MSc Program
Renewable Energy Systems

Assessment of the current state of techniques for wind turbines maintenance to ensure their effective operations – A patent-based analysis of the latest development trends

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Affidavit

I, **JANA JANICKA, MSC**, hereby declare

1. that I am the sole author of the present Master's Thesis, "ASSESSMENT OF THE CURRENT STATE OF TECHNIQUES FOR WIND TURBINES MAINTENANCE TO ENSURE THEIR EFFECTIVE OPERATIONS – A PATENT-BASED ANALYSIS OF THE LATEST DEVELOPMENT TRENDS", 113 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

Vienna, 07.03.2021

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Signature

Acknowledgements

This thesis represents the final outcome of my graduation project for the Master of Science degree in Renewable Energy Systems at TU WIEN. The completion of this thesis also means the end of my time as a student. It was a time of development from a project manager into an engineer. An engineer who has developed her academic and practical skills.

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Abstract

The operation and maintenance costs of wind turbines make up a significant part of the total operating costs during the life of the wind turbine, especially when they are used in harsh environmental conditions.

This thesis will analyse the important conditions for improving the economic performance of wind farms, which is highly dependent on the efficient operation and timely and high-quality maintenance of wind turbines.

Patent research is a mandatory attribute for wind farms operations and maintenance, and for the development of new models of wind turbines. Owners, operators and developers of wind farms are always interested in the availability of full-fledged information that reflects modern achievements regarding the reliable operation of wind turbines, including a detailed list of patented technical solutions. Thorough patent assessment is becoming a significant topic as increasing amounts of patent applications are being submitted each year. Current methods of patents analysis have limited capabilities to provide comprehensive assessments, therefore alternative methods are needed to increase accuracy of full-text documents processing. The methodology for the selection and assessment of patent documents used in this thesis has been developed by Advanced Energy Technologies (AENERT). Such methodology has made it possible to obtain a number of important information positions, such as, for instance, development trends, characteristics of leaders in certain areas, evaluation of cooperative and technological relations between participants and monitoring of quantitative patent statistics for all constituents of technological processes.

In this thesis, crucial patents are reviewed in the area of maintenance, repair, replacement of parts of industrial wind turbines with a horizontal axis of rotation.
The results of the patent analysis indicate that patent activity is growing in the area of techniques for wind turbines maintenance. There are reasonable grounds to believe that in the coming years, maintenance, repair and replacement patent activity will be largely dominated by applications related to: assembly of blades, offshore wind turbines, automatic manipulators or robots, testing static or dynamic balance of machines or structures, investigating the presence of flaws, defects or contamination, structures of working platforms for carrying out repair or diagnostic work.

The data obtained can help to identify further the most vulnerable technical operations in the general list of operations related to maintenance, repair and replacement. This can further determine the boundaries of the technical capabilities of the proposed options for technical solutions, to get closer to understanding the prospects for their practical development and effective influence on the problem of extracting the maximum possible capacity factor.

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1. INTRODUCTION

This chapter provides a linkage between the underlying challenges and the objective and goal of this thesis. The chapter consists of background and problem description followed by objective, goal and target group. Finally, an outline is presented that guides the reader throughout the composition of the thesis.

1.1 General purpose of this research

Wind energy is considered one of the most promising renewable energy sources around the globe. This is confirmed by intensive development and implementation of wind farms over the last two decades. The operation and maintenance costs of wind turbines make up a significant part of the total operating costs during their technical lifetime, especially when they are used in harsh environmental conditions.

This thesis will analyse the important conditions for improving the economic performance of wind farms, which is highly dependent on the efficient operation and timely and high-quality maintenance of wind turbines.
Patent research is a mandatory attribute both for the project development of any energy sites, including wind farms, and for the development of new models of wind turbines as well as new modes of operation and maintenance. Owners, operators and developers of wind farms are always interested in the availability of full-fledged information that reflects modern achievements regarding the reliable operation of wind turbines, including a detailed list of patented technical solutions.

1.2 Challenges of technical maintenance

The continuous large-scale development of wind technologies is impossible without solving a number of serious technological and operational problems. One of these problems is the relatively low-capacity factor, which in real practice of wind turbines rarely exceeds 30%. As a result, huge material-intensive and expensive structures of wind turbines sit idle for a considerable time without generating electricity, reducing the investment attractiveness of the industry, hindering the competitiveness within the electricity market for the turbine operator and also limiting the competitiveness of the turbine manufacture.

Ensuring the maximum capacity factor of wind turbines is hampered by objective factors in the form of local natural resources, first of all, the magnitude and range of wind speed, its stability and tendency to powerful gusts. These are undoubtedly important but inevitable costs of generating electricity from wind turbines.

The development of means of effective control of wind resources and methods of comprehensive testing when selecting sites for the construction of wind farms can significantly reduce the severity of the problem and thus increase the capacity factor.

Another option for achieving this, implemented in the last decade, is the growth of the dimensions and height of wind turbines. Since the beginning of the nineties, the average hub height of wind generators has increased from 40 to about 130 meters, and the rotor diameter from 20 meters to more than 100 meters (Energy Transition, 2020). Since wind speed increases with height, this allows for higher wind speeds combined with a larger swept area. At the same time, it is obvious that the increase in the size of wind turbines cannot be unlimited and will further be more and more actively restrained by associated negative factors, including difficulties with the transportation and installation of wind turbines, as well as due to technical restrictions.

However, there is a large group of subjective factors that impede the extraction of the maximum possible capacity factor. These include, for example:

- ineffective equipment condition monitoring, especially remote monitoring,
- poor-quality maintenance,
- untimely delivery of component parts,
- suboptimal organization of transportation or repair work,
- lack of high-performance tools for maintenance, which leads to unexpected shutdowns of wind turbines.

It should also be taken into account that below main listed technological and operational directions for the future development of wind energy that have developed in recent years, inevitably additionally and significantly accentuate the above problems:

1. Growth of the dimensions of wind turbines
2. Complication of the design of wind turbines due to automated control systems
3. Placement of wind farms in offshore zone

1.3 The role of patent information in technological development

Years of experience in wind turbine operation have created a wide range of technical and operational solutions for efficient wind turbine maintenance, which are used by the operating services of wind farms. Most of these decisions are in the form of patent applications for inventions. In this regard, patent information is the most central and detailed source of engineering knowledge.

Timely assimilation of this information by the engineering community can be the most important link in increasing the capacity factor of wind turbines. However, there is a major obstacle to achieving this. Every year around 3 million new patent applications are registered in the world and more than a million patents for inventions are issued. Of these, at least 30 thousand are directly related to wind energy and several tens of thousands to the border areas of technology (Five IP Offices, 2019).

Patent documents are registered in many countries of the world, each of which has its own language peculiarities and national requirements for describing technical solutions. This is a huge and difficult task to digest array of documents. In addition, unfortunately, existing systems for searching for patent documents, based mainly on the use of keywords, do not cope with the task of recognizing their contextual meaning, which leads to the formation of distorted lists of patent documents. Search through the indexes of the international patent classification has certain advantages. But even in this case, individual indices may be concomitant, not defining character, which complicates the classification of patent information, and often progress in the technical industry is ahead of the introduction of new indices into the patent hierarchy.

Thus, without professional selection and classification of this material, it remains largely unclaimed or even inaccessible to interested participants. In this regard, in this thesis, an attempt was made to create a systematic review of recent patent documents published from 2010 to 2019 and dedicated to the maintenance, repair, replacement of parts of industrial wind turbines with a horizontal axis of rotation. This material can facilitate the useful dissemination of patent information and the timely delivery of the latest technical solutions to interested stakeholders.

1.4 The structure of this thesis

This thesis is structured as listed in Table 1, which introduces chapters' names and briefly describes the main inputs and outputs of each chapter. The study starts with *Introduction* chapter, which provides background for the study, introduces research questions and objectives, discusses the scope of the study, and presents keywords and the structure of the thesis.

Next chapter, *The importance of wind energy in the modern energy supply,* provides an extensive overview of the importance of wind energy, but also an introduction to wind turbines market. Thereby, key attention is allocated to methods and tools for measuring wind speed, key wind speed indicators and main development directions.

Chapter 3 *Structures of modern wind turbines and their technical maintenance* creates a springboard towards the empirical part, by describing main structural elements of wind turbines, key indicators of power utilisations and challenges in the area of maintenance, replacement and repair.

Chapter 4 *Methodology of patent research* creates a structure for study's empirical part by describing the used research methods.

Chapter 5 forms the empirical part of the study. *Analysis of patents for wind turbine maintenance* shows the results of patent and trend analysis in area of maintenance, replacement and repair of wind turbines with a horizontal axis of rotation.
Conclusions summarizes the results and answers to the research questions. Furthermore, it provides a final assessment for the whole thesis, discusses limitations and proposes possible areas for future research.

Table 1: Overview on chapters of this thesis

INPUT	CHAPTER	OUTPUT
Introduction to the topic	CHAPTER 1 - Introduction	Background of the thesis, research aims, questions, scope and limitations
Wind resources framework	CHAPTER 2 - The importance of wind energy in the modern energy supply	Overview of wind resources and procedures to improve operating conditions
Wind turbines framework	CHAPTER 3 - Structures of modern wind turbines and their technical maintenance	Overview of wind turbines structural elements which may be used in patent study
Suitable patent data-based methods	CHAPTER 4 - Methodology of patent research	Structure for empirical part, description of used methods
Results of patent analyses	CHAPTER 5 - Analysis of patents for wind turbine maintenance	Patent analysis Answers to the research questions
Assessment of the results	CHAPTER 6 - Conclusions	Final assessment

2. The importance of wind energy in modern energy supply

In this chapter the importance of wind energy is discussed, and an introduction to the wind turbines market provided. Methods and tools for measuring wind speed and direction are also presented. Finally, key attention is paid to modern models of wind speed indicators and main development directions.

2.1 Natural resources of wind energy

Wind energy is one of the most significant and successful areas of modern energy based on renewable sources. Modern wind energy is undoubtedly an outstanding technical, innovative and administrative achievement of mankind, a successful fusion of advanced technical solutions, state and public patronage, and bold investment preferences.

Currently, wind power is fortified with the most advanced technologies for converting natural energy, by transforming energy of the wind into a flexible form of energy convenient for further processing and finally for meeting human energy needs, which is electricity.

Of course, modern wind turbines are not an ideal technology for producing useful energy; the underlying technology and practices have both significant advantages and disadvantages. Technical and operational solutions used in wind energy are based on existing principles and achievements and are subject to significant temporary effects. In present days, it can be reasonably argued that wind energy has reached, if not peaked, a mature development stage. This allows it to compete adequately with traditional energy resources both in terms of price characteristics, which is very important for consumers and operators, and from the viewpoint of investments, which is a serious incentive for investors.

By far, the most important advantage of wind energy is its minimal negative environmental impact on nature and mankind. Such a powerful argument, supported by competitive prices for manufactured products, is very important in modern energy and determines its rapid development. Today, despite the relatively small share of wind energy in global power supply – i.e. less than 5% in 2018, not a single energy strategy, not a single energy forecast can do without considering the role of wind energy. Nevertheless, nothing stands still, including the development of competitive technologies, so the timely identification and detailed analysis of the existing shortcomings in wind energy is the subject of serious research and the basis for decision-making.

The most painful issue for wind energy, along with some other areas of renewable energy, is the variability of the used natural resource, particularly in the case of wind. The wind is inconsistent both in its dynamic characteristics (speed, gusts, periodicity), and in direction. Hence, modern wind turbines achieve comparatively low capacity factors[1]. The designs of modern wind turbines can largely overcome these difficulties; however, this does not solve the main problem - ensuring a reliable power supply to the network from wind farms. In other words, modern wind turbines, as well as electricity consumers that rely to a large extent on the corresponding electricity generation, are in fact hostages of the uncontrolled forces of nature.

The solution to this problem is carried out in various directions. First of all, it requires a reasonable integration of wind farms into the existing electricity grid, so that interruptions in the supply of electricity from wind energy can be compensated by other forms of power supply, including storages. However, the keywords here are "available sources", which implies, firstly, their presence, secondly their redundancy, and thirdly, which is probably the most important, their flexibility, i.e. the possibility of instant power control. If, for fundamental reasons, we exclude fossil-fuel power plants from the list of electricity producers, then there will be few other options. In essence, taking into account the scale of the task, the alternative to fossil fuel-based thermal power stations could be hydropower plants and pumped storage plants, or the creation of hybrid energy parks, where the wind farm will be paired with, for example with a geothermal station. In regions rich in water resources, for example, in Austria or in the south of Germany, this is a very realistic solution, but it is not feasible in many other regions without such natural advantages.

Other technical solutions to this problem are equipping the wind turbines with storage devices, for example, lithium-ion batteries, hydraulic accumulators or compressed air storage, as well as the organization of associated hydrogen production, which can be stored separately or mixed with natural gas (power-to-gas), for subsequent balancing of power in the power system.

[1] The capacity factor of a wind turbine is the amount of energy delivered during a year divided by the amount of energy that would have been generated if the generator were running at maximum power output throughout all the 8,760 hours of a year (European Wind Energy Association, 2009:53). In simple terms this indicator can be determined by calculating the number of full load hours per year during which the turbine would have to run at full power in order to produce the energy delivered throughout a year.

2.2 Methods for measuring wind speed and direction

Wind power is based on the transformation of the kinetic energy of the wind flow into mechanical energy of rotation of the wind turbine rotor and, finally, the transformation of the mechanical rotation of the rotor shaft into electrical energy by means of a generator. The key factor in this technological sequence is the presence of wind flow. Wind is the movement of air masses on the surface of the planet Earth. Wind formation is caused by the pressure difference between two different air regions. The movement of air masses as a result of wind from a high-pressure region to a low-pressure region leads to a new thermodynamic equilibrium. The main reasons for the formation of different pressures of air masses are:

- uneven solar heating of air in different parts of the Earth, leading to the appearance of air regions with different densities,
- the rotation of the Earth, as a result of which inertial forces (Coriolis force) are formed, forcing the air masses to deviate relative to the direction of rotation,
- frictional forces of the air flow relative to the surface, determined by the degree of its roughness.

