excellent	Passable
On an elevated or suspended platform	Poor	Excellent	Poor	Poor	Excellent	Poor
Ground-based camera	Excellent	Poor	Passable	Excellent	Passable	Excellent
Drone-mounted camera	Excellent	Poor	Passable	Excellent	Passable	Excellent

Excellent Passable Poor

Sub-surface Inspection

A variety of methods have been developed for sub-surface blade inspections. Some are applied at the place of manufacture while others are used on commissioned turbines. These methods can be grouped into different categories (Table III).

Table III Sub-surface Inspection Methods

Technology / Type of inspection [14]	Inspection applicable to commissioned turbines
Acoustic emission (sound and ultrasound)	Yes
Shearography	No
Thermography	Yes
Electromagnetism (eddy currents)	Yes
Radiography (X- and gamma rays)	No
Visual inspection	Yes

Condition-Monitoring Systems

Condition-monitoring systems that ensure continuous monitoring using sensors installed on the blades or rotor shaft of the turbine are used to detect certain flaws. Although these techniques cannot be used to pinpoint the exact location of damage, condition-monitoring systems are increasingly used in combination with the aforementioned methods [15]. Data collected in this manner can help detect the presence of blade defects and plan repairs. Strain gauges are generally used to measure deformations at precise locations, while accelerometers serve to measure dynamic response and to conduct modal analysis[2] on a blade. Condition-monitoring systems present a number of challenges, including the following:

- Installation of sensors during the manufac-turing process or after commissioning;
- Sensor reliability must be maintained for approximately 20 years; and
- The robustness of data communication, storage, processing and analysis systems.

2 Modal analysis is a vibration analysis conducted to determine the resonance frequencies of an object or structure.

Table IV outlines the different inspection methods currently offered on the market.

Table IV Turbine Blade Inspection Methods

Category	Technique	Comments
Surface inspection	Ground-based or drone-mounted camera	- Telescope or high-performance lens (often robotic), or drone equipped with a stabilized camera - Fast - Can be integrated with a digital report generation system - Surface inspection only
Sub-surface inspection	Rope access or platform	- Photos taken and repairs (small and medium-sized) made by technician; - Possibility of in situ repair - Requires several hours to inspect each blade - High cost
	Ultrasound, shearography, thermography, electromagnetism, radiography	- Non-destructive inspections usually conducted on ground or on blade in laboratory or manufacturing plant - Measures waves (electromagnetic or acoustic) as they are affected by underlying structural changes - Less developed and thus more costly technologies - Methods can identify defects below the surface
Other	Condition-monitoring systems	- Sensors installed in nacelle and in blades; natural vibration and frequency trends suggest changes in blade structure (i.e. damage) - Impossible to pinpoint location of defects - High cost of system, which must be installed on each turbine

Products and Services Currently Offered

A number companies in Quebec and throughout the world offer inspection services. For example, certain companies inspect blades using rope-access techniques, while other use a robotic telescope fitted with a digital camera and a software program that can be used to record data and subsequently produce a report.

A number of software programs on the market can identify various types of defects by processing the images taken during inspections. Some companies use an elevated platform equipped with large brushes that clean the blade surface while a camera records a video of the said surface. Others inspect turbine blades using drones, which they claim are accurate to the centimetre when it comes to identifying defects.

Drone inspection

Whether performing a surface inspection or other type of inspection, verifying the state of turbine blades remains to this day a complex and costly exercise. Often installed at remote sites far from major highways and at heights that can reach or even exceed 100 m, turbine blades, generally speaking, are difficult to access. In this context, the use of drones represents a promising solution.

Photo credit : Nergica/Microdrones

Besides their use for blade inspections, drones are also proving to be highly useful for inspecting other turbine components such as nacelles and towers, as well as for fulfilling specific needs during the construction phase, e.g. geomatics, site characterization, or determining roughness or forest cover. Examples of such applications include:

- Characterization of forest cover in the resource assessment phase;
- Mapping and topography of a site prior to the construction phase;
- End-of-warranty inspections: wind turbines and their blades are often inspected before the warranty period expires so that the operator can file claims; and
- Inspection of met masts and the outsides of buildings located at wind farm sites.

Why drones?

Although the various manual inspection methods employed to date are sufficient to identify and characterize a number of different blade defects, they remain costly and time-consuming. Some of these methods, such as rope-access inspection for example, entail certain safety risks for workers.

However, the use of remote drone-assisted inspection methods – although they are more flexible, faster, less costly and safer – can limit the number of defects identified per inspection or compromise their classification. Despite these constraints, drone-based inspections do offer undeniable advantages. In fact, studies conducted together with various industrial partners have demonstrated that remote inspection methods using drones have the advantage of providing rapid and low-cost insight into the scale and distribution of blade defects present at a given wind farm.

Although drones do not offer the same degree of accuracy as other techniques, it is generally agreed that they allow a greater number of blades to be inspected in a given amount of time while limiting direct interventions to those blades that require repairs. In this regard, the use of drones represents an advance that may be poised to revolutionize the field of inspections.