To assess the wind, the World Meteorological Organization (WMO) has adopted a twelve-point Beaufort scale, which is characterized by the relationship between wind speed and visible natural phenomena on the surface (at a height of 10 meters).
A simplified Beaufort scale is shown in the following table:

Table 2: The Beaufort Scale

(Source: Royal Meteorological Society, 2018)

Beaufort number	Description	Wind speed	
		m/s	Km/h
0	Calm	0 - 0,2	< 2
1	Light air	0,3 - 1,5	2 - 5
2	Light breeze	1,6 - 3,3	6 - 11
3	Gentle breeze	3,4 - 5,4	12 - 19
4	Moderate breeze	5,5 - 7,9	23 - 28
5	Fresh breeze	8,0 - 10,7	29 - 38
6	Strong breeze	10,8 - 13,8	39 - 49
7	High wind, moderate gale	13,9 - 17,1	50 - 61
8	Gale, fresh gale	17,2 - 20,7	62 - 74
9	Strong/severe gale	20,8 - 24,4	75 - 88
10	Storm, whole gale	24,5 - 28,4	89 - 102
11	Violent storm	28,5 - 32,6	103 - 117
12	Hurricane force	>33	>118

As a result of many years of meteorological observations, it has been established that the following wind directions exist on the Earth's surface (Fig.1):

The westerlies (blue) and trade winds (yellow and brown)

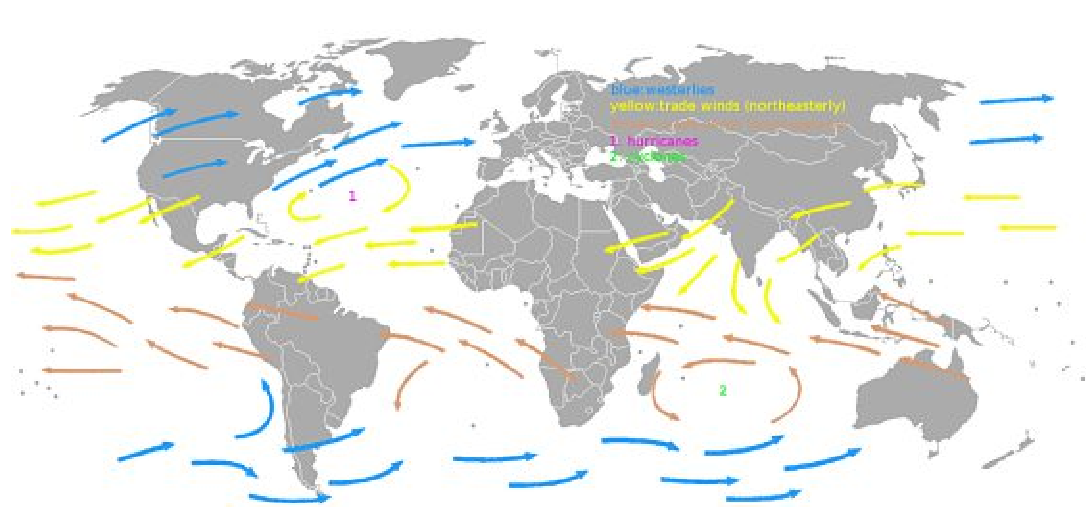


Figure 1: Prevailing winds on Earth
(Source: image adapted based on Herreshoff, 2001)

Wind is characterized by a set of parameters that are of great practical importance - wind speed, distribution of speed over time, wind direction, wind flow density, short-term wind gusts, their frequency and wind distribution over height. Despite the experience accumulated by mankind as a result of meteorological observations and the availability of various theoretical models for predicting the state of the wind at a specific point on the Earth's surface, it is rather difficult to obtain absolutely reliable data for future periods due to the presence of numerous mutually influencing factors. Therefore, meteorological observations, especially in the historical aspect, are still the main provider of information both in a practical aspect and for creating convincing theoretical models.

In order to meet the objectives of wind energy industry, special classifiers of wind flows (power density) have been created with an emphasis on the relationship between the wind speed in the real ranges of the operation of wind turbines and the height of their placement. Table 3 presents the classification of wind resources proposed by the National Renewable Energy Laboratory, which is widely used in wind energy. When assessing the table data, it can be concluded that when the altitude measurements change in the practical range from 10 to 50 meters, then the wind speed increases by about a quarter, and the power density doubles.

Table 3: Classes of wind power density at 10 m and 50 m

(Source: Wind Energy Resource Atlas of the United States, 2007)

Wind Power Class[2]	10 m		50m	
	Wind Power Density (W/m^2)	Speed[3] (m/s)	Wind Power Density (W/m^2)	Speed (m/s)
1	0	0	0	0
2	100	4.4	200	5.6
3	150	5.1	300	6.4
4	200	5.6	400	7.0
5	250	6.0	500	7.5
6	300	6.4	600	8.0
7	400	7.0	800	8.8
	1000	9.4	2000	11.9

The efficiency of any wind turbine depends primarily on the characteristics of the wind flow. It is also necessary to add the actual coefficient of energy efficiency, which is determined by its design features.

Despite the fact that it is practically impossible to accurately describe the movement of air masses in the atmosphere, it is possible to predict wind flows at a specific point on the Earth with the help of long-term meteorological observations or using special theoretical models based on this data. The importance of this information is illustrated by a simple fact laid down in the formula for the power of the wind flow (P):

$$P = \frac{1}{2}\rho A v^3$$

A - swept area of the turbine
ρ - air density
v - wind speed

In other words, the power of the wind depends on the wind speed much more strongly, growing at the power of three, while other parameters only account proportionally. When the wind speed increases threefold, the turbine power increases ninefold. Air density and swept area have a significantly smaller impact on the power of wind turbines. However, for practical purposes, it is important to keep in mind that as the

[2] Each wind power class should span two power densities.
For example, Wind Power Class = 3 represents the Wind Power Density between 150 W/m^2 and 200 W/m^2 . The offset cells in the first column attempt to illustrate this concept.

[3] Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 3%/ 1000 m elevation.

observation point moves upward from sea level, the air becomes less dense, i.e. more rarefied. For example, if at sea level under standard conditions the air density is about 1.3 kg/m^3, then at an altitude of 1 km it is already 1.1 kg/m^3. On the other hand, for offshore turbines, it is the density of the working environment that will be of decisive importance, since the density of water is about 1000 kg/m^3, while the flow rate (of water in the river, sea currents) changes within significantly smaller limits compared to natural changes in wind speed.

The swept area of modern wind turbines over the past twenty years has grown on average two to three times. Despite the only proportional dependence of the power of the wind turbine on this parameter, it has an important practical advantage. If the wind speed and air density are passive natural factors, then the swept area is a controllable value determined by the design of the wind turbine. Nevertheless, the impact of this parameter should not be overestimated, since the possibilities for increasing the scale of wind turbines are not unlimited, moreover, with their growth, the role of other negative factors is increasing (difficulties in parts delivery, installation and maintenance). Therefore, to improve the efficiency and capacity factor of wind turbines, a comprehensive and meticulous consideration of all of the above factors is required. This applies both to methods for measuring and predicting wind speed and other characteristics, as well as to optimizing the design of wind turbines and methods of their efficient operation.

Modern wind energy is trying to squeeze out the maximum possible from each wind turbine, therefore the design of wind turbines is constantly being improved (to increase energy efficiency), the height of the tower on which the wind turbines are located (with a height less than the restraining effect of surface roughness on wind speed), the diameter of the turbine rotor increases (and this increases the swept area).

When searching for a site to install highly efficient wind farms consideration should be given to the areas with satisfactory histograms of the ranges of wind speed and its stability. The latter is not always achievable in practice since the main consumers of electricity are concentrated where it has developed historically, and good wind is found in completely different places, for example in offshore areas. The seasonal factor introduces additional difficulties into this process, when, following a change in solar activity, the distribution of wind speeds changes over the usual time ranges.

For years, mechanical cup and vane anemometers have been used to measure wind speed and direction. There are simple but very effective tools, and many inexpensive variants exist.

Table 4: Overview of mechanical techniques for measuring wind speed
(Source: Own review)

Mechanical techniques				
	Technique	Overview	PROs	CONs
1.	Cup Anemometer	*Determine wind speed and consist of two sub-assemblies: the rotor and the signal generator*	Robust, easy to maintain	Not able to measure other wind components beside the horizontal Not able to proper register moment wind intensity and can be overshadowed by the attached strings of the wind measurement mast
2.	Propeller Anemometer	*A propeller mounted on a horizontal shaft that is oriented into the wind through the use of a tail vane.*	Variants of the mechanical design also use a small propeller to measure the wind speed are relatively inexpensive.	If the system is not working or if there is no wind, it would automatically report zero wind
3.	Wind-Direction Vane	*Combines a propeller and a tail on the same axis to obtain accurate and precise wind speed and direction measurements from the same instrument*	Can be suitable if it is well balanced	N/A
4.	Pilot-Tube Anemometer	*Measure the overpressure in a tube that is kept aligned with the wind vector by means of a direction vane.*	Particularly suitable for the rapid and precise determination of high air velocities of up to 80 m / s	Are less used now for routine measurements but can perform satisfactorily
5.	Hot-disc Anemometer	*There are solid-state instruments which measure the temperature gradient across a chip arrangement.*	Provides both wind speed and direction at accuracies (Makinwa et al., 2001)	Operational experience is limited so far
6.	Hot-wire Anemometer	*Use a fine wire electrically heated to some temperature above the ambient. Air flowing past the wire cools the wire*	Have extremely high frequency-response and fine spatial resolution compared to other measurement methods	Operationally they are rather unreliable, both because of excessive fragility and because their calibration changes rather fast in unclean or wet surroundings (WMO-No.8, CIMO Guide, 2018:173)

The past decades have brought new techniques for wind measurement, which can be compared in the following table:

Table 5: Overview of remote-sensing techniques for measuring wind speed
(Source: Own review)

Remote wind-sensing techniques				
	Technique	Overview	PROs	CONs
1.	LIDAR - Light Detection and Ranging	*Measuring the speed of incoming wind before it interacts with a wind turbine rotor.*	Offer a remote sensing of wind characteristics based on the diffusion of sound waves	LIDAR can have a significant impact when the intensity of wind evolution is low and the preview distance is large (Simley, 2013: 38)
2.	SODAR - Sound Detection and Ranging	*Measures wind speeds at different altitudes by using sound* *Simultaneous wind speed measurements at different heights between 20 m and 150 m with a height resolution of 5 m*	Low labour cost for measurements Continuous operation Continuous measurement Fast installation Easy to transport from one place to another place	The background noise is generated where SODAR is operating. SODAR should not be operated in areas where the noise level is high.
3.	Electromagnetic Wave (Radar)	*Interactions between the radar-transmitted electromagnetic microwaves and the high frequency gravity-capillary waves which are influenced by the effects of gravity and surface tension.*	Rapidly developed as an ocean remote sensor since it can image both the spatial and temporal variations of the sea surface with high resolutions	Another remaining challenge for wind measurements is that a calibration phase using external sensors is generally required for wind speed estimation (Huang et al., 2017:7)

Sonic techniques measure the time between emission and reception of an ultrasonic pulse travelling over a fixed distance. When first introduced to the market, ultrasonic anemometers were relatively expensive, however with the development of more cost-competitive versions, they are rapidly becoming the instrument of choice for all professional measurements.

Table 6: Overview of sonic techniques for measuring wind speed

(Source: Own review)

Sonic techniques				
	Technique	**Overview**	**PROs**	**CONs**
1.	Single Axis Sonic Anemometer	*Operates on the principle of measuring the exact length of time that a high frequency sound pulse is needed to put a certain distance between two points back.* *Single axis units will only measure the component of wind speed along the axis in which they are placed*	High durability and little accuracy deterioration Comparable in price to professional quality cup and vane	Distortion of the air flow by the structure supporting the transducers, which requires a correction based upon wind tunnel measurements to minimize the effect Lower accuracy due to precipitation, where rain drops may vary the speed of sound.
2.	Two Axis Sonic Anemometer	*Measure the horizontal wind speed and direction*	Comparable in price to professional quality cup and vane	N/A
3.	Three Axis Sonic Anemometer	*Measure three-dimensional real-time turbulence profiles*	Used primarily by the research community	Relatively expensive

2.3 Modern models of wind speed indicators

As noted above, basic information on wind resources can be obtained from long-term meteorological observations. Specific data can be found, for example, from the World Meteorological Organization (WMO) website or from the National Centers for Environmental Information (NCEI). The advantage of these sources is the availability of data for many years, sometimes exceeding one hundred years. The main disadvantage of meteorological observations is that the wind speed and its direction are measured in the time range (most often in three hours) at a height of 10 meters. However, industrial wind turbines operate at high altitudes (around 100 meters), and information on wind resources is required over a continuous time range. Thus, for a full economic and technical assessment of wind resources, it is necessary to have more detailed information.

Modern models of wind flow characteristics provide significant assistance in creating a complete picture of wind resources. There are numerous studies and sources which through wind resource assessment are providing estimates of wind power potential globally, by country or region, or for a specific site.

Most prominent sources are:

1. Research *Evaluation of global wind power* by Cristina L. Archer and Mark Z. Jacobson, from Stanford University, which had the goal quantify the world's wind power potential for the first time from data;
2. The National Renewable Energy Laboratory has developed a method for assessing wind resources of the countries of the world and their classification by the level of wind flows (power density);
3. Global Wind Atlas, provided by the Technical University of Denmark in partnership with the World Bank;
4. Map of wind database by Advanced Energy Technologies.

Research Evaluation of global wind power by Cristina L. Archer and Mark Z. Jacobson, from Stanford University

In this study from 2005, Archer and Jacobson aimed to quantify the world's wind power potential by calculating wind speeds at 80 m height, the hub height of common wind turbine with 77-m diameter at that time.

The authors calculated the wind speed based on data from meteorological observations at an altitude of 10 m and their subsequent extrapolation according to the Least Square extrapolation technique. The results were verified using Tower data from the Kennedy Space Center (Florida). Wind speed data were obtained from the National Climatic Data Center. In total, measurements from 7753 surface stations and 446 sounding stations were analysed.

As a result, the authors obtained maps of the main continents with the distribution of the studied points with wind speeds at an altitude of 80 m in the range from less than 5.9 m/s (class 1) to more than 9.4 m/s (class 7).

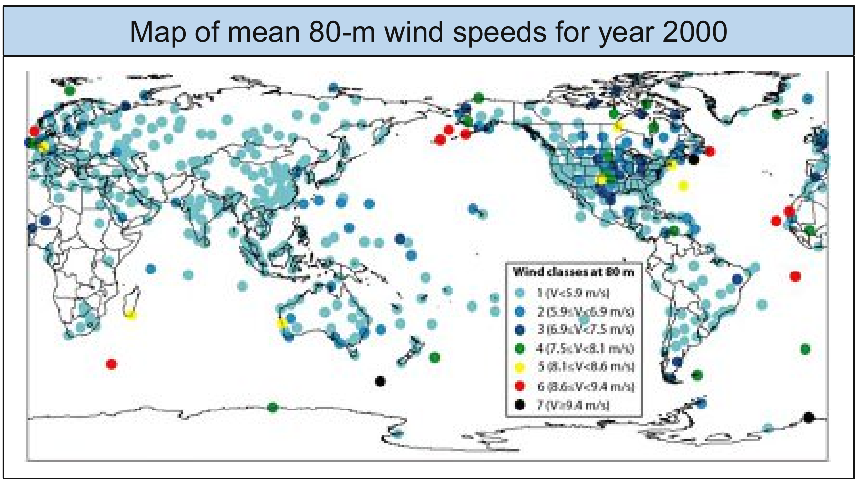


Figure 2: Map of wind speed extrapolated to 80 m an averaged over all days of the year 2000 at sounding locations with 20 or more valid readings
(Source: Archer C.L., and Jacobson M.Z., 2005)

The main conclusions of this study are:

1. Approximately 13% of the stations in the world belong to class 3 and higher, where the average annual wind speed exceeds 6.9 m/s at an altitude of 80 meters, which is quite acceptable for ensuring the efficient operation of wind turbines.
2. Areas with strong wind power potential were found in Northern Europe along the North Sea, the southern tip of the South American continent, the Great Lakes region, and the north-eastern and western coasts of Canada and the United States.
3. Offshore stations experience mean wind speeds at 80 m that are ~90% greater than over land on average.
4. The globally averaged 80-m wind speed from the sounding stations was higher during the day (4.96 m/s) than night (4.85 m/s). Only above ~120 m the average nocturnal wind speed was higher than the diurnal average.
5. Global wind power potential was estimated to be sufficient to supply all the world's energy needs, although several practical barriers need to be overcome to realize this potential. The authors estimated for the year 2000 a total global wind power potential of approx. 72 TW (approx. 54,000 Mtoe). Even if only ~20% of this power could be captured, it could satisfy 100% of the world's energy demand for all purposes (approx. 7,000-10,000 Mtoe) and over seven times the world's electricity needs of approx. 1.8 TW (Archer and Jacobson, 2005: 19).

The National Renewable Energy Laboratory (NREL) method for assessing wind resources of the countries of the world

The information for the first 25 countries is shown in Appendix 1. According to NREL, these estimates are derived from a composite of high-resolution wind resource datasets modelled for specific countries with low resolution data originating from the National Centers for Environmental Prediction (United States) and the National Center for Atmospheric Research (United States). The data represents wind power class intervals 3 through 7 at 50 meters above ground onshore wind estimates only.

As follows from the data in Appendix 1, countries with a large territory have the best wind resources. However, if the assessment is made in terms of the maximum area with wind resources of the highest classes 6 and 7, then the situation changes in many perspectives. For example, these classes of wind resources in Peru turn out to be significantly higher than in the USA or China, while in Australia or Russia they are either absent or minimal.

Global Wind Atlas, developed by the Technical University of Denmark in partnership with the World Bank

Currently, the Global Wind Atlas, which is a product of a partnership between the Department of Wind Energy at the Technical University of Denmark and the World Bank Group and first presented to the public at Wind Europe Conference in Amsterdam in 2017, is one of the most advanced sources of assessing wind potential in the world.

The methodology of this development is based on modern modelling technologies that summarize climate data and information about a specific area and its surface roughness in high resolution. As a result, the interactive cartographic materials obtained allow us to estimate the density of the wind flow, wind power density, wind roses and wind speed at an altitude of 50, 100 and 200 meters on a scale of 1 km, as well as providing a lot of other useful information. According to the authors, this development can help interested government and commercial structures in promoting wind energy technologies at a higher level and help policymakers, planners, and investors identify high-wind areas for wind power generation virtually anywhere in the world, and then perform preliminary calculations (Global Wind Atlas, 2020).

Mean Wind Speed at 100 m altitude

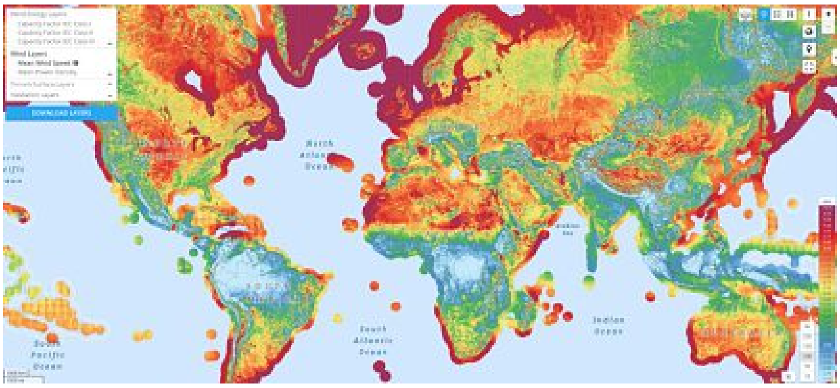


Figure 3: Global Wind Atlas and mean wind speed at 100 m altitude

(Source: Global Wind Atlas, https://globalwindatlas.info/, accessed 2020-11-07)

The Global Wind Atlas' latest version is 3.0, where wind resources have been calculated even more accurately, by:

- Carrying out 10 years of mesoscale time-series model simulations rather than ensemble modelling that cover the globe at a 3 km resolution
- Improving elevation and landcover data in the microscale modelling. The mesoscale and microscale model simulations were expanded to include

locations up to 200 km from all shorelines, to provide additional information on the offshore wind resource

- Including results at two additional heights 10 m and 150 m to reduce the uncertainty when interpolating the results in the vertical
- Adding an energy yield calculator tool, which allows users to create downloadable Geographic information system data (GIS) for annual energy production, capacity factor, or full load hours using their own custom wind turbine power curve.

Map of wind database by Advanced Energy Technologies (AENERT)

AENERT produced an interactive wind speed map based on meteorological observations from the National Oceanic and Atmospheric Administration U.S. Department of Commerce. It contains averaged data on wind speed and direction, temperature and wind gusts over a ten-year period for more than 15,000 points of observation on the planet where meteorological observations were carried out, mainly in the three-hour interval. All estimates were obtained by averaging the actual data based on the results of predominantly three-hour measurements between 2004 and 2014 and compiled into a conditional calendar year.

For each observation location, the following were calculated:

1. the average wind speed at a height of 10 metres
2. the conditional operating range in percent, when the wind speed was from 3 to 25 m/s, and the average number of measurements per interval;
3. daily maximum and minimum values of wind speed;
4. the average monthly number of wind gusts and daily maximum and minimum air temperatures during a conditional year.

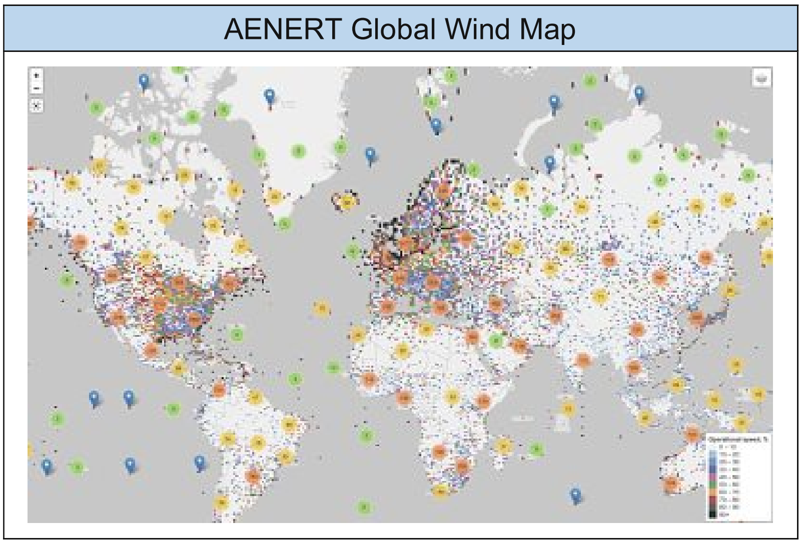


Figure 4: AENERT map of wind speed and wind direction, wind gusts and temperature for more than 15,000 meteorological observations locations

(Source: AENERT, Map of wind database, 2020)

In addition, for each location the following information can be retrieved:

- histogram of the wind speed distribution
- the diagram of the change in the wind direction
- the average monthly number of changes in the wind direction
- the total length of wind direction turns in degrees during each month of the conditional year.

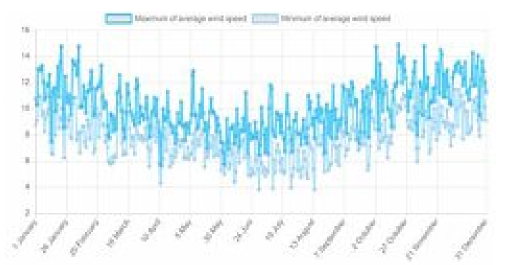
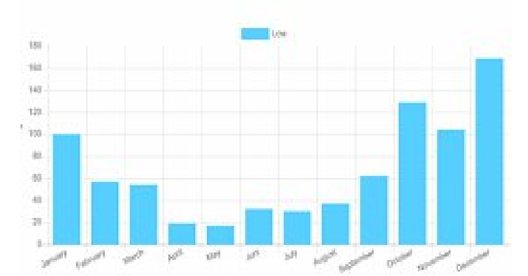
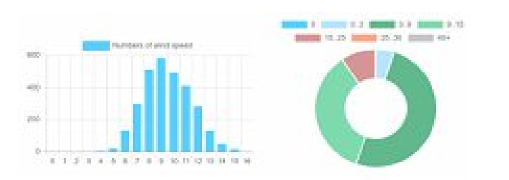
Wind speed, m/s	Gust intervals
	
Distribution of wind speed, m/s and Wind speed intervals	Wind direction and Wind direction change intervals
	

Figure 5: Examples of data for station D15-FA-1 HELIPAD OIL PLATFORM

(NETHERLANDS, Latitude: 54.32, Longitude: 2.93). The main indicators of the station - Average speed: 8.98 m / s; Operational share: 95%; Total 3 hours intervals: 154610.

(Source: Source: AENERT, Map of wind database, 2020)

The value of the information presented is that in addition to the traditional historical data on wind resources, summarized for convenience in one averaged calendar year, the stakeholder can see the monthly average distribution by gust interval, wind speed interval, wind direction change interval, which are important for predicting the operation of wind turbines. In addition, this model allows to calculate the required number of turns of the nacelle following a change in wind direction, as well as the total path of rotation.

The information presented can be useful for specialists working in the field of wind energy, students and teachers, investors, journalists and analysts.

Analysis of the results of observations and modelling

A brief analysis of the results of various types of observations and modelling of wind resources in the world shows that there is a huge natural potential for the implementation of the most ambitious plans for the development of wind energy. In recent years, highly efficient and reliable devices for continuous monitoring of wind flow indicators have been created, which paves the way for the creation of fully automated control systems for wind turbines.

The developed models for determining wind resources in almost any geographic location of the world at different heights can significantly improve the procedures for selecting the optimal sites for the location of wind farms, as well as improve the forecasting of their operating conditions. The rich historical data of long-term meteorological observations are also important. It was also found that most countries in the world have sufficient natural potential for the development of wind energy. At the same time, in a number of regions there are zones with unique wind resources - in particular, this applies primarily to onshore and offshore territories in north-western Europe, which cover several countries that are among the largest consumers of electricity in the world (Germany, Great Britain, the Netherlands, France, Scandinavian countries). The available data can truly contribute to an increase in the capacity factor of wind farms in terms of the optimal use of natural resources.

2.4 Growth of wind turbine capacity in the world and in Europe

In recent years, wind power is the most competitively priced power generation technology in many markets. According to Global Wind Energy Council (GWEC) Annual Report 2019, the cumulative wind power installed during 2001 to 2019 exceeds 600 GW and it is expected to reach 1000 GW by the end of 2024 (Global Wind Energy Council, 2020). The most large-scale development of wind energy took place in three regions of the world - China, Europe and the United States (Fig.6-left).

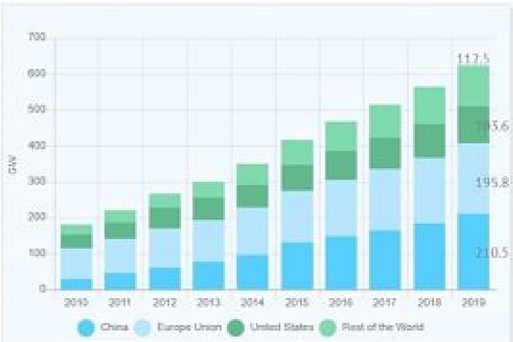
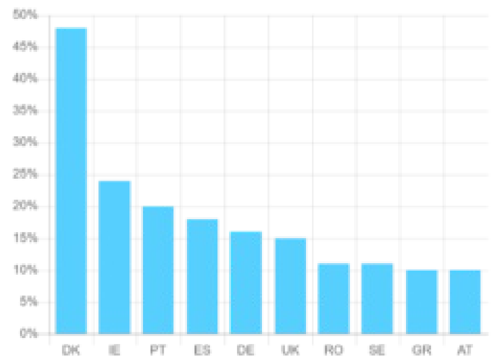
Growth of installed wind capacity in the world over the past 10 years	Countries with the largest share of wind energy in the total electricity generation in 2019
	

Figure 6: Cumulative installed wind power during 2010-2019 and countries with the largest share of wind energy in the total electricity generation in 2019

(Source: charts created based on data from "Renewable Energy Statistics 2020", IRENA, 2020)

In Europe, Germany has the largest volume of installed capacity, with a share of about 10% of the global cumulative installed wind power capacity.

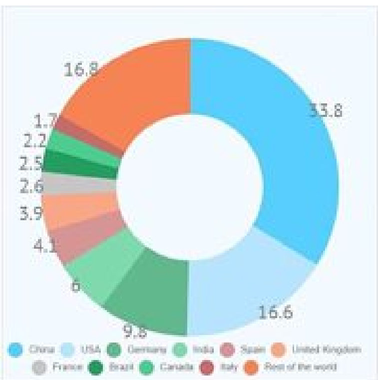
Country-specific shares in global cumulative installed wind power capacity by 2019 (%)	Country-specific shares in global electricity generation from wind power by 2019 (%)
	

Figure 7: Country-specific shares in global cumulative installed wind power capacity and in corresponding electricity generation by 2019 (%)

(Source: charts created based on data from "Renewable Energy Statistics 2020", IRENA, 2020)

Great Britain, Spain, France and Italy are also among the top 10 countries with world's biggest installed wind capacities (Fig. 7-left).
Among the other countries in the world, it is necessary to highlight India, Brazil and Canada, where wind energy plays an important role in local energy supply.

China is the undisputed world leader in terms of both the volume of installed capacity and the volume of electricity generated by wind energy. There is a discrepancy in the share ratio between the volume of installed capacity and the volume of electricity generation for individual countries. This is due to both to the peculiarities of collecting and recording statistical data, and to the real fluctuation of the capacity factor. The latter, in turn, is determined by natural conditions - the strength of the wind and its stability, as well as the technical conditions for the operation of wind parks and the reliability of wind turbines.

For a number of countries, wind energy plays a key role in electricity supply (Fig. 6-right). This can be clearly seen when calculating the share of wind energy in the total electricity generation in the country. Denmark has the highest indicators here, where the share of wind energy in the total electricity generation in the country is close to 50%. Ireland, Portugal, Spain, Germany and Great Britain have also high indicators at the level of at least 15%.

Installation of wind turbines in offshore zones, where there are more favourable natural conditions in terms of wind strength and its stability, is of great importance for the development of wind energy. For example, such conditions exist in coastal maritime areas in northern Europe. In 2019, there were over 25 GW of installed offshore wind turbine capacity in the world. However, the total share of offshore wind energy does not yet exceed 5% of the total wind energy installed capacity. Stationary wind turbines are predominant solution, when it comes to installations in the offshore zones, although there is little experience in operating floating turbines.
Offshore wind turbines require significantly higher capital and operating costs. According to Annual Energy Outlook 2020 (U.S. EIA, 2021a), the ratio of capital expenditures between onshore and offshore can reach 4 times or more in the United States. Maintenance, repair and replacement of parts for offshore wind turbines is especially difficult. Nevertheless, many companies are developing new original designs for offshore wind turbines. GE has already developed the Haliade-X offshore wind turbine with a tower height of 260 m above sea level, a rotor diameter of 220 m,

each blade length of 107 m, which is capable of generating 67 GWh of electricity annually and has a unique capacity factor, which may reach 63 percent (GE Renewable Energy, 2018). Further on, Siemens has developed the largest floating wind turbine - Siemens Wind Power SWT-6.0-154, with a capacity of 6 MW, with a rotor diameter of 154 m and a height of 101 m, which are successfully operating in Scotland (Siemens Gamesa - Offshore turbines, 2020).

The top 10 countries in the world in terms of installed offshore wind turbine capacity are shown in Fig.8. The leaders in this area are Great Britain, Germany and China. Together, these countries account for about 83% of the offshore wind power market. Forecasts of the wind energy development is in the scope of many organizations. Most analysts predict significant growth in installed capacity and electricity generation. For example, the International Renewable Energy Agency, according to one of its scenarios, assumes that by 2050 the share of wind energy in global production will reach 36% (IRENA, 2019a:12).

The ratio of the volumes of installed offshore wind energy capacities of world-leading countries in 2019

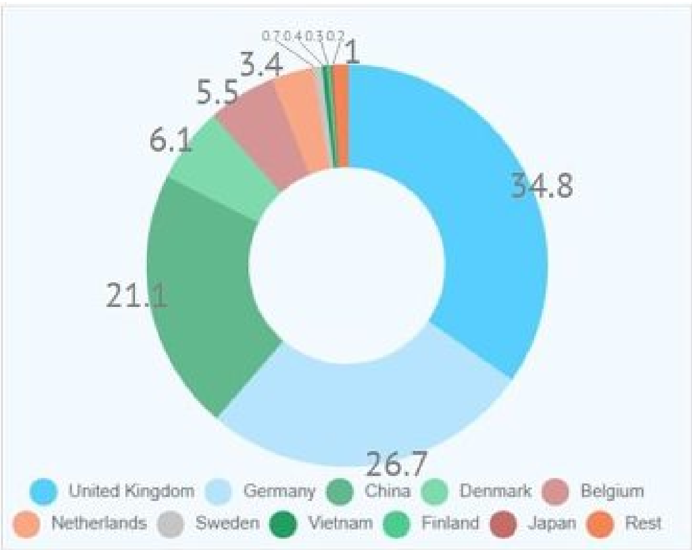


Figure 8: Installed offshore wind energy capacities, 2019

(Source: charts created based on data from “Renewable Energy Statistics 2020”, IRENA, 2020)

2.5 Main development directions

Wind energy is a rapidly developing area of modern energy, which plays an increasingly important role in the global energy supply. At the end of 2019, the volume of installed wind turbine capacity in the world exceeded 600 GW, whereas electricity generation from wind resources at the end of 2018 amounted to 1270 TWh, i.e., about 5% of the global electricity generation (IRENA, 2020:26-27). In some countries, wind energy is of key importance, for example in Denmark, where electricity generation from wind turbines is approaching 50%. In addition, wind energy is by far the leader among other renewable energy technologies.