Potential of Drone-based Inspections

Based on certain experiments, it would appear that a blade surface inspection can be completed in slightly less than 15 minutes.

Based on this assumption, it would be theoretically possible to inspect three blades in 45 minutes. However, this figure does not include the time needed to change the drone battery or turn the rotor – which, according to some estimates, can be completed in approximately 30 minutes, or in 15 minutes if both tasks are performed in parallel.

If one assumes that inspection requires 75 minutes and that it takes 15 minutes to move from one turbine to the next, it seems realistic to allow 1.5 hours (in favourable conditions) to complete the comprehensive inspection of all blades of a single turbine, whereas the same work performed using rope-access techniques generally requires much more time (Table V). Based on the assumptions and the example presented above, the use of drones, even if employed only for a visual inspection of defects, is approximately five times faster than inspections using rope-access techniques. In other words, with drones, slightly more than five wind turbines can be inspected in the same time span as would be required to inspect a single machine using rope access. Furthermore, if the production losses stemming from the stoppage of turbines during the inspection work are taken into account, using drones can offer a clear advantage for wind farm operators.

For example, a two-person team operating a drone can inspect the blades of five turbines per day and, with technological advances, this number could rise to reach ten machines per day. In comparison, the same inspection using rope-access techniques might require a complete work day for a team of three technicians [16].

Drone inspections also show highly promising potential to take maximum advantage of favourable periods for summer inspections. Indeed, an analysis of (i) meteorological data from the summer of 2016 and (ii) the factors limiting the suitable periods for performing inspections at Nergica's research site was conducted to

Photo credit : Nergica/Microdrones

Photo credit : MagBag

Table V Example of Time Required for Inspections: Drone vs. Rope Access

Inspection method	Time required for turbine inspection	Number of technicians required for inspection
Drone	1,5 h	2
Rope access	8 h	3

estimate the potential number of hours that could have been dedicated to drone inspections. Sunrise and sunset times, precipitation, wind and the cloud ceiling were all elements that were taken into consideration. The analysis revealed that a maximum of approximately 1,000 hours of inspection would have been available for the summer of 2016, which equates to 125 working days.

Additionally, drone inspections offer the advantage of being able to take images much closer to the blade than is possible with a ground-based camera. Furthermore, the quality of images taken by drones is less dependent on certain meteorological factors such as rain or fog, which undeniably compromise the quality of images taken from the ground [17].

Again, according to our assumptions, over a period of 125 working days, a team using a drone could perform blade inspections of approximately 650 turbines, while a team relying on rope-access techniques would be able to inspect just 125 turbines over the same period.

Key Elements of Drone Inspections

Although drone inspections may initially seem to be a promising solution for a number of operators, certain technical and legislative factors must be taken into consideration to guarantee the effectiveness of the inspection and the validity of the data gathered at the time thereof.

Beyond the tool itself (interesting as it may be), drone-based inspections require the use of special sensors, flight plans that take multiple factors into consideration and, lastly, proven expertise in wind power, composites and characterizing the defects and damage identified on the blades. They must also comply with all applicable regulations.

Image Quality and Sensor Selection

A number of elements must be taken into consideration when it comes time to select the sensors that will be installed on the drones. Of these, image quality often constitutes one of the most important criteria. Indeed, what is the optimal number of megapixels, or pixels per millimetre, to obtain a high-quality image? Although important, resolution is not the only criterion to be taken into account to ensure image quality and crispness. The quantity of light available, focus distance, depth of field, ISO and the type of lens also have a significant influence on image quality.

It is also important to recall that a simple camera is not necessarily the most appropriate tool in all cases. In fact, the use of cameras alone is not sufficient to identify every defect present on a blade. Other sensors such as thermal or infrared cameras can prove to be more effective for identifying blade defects. The use of infrared cameras, for example, can help detect defects that are invisible to conventional cameras. It has been demonstrated that variations in ambient temperature are sufficient to detect at the very least common defects such as cracks, delaminations and impacts [18].

Besides thermal and infrared cameras, other instruments can also be installed to increase the quantity of information collected during a drone inspection; such instruments include:

- **Lasermeter: device used to measure the distance between the drone and a point on the component;**
- **GPS system: location of drone; and**
- **RTK system: ground-based system that increases the reliability and accuracy of the GPS.**

Resolution

Expressed in millimetres per pixel, resolution is defined by the number of megapixels, the level of optical zoom and the distance between the blade and the camera. Since this distance is a key element of the resolution, it is highly recommended to always conserve the same distance between the drone and the blade in order to maintain a constant image resolution. It is also advised to opt for a resolution of at least 2-3 pixels per millimetre of blade in order to obtain images in which one can clearly make out the texture of the blade and not mistake the latter for dust or dirt.

Quantity of Light Available

The brighter the day, the higher the shutter speed can be set to take the photo. The advantage of a high shutter speed is that movements (of the blade or the drone) are frozen in the photo and the elements composing the image remain clear. In dimmer conditions, the shutter speed should be reduced, which will make moving objects appear blurry in the photo. Low-light periods such as sunrise or sunset are thus to be avoided for taking photos, as there is a greater risk that images will be blurry.