Research and innovation activity in wind energy has increased many times over the past ten years and may have peaked. Assessment of existing trends in the development of wind energy and the formation of development forecasts are important for organizing a business, investment efficiency, and also for taking into account climate change.

According to multiple sources, forecasts for the development of wind energy look optimistic. For example, the International Renewable Energy Agency, according to one of its scenarios, assumes that by 2050 the share of wind energy in global production will reach 36%, or almost 15 TWh. Thus, over the next 30 years, the growth of wind energy can be more than tenfold (IRENA, 2019a:12). Considering that wind energy generates electricity from a renewable resource, the significance of this technology is growing significantly not only as a major substitute for technologies that consume non-renewable fossil fuels, but also as a powerful means of protecting the environment, especially against the backdrop of climate warming problems.

On a global scale, the forecast of the long-term development of wind energy until 2050, as well as the distribution of projected regional capacities for 2030 is presented within the Global Wind Energy Outlook (Global Wind Energy Council, 2016). In total, four forecast scenarios were considered in this paper:

- IEA New Policies scenario
- IEA 450 scenario
- GWEC Moderate scenario
- GWEC Advanced scenario

In particular, the IEA 450 scenario is based on International Energy Agency (IEA) 2015 World Energy Outlook and determines the energy path in order to have a 50%

chance of limiting the global increase in average temperature to 2°C / 450 parts per million of carbon dioxide equivalent (ppm CO2-eq).

According to this work on the IEA 450 scenario, the total wind power in the world will be: in 2020 – 658,009 MW, in 2030 - 1,454,395 MW, in 2050 - 3,545,595 MW, which implies more than five-fold growth between 2020 and 2050, and between 2020 and 2030 - more than double. In the latter case, according to the authors of the IEA 450 scenario, the largest contribution to development will be made by: China - more than 235 GW, North America - more than 170 GW, OECD Europe - almost 165 GW and India - almost 90 GW.

A forecast for the development of wind energy in Europe until 2030 was derived by WindEurope within *Wind energy in Europe, Scenarios for 2030* report. The paper considers three scenarios: 1) low scenario; 2) central scenario; 3) high scenario.

According to the authors, by 2030, the share of wind energy in electricity generation in Europe will reach 21.6%, 29.6% and 37.6% according to the low, central scenario and high scenario, respectively. It is assumed that in this case the cumulative wind power capacity will reach 256 GW, 323 GW and 397 GW in the same sequence of consideration (WindEurope, 2017:21).

Table 7: Installed capacity, power generation and % of EU electricity demand by 2030
(Source: Wind energy in Europe, Scenarios for 2030, WindEurope, 2017:21)

	INSTALLATIONS (GW)			GENERATION (TWh)			EU ELECTRICITY DEMAND met by wind energy (%)		
	Onshore	Offshore	TOTAL	Onshore	Offshore	TOTAL	Onshore	Offshore	TOTAL
CENTRAL scenario	253	70	**323**	599	290	**888**	19.9	9.9	**29.6**
HIGH scenario	299	99	**397**	706	422	**1129**	23.5	13.9	**37.6**
LOW scenario	207	49	**256**	453	195	**648**	15.1	6.5	**21.6**

For the central scenario in 2030, the largest volume of installed onshore capacities will be in Germany – i.e. 70 GW, and the top ten countries in addition to Germany will include: France (36 GW), Spain (35 GW), Great Britain (15 GW), Italy (13 GW), Sweden (12 GW), Poland (10 GW), the Netherlands (8 GW), Portugal (7 GW) and Austria (6 GW). According to the authors, the top three leaders in terms of offshore capacity will be Great Britain, where 22.5 GW will be installed, Germany with 15 GW of installed capacity and the Netherlands - 11.5 GW. For some countries, the share of wind energy in total electricity production will exceed 50%. Among them: Denmark - more than 70%, Ireland - almost 70%, Estonia - 60%, the Netherlands - 50%.

In the second half of each year in the U.S. the Energy Information Administration traditionally publishes its International Energy Outlook, which examines in detail the development of energy in the world until 2050. In the review for 2020, the following forecasts are presented regarding wind energy (Net electricity generation, trillion kilowatt-hours): 2020 - 1.73; 2030 - 3.17; 2050 - 6.7.
By 2050, according to this forecast, the share of renewable sources will account for almost half of all global electricity production, where the share of wind energy will be a little more than 30% of all renewable sources, including hydropower. In the OECD countries of Europe, the production of electricity from wind energy from 2021 will increase from 0.5 to 1.25 trillion kilowatt-hours and by 2021 will amount to about 25% of the total of all sources of generation. For India, these indicators are projected in this way - an increase from 0.11 to 1.42 trillion kilowatt-hours and also about 25% of the share in 2050, for China - 0.52 and 2.27 trillion kilowatt-hours and a 17% share of wind energy in the total generation in 2050, respectively (U.S. EIA, 2020a).

The forecast for the development of wind energy in the United States is presented within Annual Energy Outlook 2020. A fundamentally different trend is assumed here - the main growth will be limited to the period from 2018 to 2021, reaching almost 38% in total renewable electricity generation by 2021 (U.S. EIA, 2020a:62). After 2021, it is forecasted a slow down due to the expiration of the tax benefits.
The total increase in electricity generation is expected from the level of 0.32 trillion kilowatt-hours in 2021 to 0.37 in 2030 and, finally, to 0.43 trillion kilowatt-hours in 2050 with 134.7 GW of installed capacity (for the Reference case).

Lastly an important detailed forecast for the development of renewable energy, including wind energy, is presented within Global Energy Transformation 2019 study, published by IRENA. Two development scenarios are considered - Reference case and REmap Case. In the latter, most dynamic version, the forecast takes into account the introduction of low-carbon technologies and the intensive increase in energy efficiency in order to limit global temperature to below 2°C. At the same time, it is planned to increase the world's wind power capacities from 500 GW in 2017 to over 6,000 GW in 2050. With an estimated total electricity generation in 2050 of 41,508 TWh, the share of wind energy will reach 36% (IRENA, 2019b:28).

3. Structures of modern wind turbines and their technical maintenance

This part gives the reader valuable insight into the functionality of a wind turbine, its components in terms of efficiency, performance and technical vulnerability.
This chapter also introduces the reader to methods, frequency and problems of maintenance. Finally, this chapter foremost explains O&M costs, which are continuously rising and how crucial is that operations and maintenance workflows can be optimized for increasing efficiency.

3.1 General layout of the wind turbine and the main structural elements

The familiar appearance of a modern wind turbine with a horizontal axis externally resembles windmills that have now become exotic, which for many centuries have been used to grind grain or pump out water. In the Netherlands, in the 16th century, wind energy was used to saw logs into standard-sized timber, which greatly contributed to local shipbuilding. With the invention of electric generators, windmills began to be used to generate electricity.

The first electricity generating wind turbine was a battery charging machine installed in July 1887 by Scottish Professor, James Blyth to light his holiday home in Marykirk, Scotland (Oxford Dictionary of National Biography, 2004). Some months later American inventor Charles F. Brush built an automatically operated wind turbine for electricity production in Cleveland, Ohio. He is often credited with being the first to build a practical large-scale wind turbine to generate electricity (Cleveland C., and Ayres R., 2004: 421).

Wind turbines are a single structure for converting the kinetic energy of the wind flow into mechanical energy, and then into electrical energy. This multi-stage energy conversion cycle requires the coordinated operation of all elements of a wind turbine and, accordingly, optimal design solutions. Despite the fact that there is an objective barrier on this path, since the efficiency of converting wind energy into electrical energy theoretically, according to Betz's law, cannot exceed 59.3%, there is a fairly wide field for creative search for optimal designs, given that the efficiency of modern industrial wind turbines does not usually exceed 40-45% (Burton et al., 2001: 45).

Currently, wind turbines have several defining features:

1. turbines with a vertical axis - VAWT
2. turbines with a horizontal axis - HAWT are distinguished depending on the location of the turbine rotor shaft in relation to the base on which it is installed.

Opinions regarding the benefits of each of these types of turbines are often polar. Khare et al., 2019 and Letcher, 2017 are noting in VAWT a great efficiency, ability to withstand strong winds, ease of maintenance of this type of turbine. Nevertheless, in today's industry horizontal axis turbines dominate, while the industrial deployment of VAWT turbines is still sporadic (Barnard, 2014).

Wind turbines can be two, three and multi-blade. The most widespread are three-bladed turbines, which have higher reliability (Swedish Wind Power Technology Centre, 2019). In addition, wind turbines are divided into onshore and offshore. The latter can be fixed-foundation offshore wind turbines or floating wind turbines.
The design of any wind turbine inevitably includes all the necessary equipment to convert the kinetic energy of the wind first into mechanical and then into electrical energy. The main components of a modern three-bladed wind turbine with a horizontal axis are shown in Figure 9.

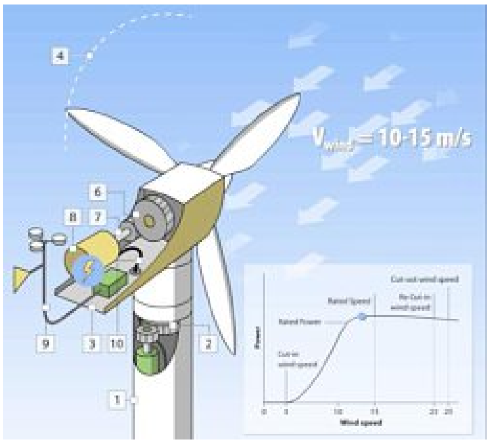
Design and cost-sharing of main components for 5 MW Wind Turbine		
Main components of a modern three-bladed wind turbine	Main components	Cost-sharing of main components
	1. Tower & main frame	29,10%
	2. Yaw system	1,25%
	3. Nacelle housing	1,35%
	4. Rotor blades	22,20%
	5. Rotor hub & bearings	2,59%
	6. Gear box	12,91%
	7. Brake system	1,32%
	8. Generator	3,44%
	9. Anemometer	-
	10. Cables	0,96%
	11. Pitch system	2,66%

Figure 9: Main components of a wind turbine and their share of the overall turbine cost for a 5 MW wind turbine

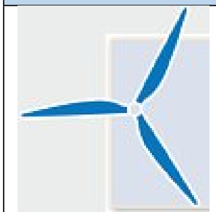
(Source: European Wind Energy Association, 2009)

Most industrial wind turbines are multi-ton constructions requiring a sustainable foundation. Plate steel turbine towers reach several tens of meters up to 260 meters above sea level (GE Renewable Energy, 2018).

In order to increase the efficiency of wind turbines, there is a continuous objective to increase the height of the tower to capture a larger wind flow and, consequently, increasing the duration of the operating range, increasing the overall share of offshore wind turbines, as well as increasing the reliability of the entire structure and reducing downtime due to repairs, improving operational technologies. The greatest efficiency is demonstrated by offshore wind farms, where more productive wind flows are concentrated. Mainly fixed foundation offshore wind turbines are being used for these purposes; however, production of floating wind turbines is expanding.

Tower	26,3%
	Range in height from 40 metres up to more than 100 m. Usually manufactured in sections from rolled steel; a lattice structure or concrete are cheaper options.

The most recognizable and important structural elements of a wind turbine are blades. They operate in extremely harsh conditions perceiving the wind flow and ensuring the rotation of the rotor. Like towers, the blades of a wind turbine are several tens of meters long, and sometimes exceed a hundred meters. With such dimensions, the blades require high strength and rigidity, with a small mass, therefore, composite materials are used in their manufacturing; these are often fibreglass and epoxy-based composites. Recently, carbon fibre materials have been used more actively, which despite a higher cost, can significantly reduce the weight of the blade and hence the load on the other components of the wind turbine.

Rotor blades	22,2%
	Varying in length up to more than 60 metres, blades are manufactured in specially designed moulds from composite materials, usually a combination of glass fibre and epoxy resin.

It should be noted that today the maintenance, repair and replacement of wind turbine parts are the most vulnerable technological aspects on the way to achieving their highest operating load, which so far remains low. In addition, these activities account for a substantial share of operating expenses. Therefore, ensuring high reliability of operation of all structural elements, especially including the blades, is a paramount task in developing technologies for the production of components of wind turbine equipment and their operation.

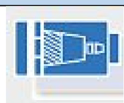
A nacelle is installed on the tower, in which the main actuators of the wind turbine are placed – the rotor and blades, a primary low-speed shaft, the gear box, generator, and a brake system.

Nacelle	1,35%
	Lightweight glass fibre box covers the turbine's drive train.

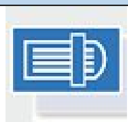
To position the wind turbine relative to the direction of the wind, the Yaw system is used, which works in conjunction with a wind vane, anemometer and has its own drive mechanism. This system allows the high efficiency of the wind turbine to be achieved and increase the reliability of mechanical components, protecting them from fatigue stress (Danish Wind Industry Association, 2003).

Yaw system	1,25%
	Mechanism that rotates the nacelle to face the changing wind direction.

Another important control system included in the wind turbine – the pitch system - controls the angle of attack of the wind flow by adjusting the angle of attack of wind by turning the blades. The location of the angle of inclination of the edge of the blade to the direction of the wind can significantly adjust the power up to a complete stop of the wind turbine.

Pitch system	2,66%
	Adjusts the angle of the blades to make best use of the prevailing wind.

Electrical equipment includes a generator, a controller that starts the turbine or stops it depending on the wind speed, and elements (cables, contactors) for connection to the electric grid. In addition, many wind turbines include a lightning protection system, a fire extinguishing system, and a de-icing protection system.

Generator	3,44%
	Converts mechanical energy into electrical energy. Both synchronous and asynchronous generators are used.

3.2 Indicators of power utilization of wind turbines - capacity factor

When evaluating the power generation performance of a wind turbine at a certain location, there are a few measurements that are commonly taken into consideration. Capacity factor of wind is a crucial indicator. The capacity factor of a wind turbine is the amount of energy delivered during a year divided by the amount of energy that would have been generated if the generator were running at maximum power output throughout all the 8,760 hours of a year (European Wind Energy Association, 2009:53). In simple terms this indicator can be determined by calculating the number of full load hours[4] per year during which the turbine would have to run at full power in order to produce the energy delivered throughout a year[5]. This can be also reflected through below equation:

$$\varepsilon = \frac{E}{P_r \cdot n}$$

P_r - rated capacity
E - electricity production per year (or month)
ε - capacity factor
n - number of hours per year (or month)

Yearly or monthly capacity factors ε can be calculated by dividing the yearly or monthly electricity production E[6] by the net installed capacity P_r and the number n of hours in a year or a month. When it comes to wind turbine power data, this can be provided by the manufacturers. A comprehensive wind turbine database providing technical data for more than 2000 turbine models from more than 500 manufacturers is available at wind-turbine-models.com.

The yearly capacity factors for wind turbines during 2010-2019 fall between 25% to 35% and preliminary data for 2020 indicate maximum 40% recorded in February and a minimum of 28% recorded in August, compared to capacity factor around 60% for some other forms of power generation (U.S. EIA, 2020b).
Maximum capacity factor of wind turbines is hampered by objective factors in the form of local natural resources, first of all, the magnitude and range of wind speed, its stability and tendency to powerful gusts. These are undoubtedly important but

[4] the number of hours during one year
[5] the capacity factor multiplied by 8,760
[6] Such data is available of numerous energy agencies, research forums, e.g. EIA: https://www.eia.gov/electricity/data/browser/

inevitable costs of generating electricity from wind turbines. However, with thorough planning before installation of a wind turbine, capacity factor can be maximized. It is very important to make sure that chosen wind turbine site receives the optimal wind resources. This does not only mean stable wind flow, but also ensuring there is little to no obstacle that could block incoming wind. The more wind resources the turbine receives, the more power it can potentially generate.

Capacity factors are not only decided by wind resources. The design of the wind turbine affects the turbine's ability to pick up energy from incoming wind. Low wind speeds and turbulent wind are two main challenges for turbine operation. Therefore, modern turbines that can generate power at lower wind speeds increase their capacity factors. Wind turbines that function under turbulent wind also have competitive advantages. Selecting the right type of wind turbine that operates best to local wind condition is essential to ensure optimal power output.
According to BloombergNEF (Shankleman J. et al., 2017), starting in 1990, the average height of wind generators increased from 40 to 128 meters, and the rotor diameter from 24 meters to 109 (Fig. 10). This made it possible to increase the capacity of wind turbines by more than 50 times.

Wind turbines are 50 times more powerful than 20 years ago	By 2025, wind turbines will be as tall as the Eiffel Tower
	

Figure 10: Development in size and power of wind turbines

(Source: BloombergNEF, Shankleman J. et al., 2017)

With the increase of height of wind generators and rotor diameters, the capacity factor as well significantly increased both globally and in key countries (Fig.11).

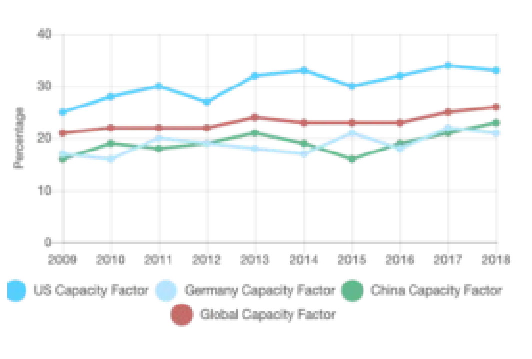
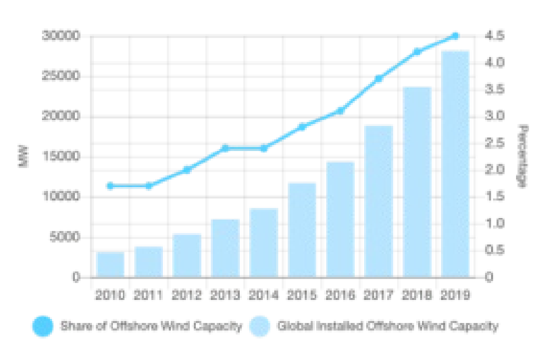
Dynamics of change capacity factor by wind power generation	Share of offshore wind capacity in global wind capacity
	

Figure 11: Dynamics of capacity factor and share of offshore wind capacity

(Source: charts created based on data from "Renewable Energy Statistics 2020", IRENA, 2020)

This is clearly the result of:

- increasing the efficiency of wind turbines, including by increasing the height of the tower to capture higher wind speeds at more constant flow;
- increasing the duration of the operating range;
- increasing the overall share of offshore wind turbines;
- increasing the reliability of the entire structure;
- reducing downtime due to repairs;
- improving operational technologies.

The greatest efficiency is demonstrated by offshore wind farms, where more constant and higher average speed wind flows are concentrated. Mainly fixed foundation offshore wind turbines are being used for these purposes; however, production of floating wind turbines is expanding.

In order to continuously improve the efficiency and capacity factor of wind turbines, a comprehensive and meticulous consideration of all of the above factors is required. This applies both to methods for measuring and predicting wind speed and other characteristics, as well as to optimizing the design of wind turbines and methods of their efficient operation.

It is also crucial to differentiate that capacity factor is not an indicator of efficiency. Efficiency is the ratio of the useful output to the effort input – in this case, the input and output are energy. The types of efficiency relevant to wind energy production are thermal, mechanical and electrical efficiencies. Wind power plants have a much lower capacity factor but a much higher efficiency than typical fossil fuel plants. A higher capacity factor is not an indicator of higher efficiency or vice versa.

3.3 Main methods, frequency and problems of maintenance

Wind turbine components are deteriorating constantly due to mechanisms such as fatigue, corrosion, wear and erosion. Such maintenance problems occur within one of the below main scenarios:

1. The component is not maintained in time
2. The component is maintained in time

In case the component is not maintained in time, the probability of component failure will increase, and corrective maintenance should be scheduled. Generally, downtime during unplanned corrective maintenance is high because of the long lead time of transportation and lead-time to the wind farm.

In the case the component is maintained in time, preventive maintenance is scheduled before the component fails. As stated in (ECN, 2014), in this scenario, maintenance is planned preferably during periods of low wind speeds and transportation is booked in advance. This may positive influence downtimes since they are expected to be significantly lower in the case of preventive maintenance compared to unplanned corrective maintenance. Above maintenance scenarios and efforts can summarized into below schematic overview of different types of maintenance:

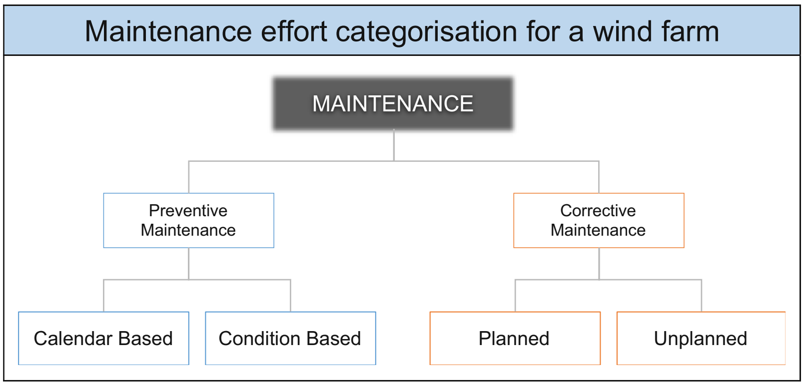


Figure 12: Schematic overview of the different types of maintenance

(Source: Wind Energy The Facts: https://www.wind-energy-the-facts.org/commissioning-operation-and-maintenance.html , accessed 2021-01-10)

Preventive maintenance is organized in order to prevent a component or system from not fulfilling its designed purpose. Whereas corrective maintenance is necessary to repair or replace a component or system that does not fulfil its designed purpose anymore. Further on, preventive and corrective maintenance can be organized in different ways, depending on the type of application and depending on what levels of detail are used and this can be visualised in Table 8:

Table 8: Overview of planning and execution of different types of maintenance

(Source: Own assessment)

Maintenance type	Trigger for initiation	Frequency	Example
Preventive – Calendar Based	A defined schedule by turbine manufacturer	One or two fixed inspections/repairs per year	*A wind turbine manufacturer schedules an inspection/repair, regardless of the damage state of components.*
Preventive – Condition Based	After observed degradation of a component the failure is expected, but is not known when it happens	Depending on each component, however overall, several times during the lifetime of a wind turbine	*The oil filter is monitored and the replacement will be done depending on the pollution state of the filter.*
Corrective – Planned	When a component is expected to fail in due time and should be maintained before the actual failure does occur	Depending on each component, however overall, several times during the lifetime of a wind turbine	*On contrary to the example above this maintenance initially id not foreseen, but as it is not necessary to shut down the turbine, the maintenance can be planned such that it can be carried out at a suitable moment.*
Corrective – Unplanned	After identification of an unexpected failure of a system or component	Ad-hoc	*A component failed without any prior knowledge and the turbine is shut down until the component is maintained.*

Corrective planned maintenance can be interpreted as a better maintenance strategy. However, multiple case studies identified that it is difficult and costly to obtain accurate information about the damage state of all wind farm components and to predict their failures before they occur (ECN, 2014; ETIPWind, 2020).

An important role about monitoring and data collection about the damage state of components is attributed to Condition Monitoring Systems (CMS). However, predictive maintenance currently represents only between 10 and 30 percent of overall maintenance activity (Accenture, 2017). Pragmatically, this cannot be done for all wind farm components because of the high costs. However, in some cases, where the investment in data analytics from the equipment sensors is limited, planned activity can account for up to 80 percent of all maintenance activity. With more advanced controls, condition-based monitoring can account for up to 80 percent of all maintenance activity. In both cases, moving to a greater share of predictive maintenance could minimize downtime and optimize O&M. Nevertheless, in order to retain high wind availability, it is crucial for operators to respond quickly to maintenance issues and find the trade-off between condition monitoring and preventive maintenance costs and the reduction in corrective maintenance costs.

3.4 Price parameters for wind energy

Capital Expenditure (CAPEX)

CAPEX includes all one-time expenditure associated with wind farm development, deployment and commissioning up to the point of issue of a takeover certificate. CAPEX for the construction of wind farms and Levelized cost of energy (LCOE) of wind energy in comparison with other energy producers can consider both advantages and disadvantages depending on the direction and range of differences. According to Annual Energy Outlook 2020, overnight costs for onshore and offshore wind farms are indicated to the amount of slightly more than $1,300 and $5,500/kW, respectively. According to this source, capital costs for the construction of wind power facilities are quite comparable with competitive renewable energy technologies, but are noticeably higher than advanced technologies of fossil fuels as presented in the following table:

Table 9: Cost of electricity-generating technologies (2019)

(Source: Cost and Performance Characteristics of New Generating Technologies, U.S. Energy Information Administration / Annual Energy Outlook 2021a: 2)

#	Technology	Total overnight cost *(USD/kW)*	Variable O&M *(USD/MWh)*	Fixed O&M *(USD/kW-yr)*
1.	Conventional gas/oil combined cycle – single shaft	1 079	2.54	14.04
2.	Advanced combined cycle – multi shaft	954	1.86	12.15
3.	Conventional combustion turbine	710	4.48	6.97
4.	Advanced nuclear	6 317	2.36	121.13
5.	Biomass	4 104	4.81	125.19
6.	Geothermal	2 680	1.16	113.29
7.	Municipal solid waste - landfill gas	1 557	6.17	20.02
8.	Conventional hydropower	2 752	1.39	41.63
9.	**Wind onshore**	**1 319**	**-**	**26.22**
10.	**Wind offshore**	**5 446**	**-**	**109.54**
11.	Solar PV – tracking	1 331	-	85.03
12.	Solar thermal	7 191	-	15.19

Earlier according to NREL and Black & Veatch (2012), these costs were estimated on average at about $2,000 and $3,300/kW (with variations of +/-25-35%) in the same sequence, but for the period until 2010. The authors took the US market as an example.

The historical trends of installed cost of wind farms are described in Figure 13:

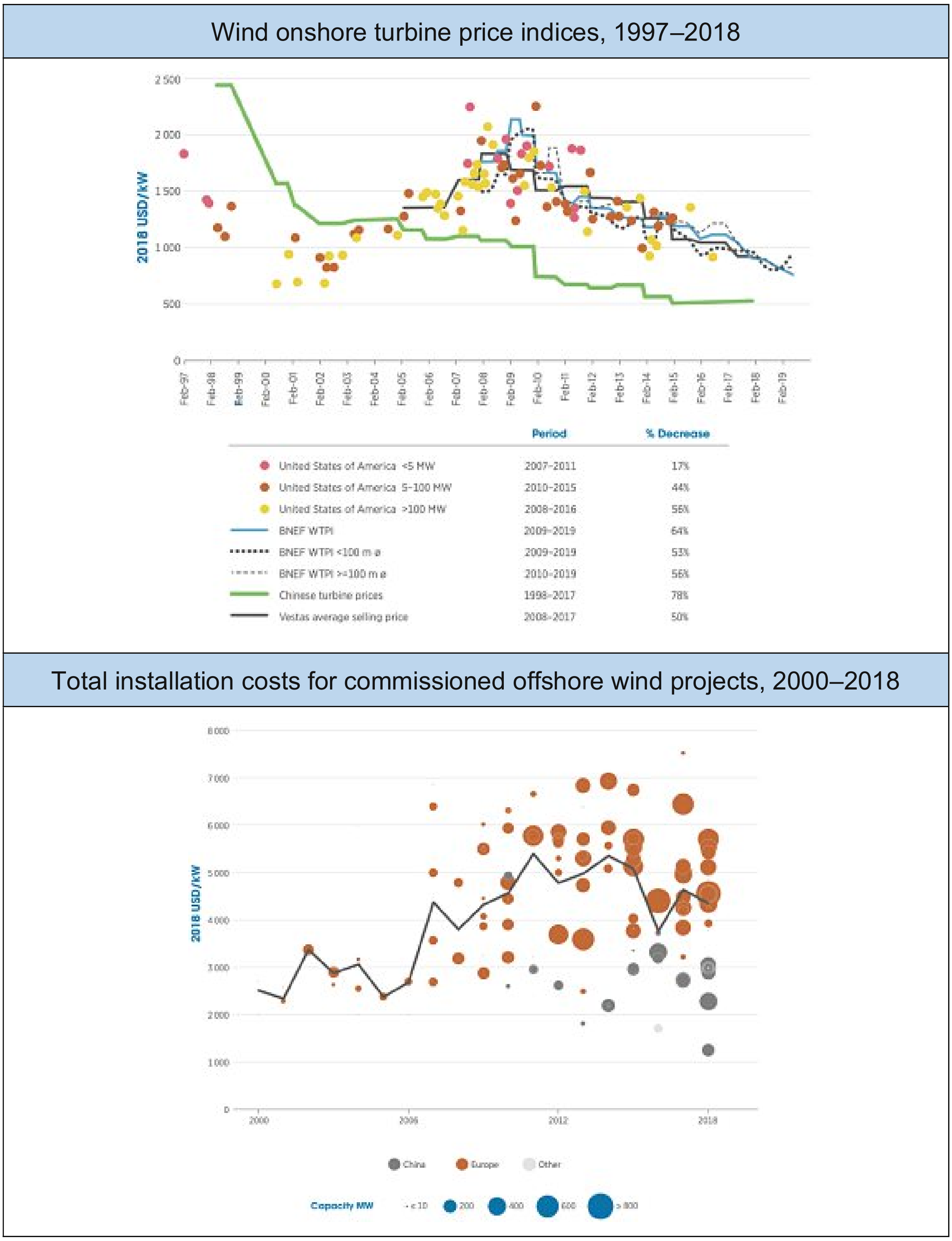


Figure 13: Wind onshore and offshore turbine price indices

(Source: "Renewable Power Generation Costs in 2018", IRENA, 2020: 32, 51)

The global reduction in capital costs in onshore wind energy occurred between 1983-2000 (from $5,000/kW to $2,000/kW), then the stabilization period began until 2012, after which there is still a moderate cost reduction. During the latest period, costs decreased from about $2,000/kW to $1,500/kW. A smoother decrease in this indicator is typical for countries such as India, China and Germany. The history of the cost of installing offshore wind farms has a completely different character. Here, after a relatively long increase in cost (2000-2013) from about $2,500 to $5,400/kW, a period of marked decrease began to $4,300/kW in 2018 (IRENA, 2019c: 51).

Operating Expenditure (OPEX)

OPEX includes all expenditure occurring immediately after point of takeover, whether one-time or recurring, related to the wind farm, measured on an annual basis. Excluded are expenses inherent to the operation of the operators business but not directly related to the operation and management of the wind farm.