It is also worth noting that direct sunlight can sometimes create strong contrasts that result in certain details being masked or magnified. Ideal lighting is often obtained when the sky is covered with a thin layer of clouds that diffuse the sunlight.

ISO Sensitivity

The ISO is the sensitivity of the sensor to light. The higher the ISO, the more sensitive the camera will be to light and will be able to compensate for periods of low light. On the other hand, the higher the ISO value is, the more grain the image will show. Automatic adjustment of the ISO is recommended to optimize the aperture size (for depth of field) and shutter speed (to freeze movements) settings. The amount of grain also depends on the quality of the camera. A quality camera will take photos at a higher ISO and with less grain. It is recommended to run tests to determine the maximum ISO value at which the grain level remains acceptable.

Lenses

One very important element to consider when selecting the lens is the presence or absence of an image stabilizer. This function serves to minimize small vibrations in order to enhance the clarity of photos and especially videos. Inarguably, this is highly relevant in the context of a turbine blade inspection using a drone. Another element that might be important is the presence or absence of a varifocal lens (zoom).

Camera Bodies

Three aspects are particularly important when selecting the camera body, namely the number of megapixels, weight and lens interchangeability. In this regard, mirrorless cameras, also known as hybrids, are a wise choice due to their light weight and can offer excellent performance.

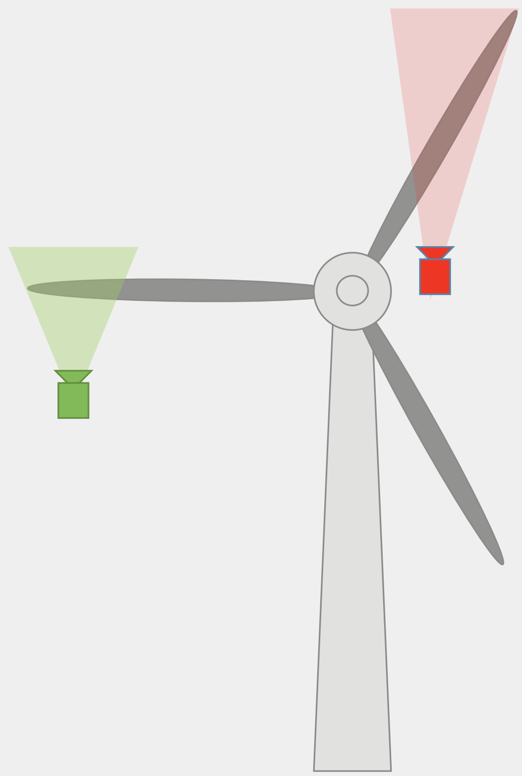
Depth of Field

The depth of field corresponds to the area of sharpness in a photo. Similar to the human eye, a camera cannot simultaneously focus on both proximate and distant objects. It is therefore preferable that the elements that must be in focus in a photograph be placed equidistant from the camera.

A simple way to bring all elements of a blade into focus is to ensure that the camera remains perpendicular to the blade (green camera in Figure 8). In the event that the blade is not horizontal, a gimbal may be used to control the position of the camera. Although this method is preferred for its simplicity, the photo must sometimes be taken non-perpendicular to the blade (red camera in Figure 8). In such cases, a few guidelines will nevertheless help increase the depth of field, namely:

1) Move away from the blade;
2) Adjust the camera to have a small lens aperture;
3) Use the smallest focal length possible;
4) Refrain from using the zoom;
5) Ensure that there is good lighting on the blade.

Figure 8 Depth of Field with Perpendicular and Non-perpendicular Camera



Gimbals

Gimbals are camera stabilizers that help maintain the orientation of the camera independently of that of the drone.

Optimal Flight Plan

The best flight plans are those that require the least amount of time and offer the best viewing angles to diagnose any defects on the blades.

A number of factors should be taken into consideration when optimizing the flight plan, namely:

- Elements targeted by inspection: suction side, pressure side, leading edge, trailing edge;
- Height of highest blade tip;
- Camera orientation;
- Minimum and maximum distance between drone and wind turbine;
- Areas with no GPS signal;
- Meteorological conditions (wind speed and gusts);
- Need for the drone operator to keep the de vice within his or her field of view at all times;
- Legislative constraints that drone operation is subject to;
- Drone battery life, quality of charged batteries and time required to recharge a battery;
- Practicality of turning the rotor.

There are two flight trajectories that meet most of the above-mentioned factors particularly well.

1) Flight Trajectory 1: Inspection of Three Blades without Turning the Rotor

The first flight trajectory consists of placing the turbine blades in the so-called “rabbit ears” position (Figure 9).

This position allows the three blades to be inspected without the need to rotate the rotor and images to be taken with a camera that remains perpendicular to the blades (Figure 8). However, this trajectory requires the technician to guide the camera so that it remains perpendicular to the blade for the entire duration of image taking.