Operation and Maintenance (O&M)

O&M starts from take-over, on completion of building and commissioning of a wind farm, or of at least parts of it. It contains servicing of turbines and other parts (including also grid connection) during the wind farms' operational lifetime. More precisely, it does include insurance for the replacement of faulty/broken components or defective work but does not include coverage of this by warranties.

O&M costs in the wind industry are set to rise globally to 17 billion USD by end of 2020 (Global Data, 2016). Therefore, it is crucial that operations and maintenance workflows can be optimized for efficiency.

In OPEX, the maintenance aspect is usually the costliest. For example, for offshore wind farms, this part of expenses can reach 38%, even larger than that for port expenses - 31% (UK - Renewables Advisory Board, 2010).

COVID-19 is leading to decrease wind turbine O&M costs thanks to more efficient practices, according to industry survey conducted by OnyxInsight (OnyxInsight, 2020).

According to this detailed survey of globally diverse senior wind executives, working across the wind technology and operations space, it was identified that wind farm owners and investors:

- Increased focus on tackling critical correctives, with an emphasis on deferring or delaying maintenance where not absolutely necessary.
- Followed a rapid reduction in external subcontractors, coupled with increased overview and daily management of internal teams and their equipment.

- Adopted virtual working practices for non-essential kit monitoring and analysis.

Despite the clear acceleration from preventative to predictive-based maintenance strategies and reduction of the frequency of uptower work, there are increased risks for the upcoming quarters a disproportionate amount of maintenance work. Many operators are therefore already concerned about the availability of quality labour and workmanship due to the current size and scale of layoffs and the ability for planned maintenance to be undertaken within revised project timescales (OnyxInsight, 2020:14).

Even before COVID-19 pandemic circumstance, the competitiveness of wind energy was very visible. Based on summarized data on the cost of electricity generation from renewable and traditional sources in Germany in 2018, it can be seen that wind energy is a very competitive source of energy production (Fraunhofer ISE, 2018). The cost of electricity production by onshore wind farms in 2018 was between 3.99 € cent/kWh and 8.23 € cent/kWh with a unit cost between €1,500/ kW and €2,000/ kW. This is comparable to the cost of electricity production by photovoltaic plants, as well as coal plants using lignite (between 4.59 € cent/kWh and 7.98 € cent/kWh) or coal based (between 6.27 € cent/kWh and 9.86 € cent/kWh) as well as natural gas power plants with a combined cycle (€7.78 up to 9.96 € cent / kWh). For offshore wind farms, the numbers are less competitive - with unit capital costs between €3,100 and €4,700/ kW, the cost of electricity is in the range of 7.49 and 13.79 € cent/ kWh (Fraunhofer ISE, 2018: 2).

Predicted comparative LCOEs of various technologies in the USA in 2022, 2025 and 2040 as part of the National Energy Modeling System (NEMS) are presented by U.S. Energy Information Administration's within Annual Energy Outlook 2020. For example, in 2025, the predicted LCOE for onshore wind is $34.10 / MWh, and for offshore wind $115.04 / MWh, while for power plants with conventional combined-cycle (natural gas) this value was estimated at $36.61 / MWh. Solar photovoltaic has the lowest LCOE values of $30.39 / MWh (U.S. EIA, 2021b:6).

4. Methodology of this thesis for analysing patent research data

This chapter begins with a brief review of methods and research approaches for analysing patent documents, indicating how information can be gathered and how factors that determine the quality of the study can be identified. The approach used for the patent research within this thesis is then described in further detail.

4.1 Introduction to patent analysis methodology

Search, systematization and analysis of patent solutions are imperative constituents of successful development for any kind of business that relies on advanced technological achievements. Growth in the number of patent documents in the last two decades, expansion of their geographical diversity and the ever-growing mutual penetration of various technical disciplines during the development of new inventions cause substantial difficulties for proper and timely acquisition of essential patent information. According to the statistical data provided by the World Intellectual Property Organization, more than 3.3 million patent applications and more than 1.4 million patents were published globally in 2018 (Five IP Offices, 2019).

Remarkable progress in the provision of efficient access to patenting information is a corresponding reaction to this process and is achieved by the improvements in patent search systems, mutual cooperation of patent offices in different countries and the employment of modern software solutions. Nowadays, excellent facilities to search for necessary patent documents and their preliminary analytical processing can be found not only in commercial patent search systems, but also in generally available systems that aggregate patent documents from various national patent offices, for instance, Espacenet, Lens, Patentsope and Google Patent. In addition to multi-million archives of documents, oftentimes presented in full-text, these systems also provide a range of additional services, such as detailed bibliographical data, extensive citation lists, patent family data, lists of similar patent solutions, analytical statistics and a lot more. Tremendous progress towards the achievement of harmony between the suppliers and the consumers of patent data was made by the foundation of a unique Global Dossier, which combined patent information from the five leading patent offices of the world – United States, Japan, China, Europe and South Korea. These offices collectively publish more than 90% of the total global volume of annually-registered patent applications and granted patents (Global Dossier, 2020). Also of great importance is the continuous modernization of patent classification methods and an increase in the volume of patent documents from national patent offices provided with high quality translation into the English language.

4.2 Methodology for patent research applied in this thesis: methods for selecting patent documents & development of a patent database

The methodology for the selection and assessment of patent documents used in this thesis has been developed by Advanced Energy Technologies (AENERT – www.aenert.com). This methodology facilitates processing of patent bibliographic data and the development of diverse analytical products. Such methodology has made it possible to obtain a number of important information positions, such as, for instance, development trends, characteristics of leaders in certain areas, evaluation of cooperative and technological relations between participants and monitoring of quantitative patent statistics for all constituents of technological processes (AENERT, interview no.1).

There are numerous similar methodologies which offer aforementioned capabilities, and due to these multiple methodologies, interested consumers, such as manufacturers, developers, engineers or researchers, can often be frightened by the abundance and continuous growth in the number of patent documents and how they can be assessed. The prospect of involving young inventors, students or managers of moderate-size companies who lack experience in understanding sophisticated patent texts or interpreting analytical findings in the process of patenting and usage of advanced statistics is looking particularly discouraging against the backdrop of a sharp rise in patenting activity. In the majority of cases, it is related to the fact that the methodologies predominantly only handle bibliographical data of patents and applications, which doesn't allow them to make a comprehensive analytical systematization of patent information.

Attempts to perform individual computer processing of full-text documents, in addition to time expenditures and expertise difficulties, face the problems related to the varieties of forms of patent documents, different narrative styles, dissimilar requirements to the list of claims, which are inherent to national patenting traditions. Moreover, the diversity of terminology used to specify one and the same technology element or problem; semantic ambiguity of the phraseology used; keywords used in cases that do not correspond to the expected subject – all this considerably complicates and harms the process of invention search and interpretation of their technical solutions, as well as limits the possibilities of computer-based analytical processing. However, without a thorough analysis of the full-text content of a patent document, the most important parts of the invention, such as the essence of the disclosed technical solutions, their significance, their evolution within relative documents, and many other aspects remain inaccessible.

The chosen methodology in this thesis represents an attempt to partially resolve these problems connected with some of the advanced energy technologies:

- Firstly, straightforward manual processing of patent document texts is used for this purpose, which is labour-intensive, but probably the most credible and reliable processing method;
- Secondly, a specially developed list of unified technical and subject-related indicators for patent documents is used to combine multiple phraseological semantic variants from patent document texts into unambiguous, understandable and easily recognizable items;
- Thirdly, a novel configuration for patent document combinations is used based on their unified indicators and conventional bibliographical data, which allows detailed analytical conclusions with regard to, inter alia, individual inventions, to be drawn and new useful types of batch patent document lists to be composed.

4.3 Patent document search and formation of source subject-based lists

The selection of patent documents in this research thesis was performed based on specific criteria in the generally accessible databases, such as Google Patents, PATENTSCOPE (WIPO), USPTO and Global Dossier.

In this thesis, the patent document selection criteria are bound to the applicability of the proposed patent solutions to wind energy as declared by the authors in each particular invention, or at least in one of the inventions that is a member of a simple patent family[7]. At the same time, the validity of the statements made by the authors in their patent document descriptions is intentionally not disputed, although it can be discussed in the course of subsequent analysis.

This methodology developed by AENERT includes multiple lists of inventions, followed by their individual and detailed analysis. The search for patent documents is carried out in several stages (AENERT - Patent Analysis Methodology, 2020:5):

[7] **Simple patent family** - is a collection of patent documents that are considered to cover a single invention.
The technical content covered by the applications is considered to be identical.
Members of a simple patent family will all have exactly the same priorities (EPO, 2020)

Table 10: Main stages for patent documents search

(Source: Table adaptation from AENERT - Patent Analysis Methodology, 2020)

#	STAGE	STAGE Description
1.	**Search by keywords or classification codes**	In the first step, the simplest combination of keywords best corresponding to a technology discipline of interest, such as “wind turbine”, or relevant patent classification codes, is entered into the search field of one of the aforementioned patent databases to produce a starting list of patent documents.
2.	**Abstract review**	Patent documents are selected from the obtained preliminary patent list via analysis of their abstracts.
3.	**Detailed analysis**	Patent documents are selected via a detailed analysis of the texts of inventions.
4.	**Key documents identification**	From the selected documents, a list of documents cited by the authors and within the time period of interest, as well as a list of documents that make up a simple patent family, are identified and formed.
5.	**Fine-tuning scope of documents**	All newly found cited documents are thoroughly analysed to extract those corresponding to the scope of this research paper. For simple patent families a core document is usually analysed, which in this case means a patent document with the original variant of full-text description available in the English language or in other understandable language.
6.	**List of Inventors and list of technical terms**	Simultaneously, in the process of selecting patent documents the lists of mentioned applicants and inventors are formed along with the list of the most frequently-encountered specific technical terms.
7.	**Advanced search**	Then, more sophisticated search queries are entered into the search system, including the combinations of relevant patent classification indices with the newly-found specific technical terms or the names of applicants and inventors, as well as their different variations. The newly-generated list of patents documents is subjected to subsequent thorough analysis.
8.	**Master table creation**	The patent documents collected in each phase of the search process are saved in a master table.
9.	**Repeated advanced search**	The sequence of advanced search and documents selection is repeated multiple times until the final list of inventions corresponding to the desired search criteria is formed. The choice of such a laborious technique for patent documents selection for this research paper, based on a detailed analysis of texts or abstracts of inventions, is due to the fact that the existing International Patent Classification index system (IPC) does not allow for unambiguous selection of documents relevant to the topic under consideration, and the main commonly-used keywords containing, for example, "wind turbine”, “wind energy”, or similar, have many extraneous contextual meanings.
10.	**Recording unified indicators**	For each patent document selected all available bibliographic data are recorded, and special unified indicators are assigned, the essence of which is explained further on in this chapter

4.4 Patent document indicators and patent document processing methodology

The majority of patent documents published by patent offices contain a complete list of individual bibliographic indicators that allow numerous technical and legal aspects of the proposed technical solutions to be identified to a considerable degree. Such indicators include:

- document kind (patent or application);
- the patent office where a patent was granted, or patent application was registered;
- IPC indices or other equivalents, such as Cooperative Patent Classification (CPC) indices, which were assigned to a patent document by a patent office;
- priority date and publication date;
- country of applicant and country of inventor;
- number of claims.

In addition, supplementary bibliographic data can easily be determined by means of calculations or analysis:

- residence of applicants or inventors;
- applicant type (company - mainly commercial legal entities, organization - mainly non-profit legal entities, person - private individual);
- patent pending time (timespan between the date of priority and the date of official publication of the patent);
- whether a document belongs to a patent family.

However, this list does not allow to adequately determine a number of technological and other helpful characteristics of patent documents (challenges, precise technological affiliation, technical solution type, and others) that are necessary for their accurate classification. The only bibliographic indicator that partially provides such possibility is the list of IPC indices, which reflects a technological affiliation of invention. As a result, the only possibility of complete determination of technological features of patent solutions is by performing a thorough analysis of the texts of inventions. Moreover, when the necessary information is collected directly from the texts of patent documents, the researcher inevitably has to deal with a great diversity of phraseological and semantic variations, even for one and the same concept in one and the same language, and particularly when it involves Natural Language Processing (NLP). For instance, to identify a widespread concept of "low efficiency" numerous synonyms are widely used in patent documents, such as "modest productivity", "poor performance", "poor profitability", "low output per unit", "high resource consumption", "low utility", "unsatisfactory ratio of energy consumption" and "low yield". In fact, this extremely encumbers detailed classification of inventions by conventional methods.

As a partial solution to this problem, the methodology developed by AENERT and selected in this Master Thesis involves a thorough analysis method of a patent document text to identify the main set of technological characteristics, to which the authors of inventions made specific indications. Based on the interviews conducted with AENERT developers, such indications that are identified in the texts of inventions are marked by using the following unified indicators (AENERT, interview no.1):

- **Technology categories** - are unified indicators reflecting the applicability of technical solutions in the selected batch of patent documents to a particular sector in one of the energy industry's directions as declared by the authors of inventions and characterised by an established term or phraseological structure that is widely used in technological practices.
- **Technology elements (components)** - these are indicators with a specific level of detailing for the production process in a particular energy industry sector represented as a list of major phases of production technology chain or independent technological processes. These can be the main units of an equipment, as well as the combinations of components, which are considered inherent to the respective sector of energy production industry. The list of technology elements is formed in a generalized and abstract way and is limited from further detailing, both in order to simplify the perception of statistical data and to minimize the influence of subjectivity of interpretation of the texts of invention on a particular patent document or any specific technology element.
- **Problems** - represent an aggregation of technical, economical, ecological and other challenges declared by the authors in a patent document, where the proposed invention aims to solve. Since there is a wide variety of challenges, how they are formulated, how they are mentioned in the texts of patents and patent applications, this list was shortened as much as possible by means of semantic generalization to the number understandable by a broad range of readers.
- **Technical solution types** - this can be a device, a method, composition, or combinations thereof described in a patent solution.

When the aforementioned unified indicators coincide, patent documents form group combinations with identical unified indicators that are fairly close in their technical essence. When such patent documents also have additional similarities in bibliographic indicators, then, in accordance with the presented methodology, such structures form more closely related combinations that are herein called patent **clusters**. Such clusters often fully correspond to patent families but in some cases are noticeably different from extended patent families, mainly because of a different list of problems solved or other types of technical solution. Naturally, this is possible in cases when the data provided by the authors of inventions was precise and of a substantive nature, which is not always the case in real-world practice. Nevertheless, the described methodology is oriented exclusively towards the data provided in the texts of inventions, and therefore has a respective natural error. General outline of patent indicators and their combinations is provided in the Fig.14.

General outline of patent indicators and their combinations

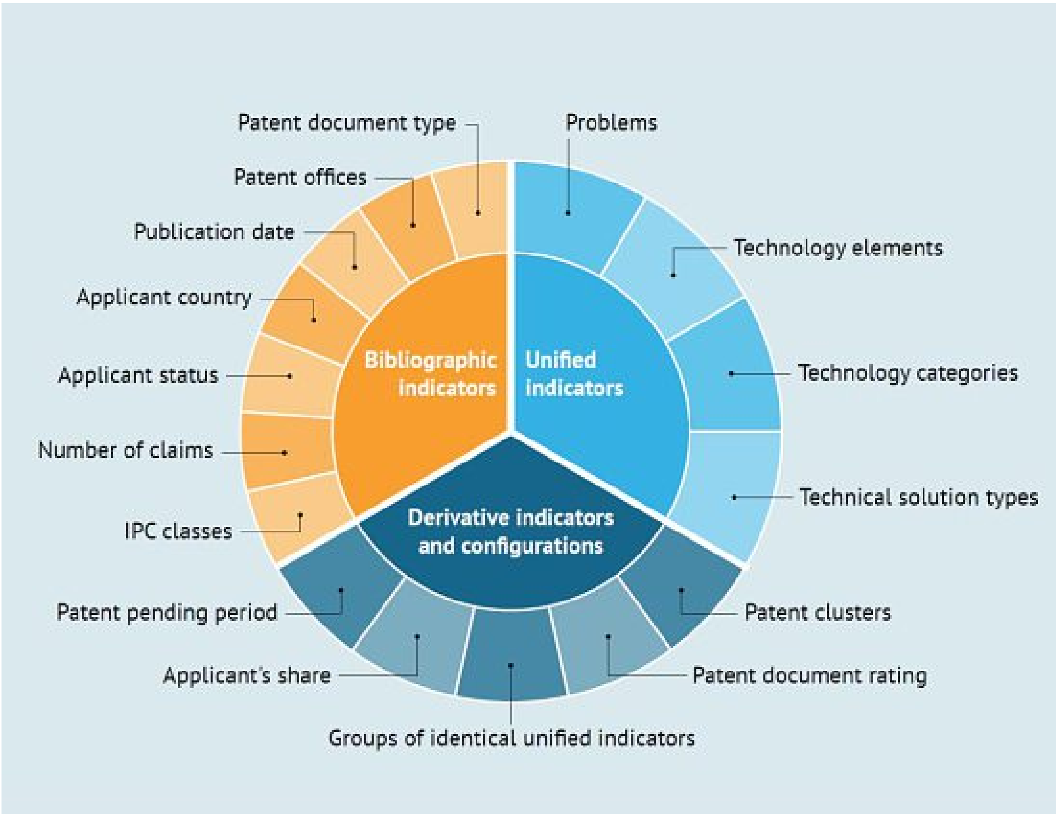


Figure 14: General outline of patent indicators and their combinations

(Source: graphical adaptation from "Patent Analysis Methodology", AENERT, 2020)

Each of the unified indicators includes a limited list of specialized universal features that disclose the details of a particular indicator. A key distinctive characteristic of such lists is the fact that all of the features are universal and to a considerable degree abstract, which allows correlation with patent information of any complexity, regardless of the diversity of phraseological structures in any language.

The aforementioned approach facilitates to:

- reduce the enormous total number of phraseological combinations of interpretation of all terms used in the descriptions of inventions to a finite value;
- perform full-scale statistical processing of patent documents;
- open the way for developing advanced computer programs for patent document text processing.

During the follow up interview with AENERT methodology developers, an assessment was conducted on the unified indicators related to wind turbines (AENERT, interview no.2). As a final outcome of the interviews and individual evaluations, below complete list of unified indicators was formed, which was used for the analysis of patent documents related to wind turbine with horizontal axis:

Table 11: List of unified indicators for the analysis of patent documents in the field of wind turbine with horizontal axis

(Source: AENERT interview no.2 Unified indicators for the analysis of patent documents)

Technology categories	Technology elements	Problems	Technical solution types
HWT Horizontal axis wind turbine in general	AC Aerodynamic casings (nacelles, shrouds, etc.)	AOP: Administrative and organisational problems	C: Composition
WTU Wind turbine type unspecified	B Blades and components thereof	ESI Environmental and social impact	D: Device
OFT Offshore wind turbine	CSS Control and safety systems	HCC High CAPEX / Plant construction	M: Method
ONT Onshore wind turbine	EE Electrical equipment and generators	HCG High costs in general	
	ESH Energy storage and hybrid generation systems	HCP High CAPEX / Equipment production	
	GT Gearbox and transmission	HOM High OPEX / Operational maintenance	
	MRR Maintenance, repair and replacement	HOR High OPEX / Repair and replacement	
	OTE Other technology elements	LEG Low efficiency in general	
	R Rotors and components thereof	LEKM Low kinetic-to-mechanical power conversion efficiency	
	SE Structural elements	LEME Low mechanical-to-electric power conversion efficiency	
		LEN Low efficiency caused by secondary natural factors	
		LES Low efficiency of secondary equipment	
		LEW Low efficiency caused by wind variability	
		UP Unclear problem	

For further accuracy, the technology element *MRR Maintenance, repair and replacement* was scoped to further classification to reach greater detail. At the same time, the following technological elements of the second level were identified:

- Rotor blades (*methods, assembly and system for mounting wind turbine blades and blade replacement, inspection of wind turbine blades*);
- Maintenance of offshore wind turbine (*transport of a wind turbine, installation method and recovery method for offshore wind turbine*);
- Temporary maintenance enclosures and methods of maintaining wind turbine;
- Heavy lifting apparatus;
- Wind turbine assembly and management robots;
- Maintenance systems for wind turbine equipment.

4.5 Rating evaluation of patent documents and their detailed analysis

Ranking of patent documents takes an important position among all derivative indicators. In the methodology chosen in this Master Thesis, rating evaluation is the sum of evaluations of individual bibliographic and unified indicators of a patent document which takes into account, among other things, type of document, number of registered claims, declared problems and technological belonging of the document, technical solution type, breadth of geographical distribution of the document and its family throughout different countries, activity of the authors, patent pending time and others.

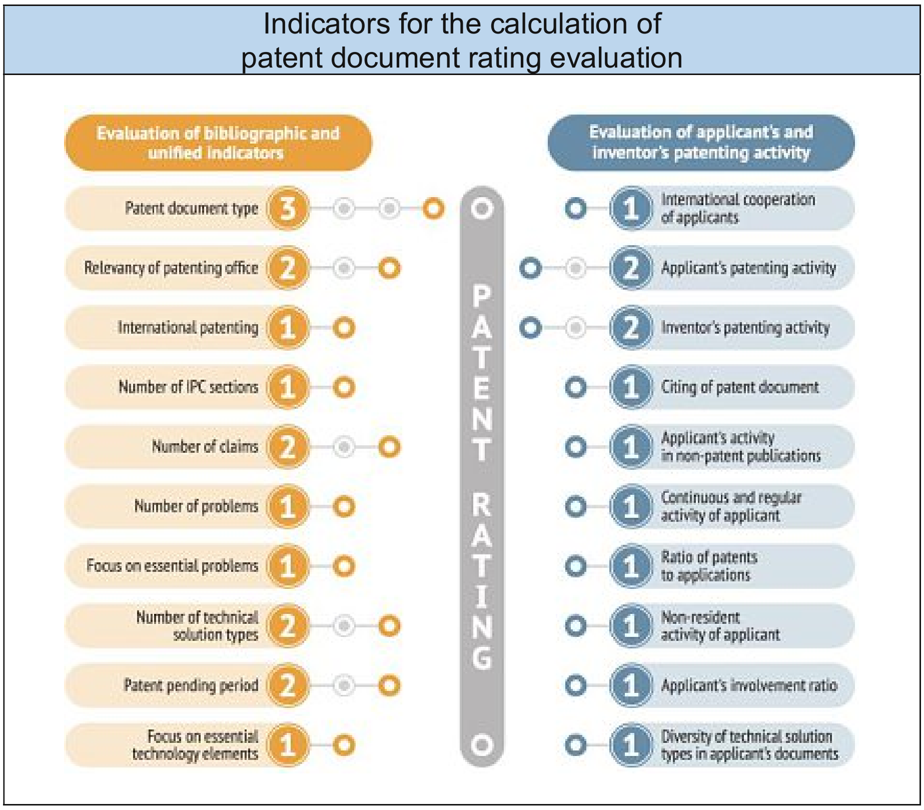


Figure 15: Indicators for the calculation of patent document rating evaluation

(Source: "Patent Analysis Methodology", AENERT, 2020: 11 and AENERT Interview no. 3 Rating evaluation of patent documents, 2020-12-19)

One to three evaluation points are assigned to each indicator, depending on its saturation. All of the indicators mentioned below consist of two groups:

1. indicators that directly concern the patent documents under revision;
2. indicators attributed to the creative activity of inventors and applicants who developed the patent documents under revision.

In addition, a portion of documents is evaluated with respect to the presence of one or another feature in the document, regardless of the presence of such features in other documents of the patent selection. The other portion is evaluated with respect to the position of the document under revision among other documents in the patent selection. Thus, the proposed rating evaluation depends greatly on the volume of patent selection, time span of a patent document's existence and the activity of its applicants.

The main steps of patent document processing and their detailed analysis based on AENERT methodology includes:

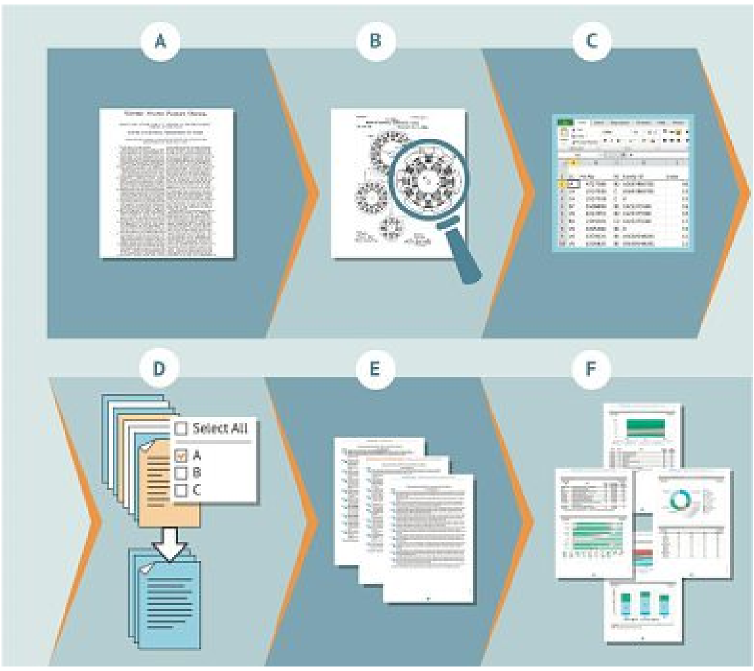
Patent document processing steps

A. Patent document search and primary control with regard to their correspondence to the search criteria set; B. Determination of the bibliographical and unified indicators of patent documents; C. Incorporation of the collected information into an Excel file; D. Determination of the patent document classification; E. Detailed analysis of patent documents within the groups they formed; F. Visualization of the collected results (lists of patent documents in groups, charts, tables, diagrams)

Figure 16: Patent document processing steps

(Source: "Patent Analysis Methodology", AENERT, 2020:16)

Within the next chapter, based on the chosen methodology, below main elements of patent document will be extracted, the main statistics elements will be determined, and finally detailed analysis of patent documents will be conducted.

Table 12: Main elements and data analysis of patent documents

(Source: Table adaptation from "Patent Analysis Methodology", AENERT, 2020)

#	Group of elements	Detailed deliverables
1.	***The main elements of the analysis of patent documents***	• Summarized statistical data of the patent document selection declared • Distribution of patent documents by patent offices and their statistical characteristics • Distribution of patent documents among residents and non-residents • Major applicants • Characteristics of unified groups and clusters • Prominent patents • Evolution of technical solutions
2.	***Major elements of graphical visualization of statistical data***	• Distribution of patent documents by publication date; • Patent to application ratio by years; • Patent document rating; • Distribution of patent documents by patent offices; • Ratio of resident applicants to non-residents in patent documents; • Most popular patent offices among non-resident applicants; • Distribution by IPC indices; • Distribution of patents by technology elements (second Level); • Distribution of patents by problems; • Distribution by technical solution types; • Distribution of patents by identical uniform indicator groups; • Best applicants by intellectual property share
3.	***Detailed analysis of patent documents***	• Classification of patent documents and technical solutions disclosed by groups of technology indicators; • Calculation of rating points for the inventions found; • Analysis of the essence of technical solutions involved for main patents and patent applications in the groups of identical unified indicators and clusters; • Analysis of evolution of technical solutions for specific technology elements, including problems, statistical indicators, applicants, and IPC indices; • Determination of the most prominent inventions by various criteria

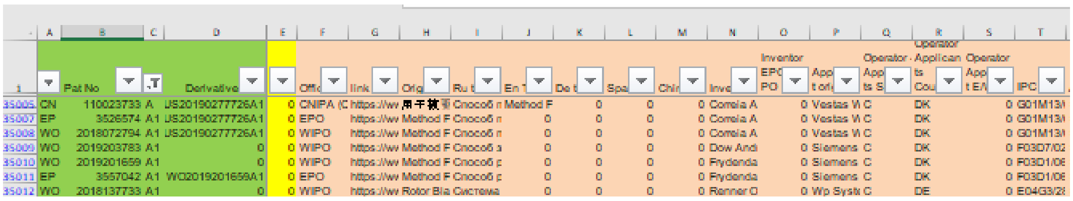
5. Analysis of patents for wind turbines maintenance

This chapter is dedicated to the results of the patent analysis. The analysis covers the assessment of technical solutions, main patent holders, main groups of identical unified indicators and trends in development of techniques for the maintenance of wind turbines.

5.1 Analysis of patent documents related to maintenance, repair and replacement

This section examines the statistics of selected patent documents. Identified patent applications in the area of *Maintenance, repair and replacement*, were grouped in a special table from which the scoped data was extracted. A general view of the Excel spreadsheet with patent applications for 2010-2019 is shown in the Fig.17:

General view of the patent database in Excel format



1	A	B Pat No	C	D Derivative	E	F Offic	G link	H Orig	I Ru t	J En T	K De t	L Spa	M Chi	N Inve	O Inventor EPO PO	P App t of	Q Operator App ts S	R Operator Applicants Cou	S Operator App t EA	T IPC
35005	CN	110023733	A	US20190277726A1	0	CNIPA (C	https://ww	用于拔	Способ п	Method F	0	0	0	Correia A	0	Vestas W	C	DK	0	G01M13/
35007	EP	3526574	A1	US20190277726A1	0	EPO	https://ww	Method F	Способ п	0	0	0	0	Correia A	0	Vestas W	C	DK	0	G01M13/
35008	WO	2018072794	A1	US20190277726A1	0	WIPO	https://ww	Method F	Способ п	0	0	0	0	Correia A	0	Vestas W	C	DK	0	G01M13/
35009	WO	2019203783	A1	0	0	WIPO	https://ww	Method F	Способ з	0	0	0	0	Dow Andı	0	Siemens	C	DK	0	F03D7/02
35010	WO	2019201659	A1	0	0	WIPO	https://ww	Method F	Способ р	0	0	0	0	Frydenda	0	Siemens	C	DK	0	F03D1/06
35011	EP	3557042	A1	WO2019201659A1	0	EPO	https://ww	Method F	Способ р	0	0	0	0	Frydenda	0	Siemens	C	DK	0	F03D1/06
35012	WO	2018137733	A1	0	0	WIPO	https://ww	Rotor Bla	Система	0	0	0	0	Renner O	0	Wp Syst	C	DE	0	E04G3/28

Figure 17: Preview of list with patent applications related to Maintenance, repair and replacement of wind turbines

(Source: Extracted from AENERT database based on search criteria part of research scope)

In total, 3723 patent applications were considered, which were prepared by 1069 applicants from 28 countries and submitted to 37 patent offices during the period from 2010 to 2019. As follows from the graph in Fig.18, there is a steady upward trend in the number of newly registered patent applications over the past decade. This clearly indicates the high research interest of inventors in the area of *Maintenance, repair and replacement*.

Distribution of patent applications by year

Figure 18: Distribution of patent applications by year

(Source: List of patent applications related to Maintenance, repair and replacement)

Within this group of patent documents, 13% or 484 documents are positioned as single applications that are not assigned to previously formed patent families, and which offer completely new patent solutions, providing additional evidence of the relevance of this area chosen within this thesis.