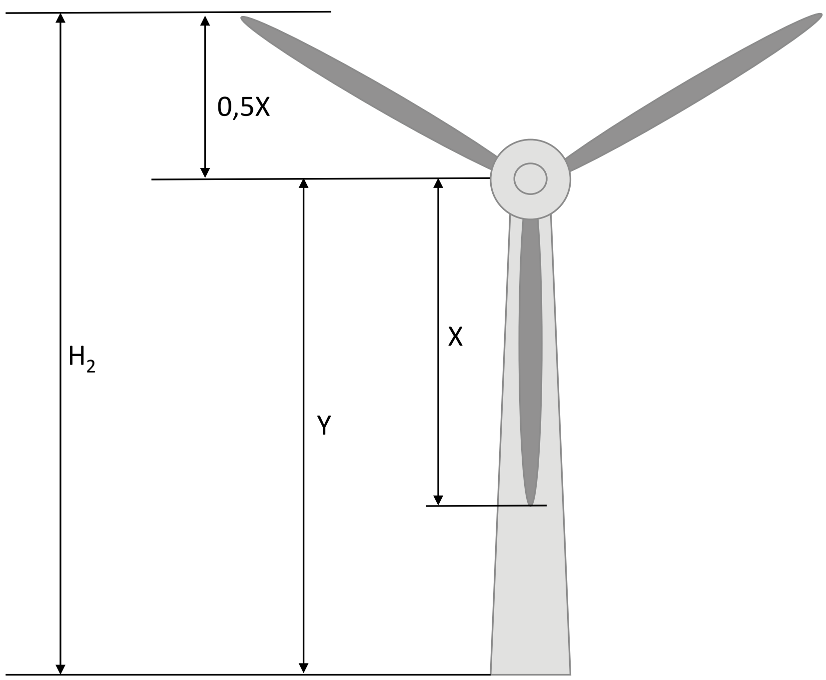
2) Flight Trajectory 2: Inspection of Three Blades by Turning the Rotor

Unlike the preceding flight plan, Flight Trajectory 2 requires at least two rotations of the rotor to allow images to be taken of each side of the three blades.

In this inspection scenario, first the vertical blade is inspected, after which the rotor is turned to align the next blade with the tower. With this trajectory, the camera can be aligned perpendicular to the blade without the need to handle the blade directly.

In conclusion, there is no such thing as an ideal flight plan. Although Flight Trajectory 1 generally requires less time (no need to turn rotor), other factors such as camera manoeuvrability or wind speed may result in Flight Trajectory 2 being the best option for a given inspection. Furthermore, this second trajectory can provide greater consistency in the image quality of each blade surface (suction side, pressure side, leading edge). In any case, selecting the flight plan remains a key element for obtaining quality images that will subsequently allow for an informed diagnosis of the condition of the components.

Figure 9 **Preferred Rotor Position for Inspection**



The most common rotor position for blade inspections is the "rabbit ears" position. This position has the advantage of providing a low vertical blade for inspection and the lowest possible blade tip height. For example, for a turbine with a hub height of 80 m and a rotor diameter of 92 m, the maximum height in the "rabbit ears" position would be 103 m. The maximum blade tip height for the same turbine, all positions considered, would be 126 m.

For an Informed Diagnosis

Defect diagnostics is an essential element that represents added value for any type of inspection service. Characterizing the state of a wind turbine or wind farm, however, requires in-depth knowledge of a number of parameters and the use of various tools and software for processing the information and data collected. This is why this type of report must generally be supervised and approved by a competent individual.

"Be more than a picture-pusher!"

Although a number of companies have specialized in drone inspection services, few have successfully managed to combine this expertise with advanced knowledge of composite materials and turbine components. This means that operators must simultaneously contract the services of (i) inspection experts who are capable of taking clear, high-quality images, and (ii) experts in composites and blade repair who are able to identify defects requiring repairs, establish priorities and address urgent situations, if any.

Nevertheless, a number of software programs are available for image analysis and diagnostics, including notably those provided by Collineo, EdgeData and SkySpecs.

Photos credit : Nergica/Microdrones

Wind Turbines: Nomenclature, Faults and Critical Areas

Nomenclature

Wind turbines generate electricity by converting the energy in the wind into mechanical rotational power thanks to a large rotor attached to a nacelle mounted on top of a tower (Figure 10). Comprising three blades (Figure 11) attached to the hub, the rotor is attached via the main shaft to a gearbox, which increases the rotational speed of the shaft connected to the generator. A number of other components required for the turbine to operate properly are also found in the nacelle, including the cooling unit and the yaw drive.

Figure 10 Wind Turbine Nomenclature [19]

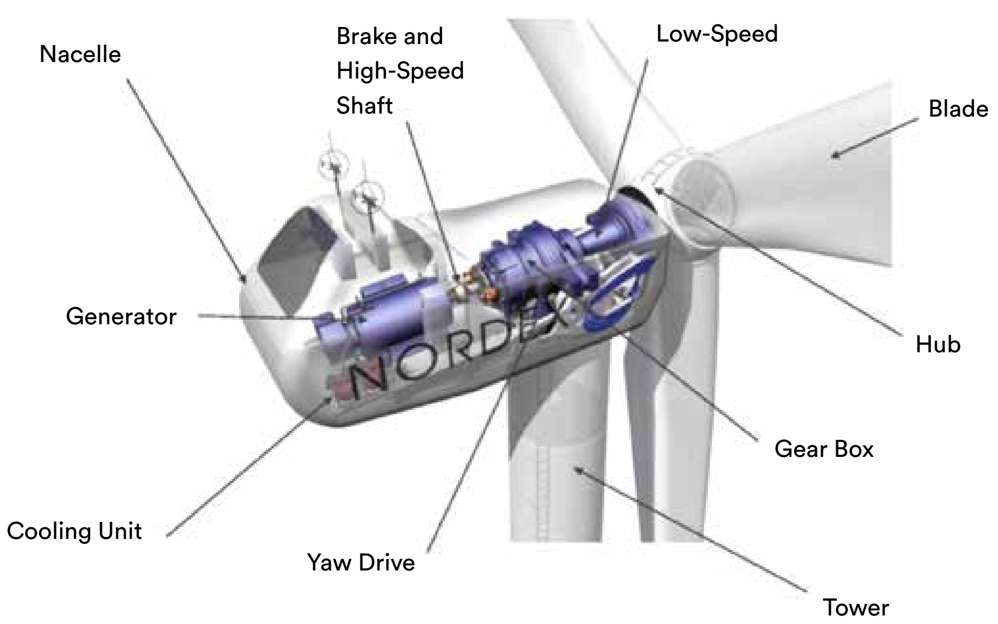
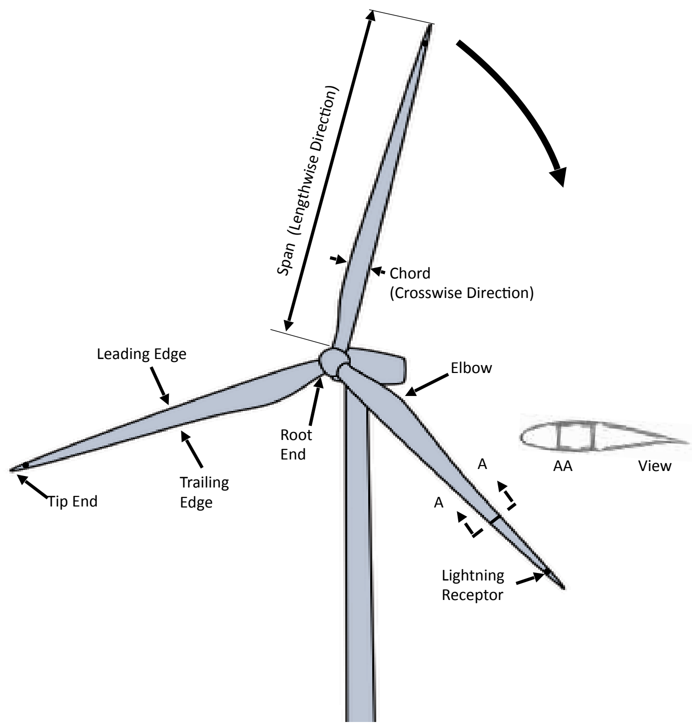
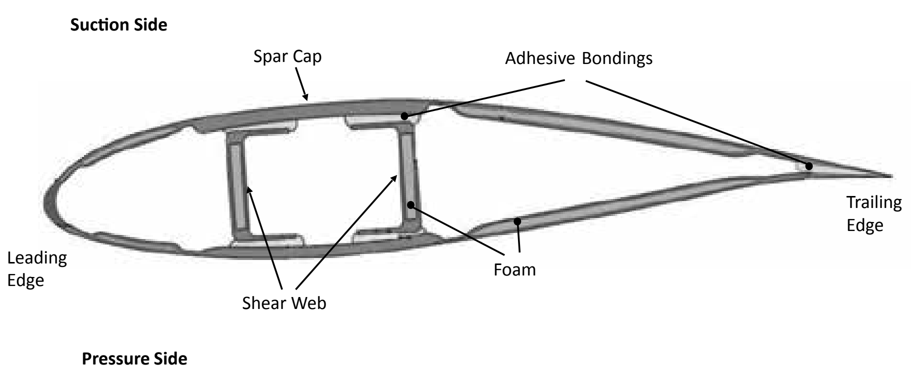


Figure 11 Blade Nomenclature



A cross section of the blade is useful for illustrating various structures (Figure 12). The reinforcing material used in these structures is glass or carbon fibre. The resins used are generally polyester resins or epoxies. Synthetic polymer foams or certain types of wood such as balsa are typically used as core materials.

Figure 12 Cross Section of Turbine Blade



Note : figure adapted from M. Doroshtnasir, T. Worzewski, R. Krankenhagen and Mathias Röllig [20]

Defect Types and Origins

The most frequently encountered defects on turbine blades are surface defects. Examples of such defects are described below.

Erosion
wear caused by high-speed collisions between the blades and airborne particles (hailstones, water droplets, sand, insects).

Dry glass
Area within laminate devoid of resin and hence showing a different colouration.

Delamination
Separation of laminate layers caused by poor infusion at the plant (Figure 13).

Cracks
Failure of laminate or adhesive bonding. Even if it appears to be benign, a crack must never be neglected. It may be more serious than it looks and it can spread (Figure 14).

Stress cracks
Cluster of multiple cracks at the root section of the blade and along the leading edge and surfaces, vis-à-vis the spars[3].

Micro-cracks
Cracks or flaking, often finer than the gelcoat, caused by poor infusion at the manufacturing plant. They are difficult to detect and their identification depends on the quality of images examined by the inspector.

Blisters
Poor adherence of gelcoat to the laminate, causing localized debonding of the gelcoat.

Deep cavity
Cavity that extends down one or more layers from the surface.

Figure 13 Délamination [21]

Figure 14 Cracks in Adhesive Bonding [21]

3 Beam that runs the length of the blade and that supports the majority of its weight.

Figure 15 Cracks and Flaking in Gelcoat [22]

Scratches
Blade surface damage that may or may not be superficial.

Pitting
Cavities measuring at least 1 mm that are produced if the gelcoat is poorly applied or poorly controlled.

Flaking
Partial (chipping) or complete (exposed laminate) debonding of the gelcoat (Figure 15).

Other defects observed on blades occur on their integral components or add-ons. The following list briefly describes some of them.

Leading edge protection tape
Transparent polyurethane tape that can peel or tear.

Vortex generator and stall strip
Accessories added to improve blade aerodynamics, but which can easily become detached.

Spoilers
Add-on to root section of blade (along the span) to enhance its aerodynamics. Spoilers can break, debond or crack.

Stall barriers
Add-on to root section of blade (along the chord) to enhance its aerodynamics. Stall barriers can break, debond or crack.

Drain
Hole at the blade tip that serves to drain any water that has entered into the blade. It can become clogged and result in breakage due to expanding ice.

In addition to blades, other turbine components must also be regularly inspected. The following list provides an overview of the most important areas.

Nacelle roof
The met mast, measurement instruments and top of the nacelle can be damaged by ice shedding off the blades. Anchor points must also be inspected in order to detect problematic cracks.

Tower:
Rust can form between two sections of the tower, which can cause the paint to chip or flake off.

Transformer
The top of the transformer can be damaged by ice that sheds off the blades.

Origin of Defects

Defects encountered on a turbine blade can stem from its design, manufacture, handling, operation or repair. Additionally, a defect can have multiple origins.

Design

Under-estimation of loads and poor characterization of defects can lead to damage during operations or handling.

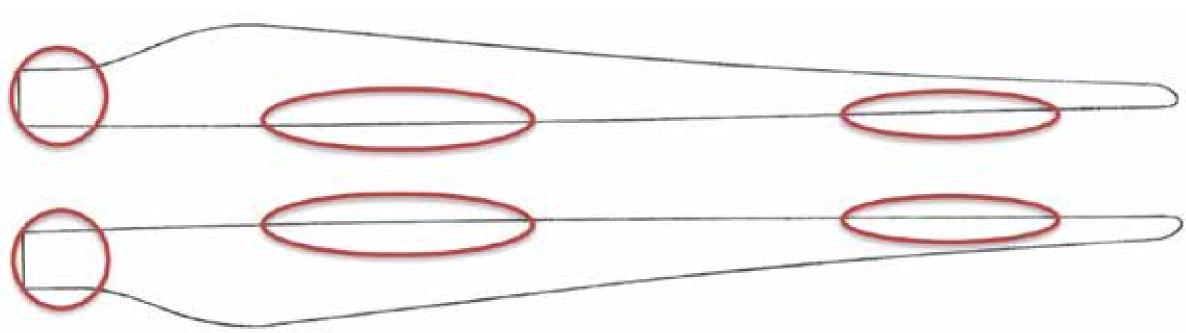
Manufacture

The manufacturing processes used by the wind industry are not yet highly automated. Despite the efforts and rigour applied in quality control, certain defects overlooked during inspections such as dry fibre or a rich fibre ratio can lead to localized delamination.

Handling

Blades can sometimes travel long distances between their place of manufacture and their place of installation. Handling blades with cranes, for example, can cause scratching, flaking (especially on the leading and trailing edges) and cracks in the gelcoat at the points of support, particularly in those places where there are compressions or shocks (Figure 16).

Figure 16 Critical areas when handling turbine blades during transport



Note: Potential sources of damage are circled in red [23].

Figure 17 Evolution of Erosion of Leading Edge through Normal Wear [24]

Note: The gelcoat (in white) wears away until the laminate is exposed (dark gray) and then damaged, as shown in the photo on the right.

Figure 18 Example of Damage Caused by Lightning [22]

Operation

Once in operation, the blade is subject to multiple potential causes of wear and breakages, including erosion of the leading edge (Figure 17), lightning (Figure 18), icing, particulates from agricultural land, ultraviolet rays, saline air, birds and insects.

Repair

Repairs that are poorly executed, whether at the place of manufacture or after commissioning, can generate new defects or more severe damage.

At the Operation & Maintenance Summit organized by the Canadian Wind Energy Association (CanWEA) in Toronto in February 2015, Complete Wind, a company specializing in turbine blade inspections and repairs, presented several statistics concerning wind turbine defects [11].

A sample of 4,860 blades from seven different manufacturers and installed on turbines rated between 0.66 MW and 3 MW was studied, with the following key findings:

- 48,370 defects were discovered;
- 85% of blades inspected showed defects; and
- An average of 10 defects were identified per blade.

Distribution of blade defects according to their origin:

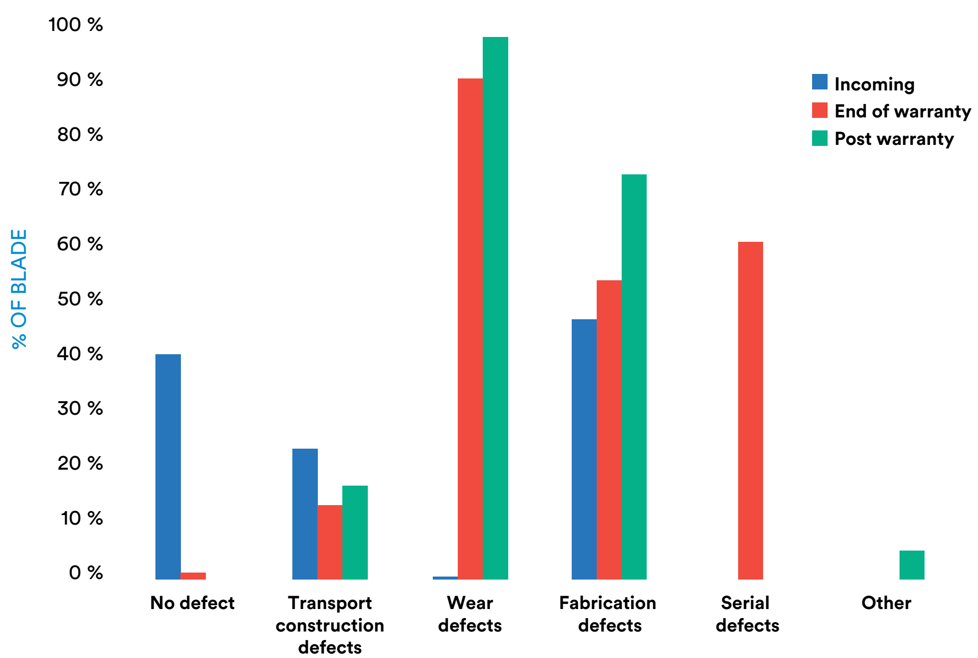
- Manufacture: 52%
- Wear: 44%
- Transport and construction: 3%
- Other: ~1%

Percentage of blades at end of warranty that showed a manufacturing defect: >50 %

- Wear: >90 %
- Transport and construction: ~15%

Figure 19 illustrates in greater detail the distribution of defects by type for a newly installed blade, an end-of-warranty blade and a post-warranty blade.

Figure 19 Distribution of Blade Defect Types Identified by Life Cycle [11]



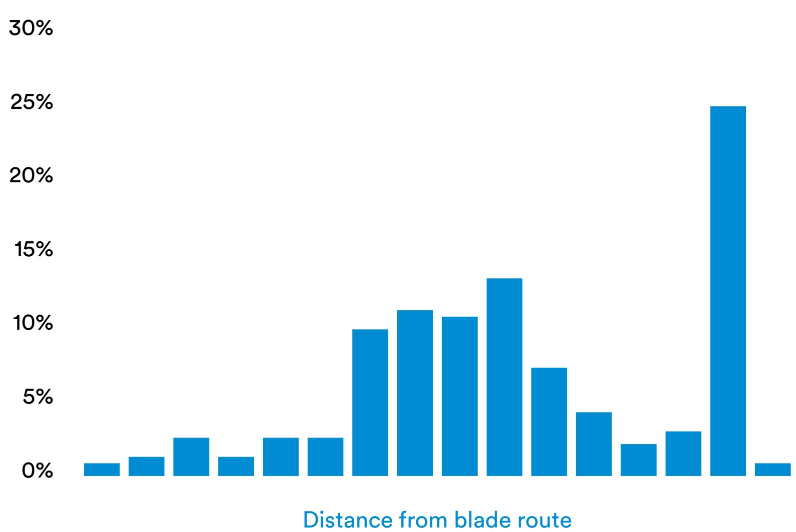
Critical Blade Areas

The distribution of defects on blades of the same model is highly dependent on the environment in which the blade is operating. Further, different blade models can exhibit distinct defect distributions. There remains much research to be done on the effects of multiple causes of wear on the defect distribution.

Figure 20 presents an example of the distribution of defects on an operating blade for a given wind farm, while Figure 21 illustrates the areas that are generally most prone to defects. Each of these areas contains different potential sources of defects, some of which are described below:

- The middle of the blade is more often affected during transport and installation;
- The middle of the blade is subject to high strain caused by bending when the turbine is operating;
- The leading edge far from the root section is particularly prone to erosion;
- Blade tips are exposed to lightning and the accumulation of water inside the blades.

Figure 20 Distribution of Blade Defects for a Site based on the Distance from the Root Section [25]



Note: On the x-axis, the origin of the graph corresponds to the root section of the blade.

Figure 21 Areas where Defects are Generally More Concentrated on a Turbine Blade [25]

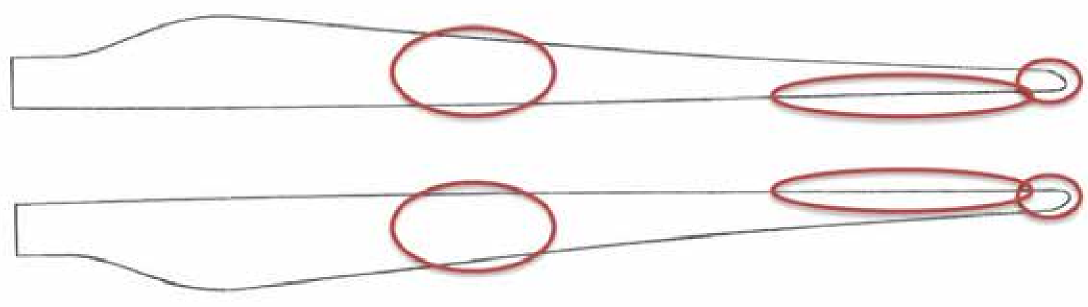


Photo credit : MagBag

Automation: Solution for the Future?

Recent technological advances in various fields such as artificial intelligence, image analysis and geomatics are increasingly enabling companies to envisage the complete automation of turbine blade inspections as a solution of the future. A number of companies are interested in commercializing this solution and one of them, which is based in the US, already offers 100% automated inspection services.

Photo credit : Nergica/Microdrones

Full automation of the blade inspection process implies the use of a drone that operates completely independently of a pilot. The self-guided drone thus flies according to a program and a pre-established trajectory and then, once the images have been analyzed, generates an automatic report.

Automation raises interesting questions in terms of both technological development and the adaptation of applicable regulations. For example, will Canadian standards evolve to the point that drones will one day be able to fly without constant surveillance? What about image analysis? Will automation of the latter help facilitate reliable diagnosis of the condition of blades at a wind farm?

Regardless of these questions, automation will invariably coincide with the development of advanced flight technologies, image analysis and diagnostics routines, defect codification and the generation of a report that can be used to make informed O&M decisions. These conditions call for numerous advances in the field of computer science, the development of sufficiently powerful batteries and increasingly accurate sensors, state-of-the-art computers capable of processing significant quantities of data and generating reports and documented track records. In other words, drones represent a solution that, although beginning to gain traction, still present a few interesting challenges for companies and research centres.

Conclusion

In light of the prospects for growth in renewable energy integration, the wind industry is shifting, and rightfully so, toward advanced solutions to optimize project productivity in a cost-competitive manner. O&M activities are also part of this trend and are forcing the inspection market to offer innovative solutions to overcome the challenges associated with inspecting operational turbines.

Although the use of drones to inspect wind turbines is a relatively recent development, it represents clear advantages to perform more economical diagnostics that can contribute to informed maintenance-related decisions. In this context, this promising solution warrants further research and *in situ* validation of these new technologies.

Regardless of whether complete automation is considered a distant dream or a reality, it goes without saying that it is a turbulent market, that the technologies exist and are evolving rapidly, and that Nergica is positioning itself as a key player in the implementation of innovative solutions.

Who we are

Nergica is a centre of applied research that stimulates innovation in the renewable energy industry through research, technical assistance, technology transfer and technical support for businesses and communities. Its mission: creating new opportunities for renewable energy.

More precisely, Nergica specializes in developing solutions for renewable energy integration, optimizing wind farm and solar array performance and supporting growing SMEs. The organization carries out its activities by drawing from a multidisciplinary team of experts, research infrastructures in a natural setting that are unavailable elsewhere in Canada, and custom services that support innovation.

Initially recognized for its expertise in cold climates and O&M, Nergica also offers advanced services for the development and assessment of new technologies, commercialization of innovations, adapted meteorology, microgrids, energy storage and grid management. Initially known as the TechnoCentre éolien when it was founded in 2000, Nergica is an official college centre for technology transfer (CCTT) and is affiliated with the Cégep de la Gaspésie et des Îles.

Nergica: The Natural Progression of the TechnoCentre éolien

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