Single applications, indeed, faced a tremendous growth in recent years. For example, if during 2013-2014, only 7 single applications were registered per year, then in 2018 - 138, and in 2019 - an impressive 182 patent applications were registered. However, it should be noted that this growth was mainly driven by Chinese inventors and the Chinese patent office. The distribution of patent documents by patent office and residency is shown in the Fig.19:

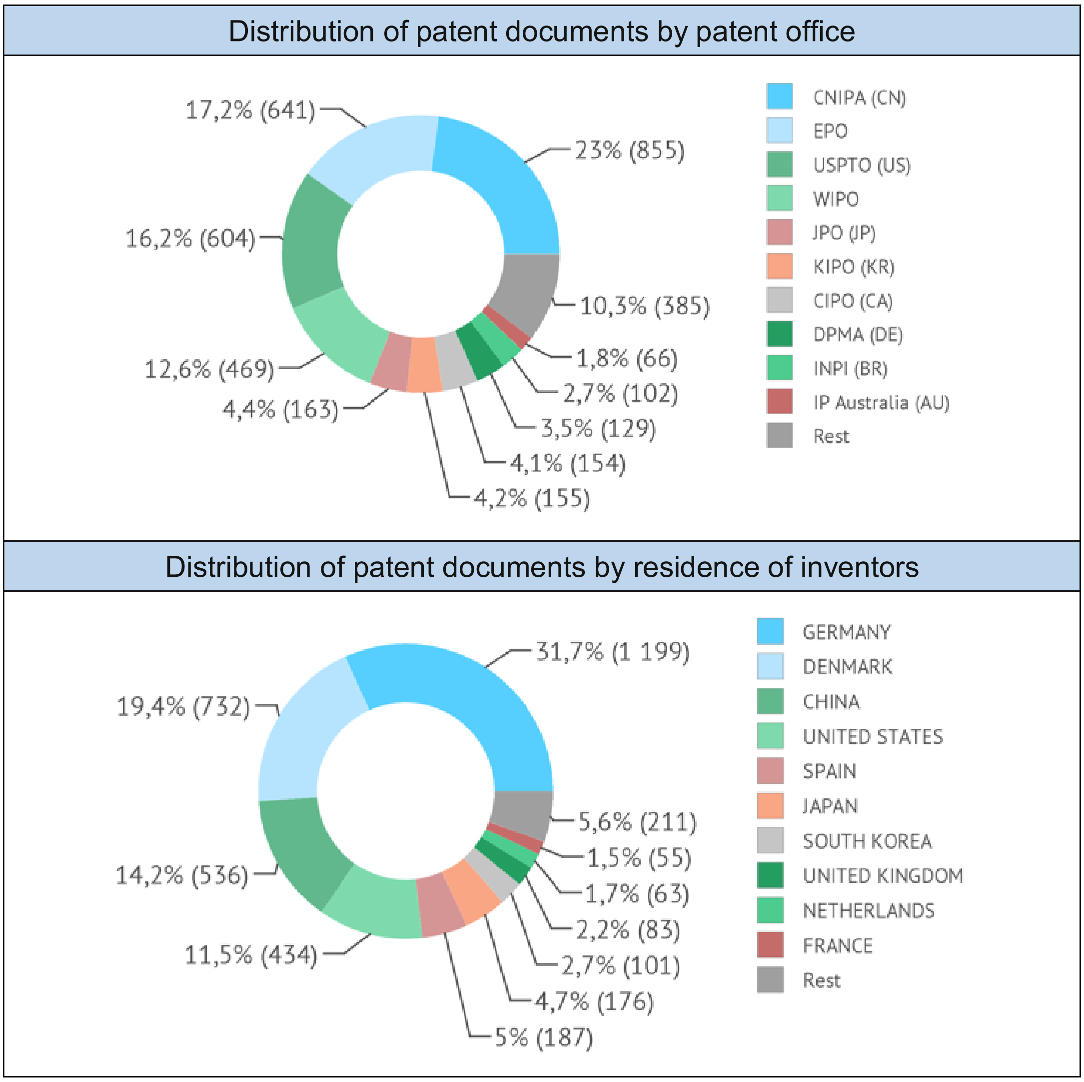


Figure 19: Patent documents distribution by patent office and residence

(Source: List of patent applications related to Maintenance, repair and replacement)

Among patent offices, the leaders in the number of registered patent applications were the:

- Chinese office of CNIPA (China National Intellectual Property Administration);
- European office of the EPO (European Patent Office);
- American office of the USPTO (United States Patent and Trademark Office).

These three offices accounted for over 45% of all registered patent applications. The top 10 patent offices also include Japanese JPO, South Korean KIPO, Canadian CIPO, German DPMA, Brazilian INPI and Australian IP Australia.

About 13% of applications were registered at the World Intellectual Property Organization (WIPO). The remaining 27 patent offices accounted for just over 10% of applications. The Chinese Patent Office has emerged as the sole leader since 2017 and has steadily maintained its leadership ever since. Lastly, it is worth to indicate that in 2019, 196 documents were registered at CNIPA, while only 76 at EPO and 64 at USPTO.

From Fig. 19, in contrast to distribution of patent documents by patent office, where the CNIPA was the leader in the number of registered patent applications, the distribution by country of applicants-residents, it can be seen here that the largest number of documents was created by applicants from Germany (over 30%) and Denmark (almost 20%). Chinese and American applicants received 14% and 11% of applications, respectively. Thus, there is a clear dominance of European inventors, wherein the top-10 world applicants, the share of European inventors exceeded 60%.

Most of the patent documents in the texts of inventions clearly state that technical solutions can be applied to wind turbines with a horizontal axis of rotation, however, for almost 35% of applications this clarification is not defined firmly. Nevertheless, all selected patent applications, refer to matters related to Maintenance, repair and replacement, which is an overall prevalent terminology. In more than 17% of applications, the technical solutions relate to offshore wind turbines.

The distribution of patent documents by the problems related to Maintenance, repair and replacement are shown in Fig. 20:

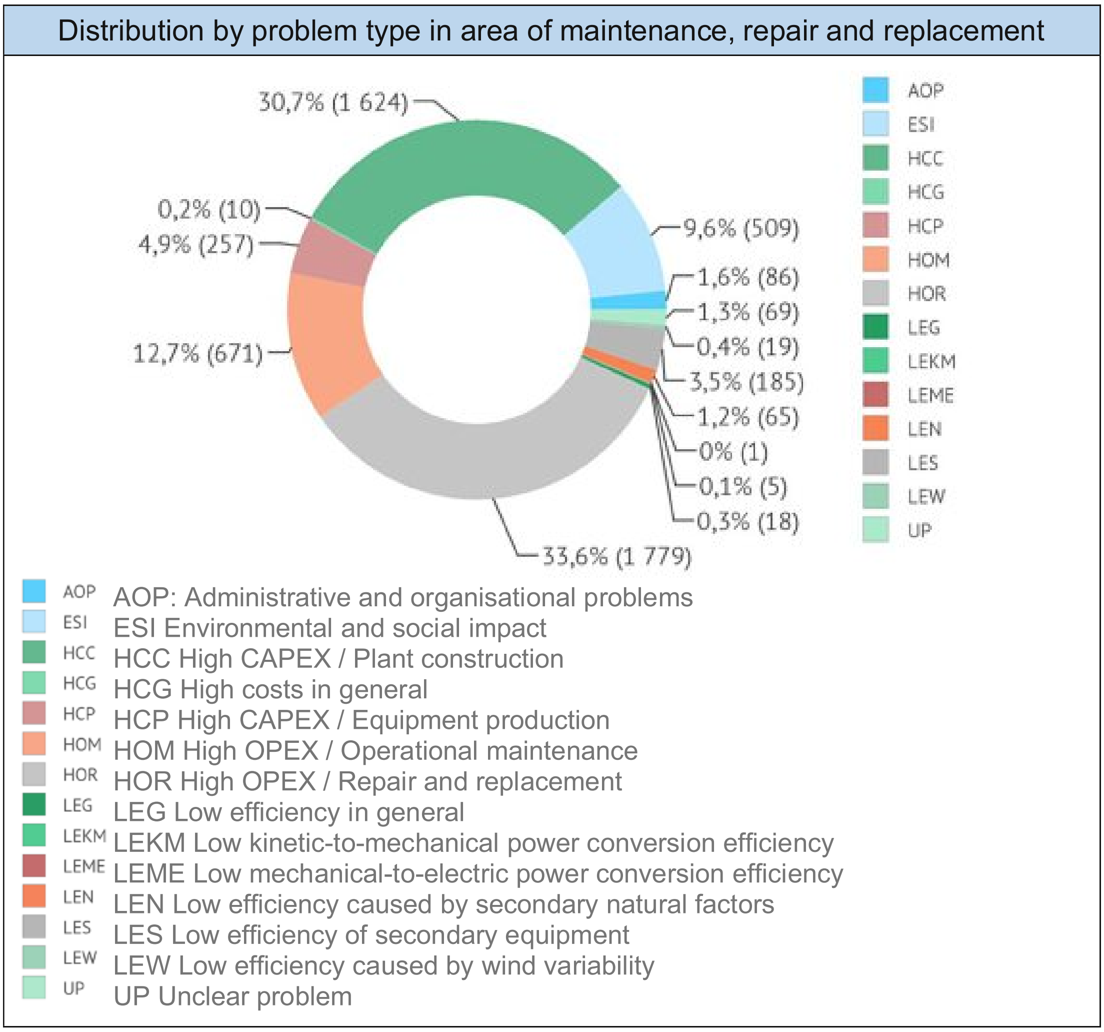


Figure 20: Distribution of patent documents by problem type

(Source: List of patent applications related to Maintenance, repair and replacement)

In more than 30% of patent applications, inventors offered technical solutions dedicated to reducing the operating costs associated with the repair and replacement of wind turbine parts (High OPEX/Repair and replacement), as well as related to the high capital costs of the construction of wind turbines (High CAPEX/Plant construction). To a much lesser, but significant extent, inventors were interested in the problems of high cost of maintenance (High OPEX/Operational maintenance) and the impact on the environment (Environmental and social impact).

Patent applications that relate to *Maintenance, repair and replacement* issues often referred to other technological elements at the same time. Most often technological elements were: *Blades and components* (about 13% of applications), *Structural elements* (more than 7%), *Control and safety systems* and *Electrical equipment and generators* (about 3.5% each).

A list of the top ten applicants with the largest number of *Maintenance, repair and replacement* patent applications is shown in Table 10.

Table 13: Largest patent applicants in area of maintenance, repair and replacement (2010-2019)

(Source: List of patent applications related to Maintenance, repair and replacement)

Country	Applicant	Application
DE	Wobben Properties GmbH	441
DK	Vestas Wind Systems A/S	397
DE	Siemens AG	245
US	General Electric	244
JP	Mitsubishi Heavy Industries, Ltd.	96
ES	Gamesa Innovation & Technology S.L.	67
DE	Repower System AG	61
DE	Wobben Alloys	58
DE	Senvion S.A.	50
CN	Beijing Goldwind Science & Creation Windpower Equipment Co Ltd.	47

Among the most productive applicants are the German companies Wobben Properties GmbH, Siemens AG, Repower System AG, the Danish Vestas Wind Systems A/S, the American General Electric, the Japanese Mitsubishi Heavy Industries, Ltd., the Spanish Gamesa Innovation & Technology SL.

Chinese Beijing Goldwind Science & Creation Windpower Equipment Co Ltd. also entered the list of top 10 applicants. Both Wobben Properties GmbH and Vestas Wind Systems A/S contributed with more than 10pp from all registered applications in the register of intellectual property. Among the single applications, Danish Vestas Wind Systems A/S was in the lead with 23 patent applications registered during 2010-2019. The approximate distribution of patent documents by the leading applicants among the patent offices of the world, as well as the targeted problem areas, is presented in the Fig.21.

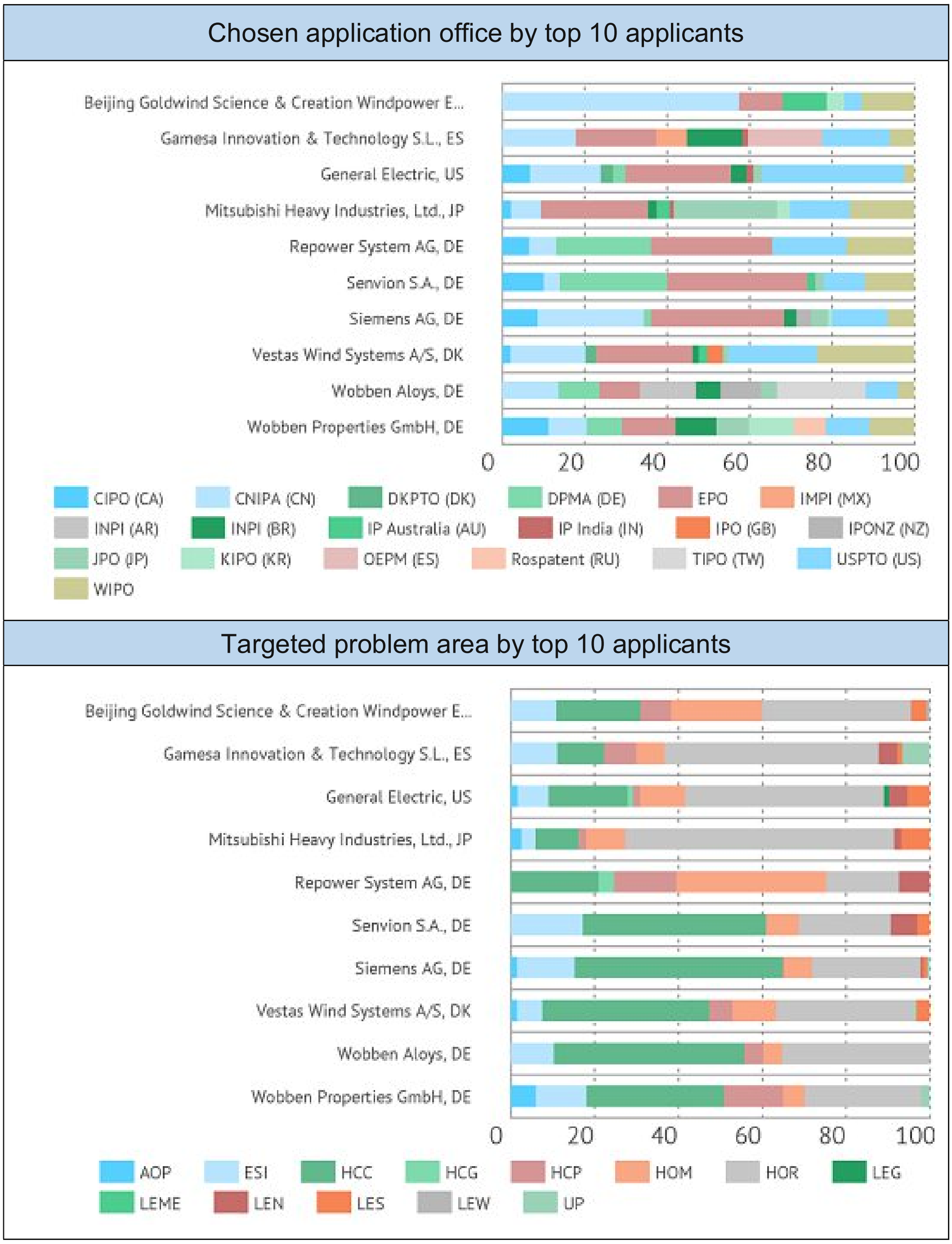


Figure 21: Application office among top applicants and targeted problem area

(Source: List of patent applications related to Maintenance, repair and replacement)

Most of the top 10 applicants have registered their applications with many overseas offices. Wobben Properties GmbH, in addition to patenting in EPO, WIPO and DPMA in Germany, is also noted in seven other national patent offices.

In most cases, all participants in the list directed their inventions to solving the problems of High CAPEX/Plant construction and High OPEX/Repair and replacement.

Table 14 indicates top IPC groups that have been assigned in the patent documents. The share of these top 10 groups in the total array of group indexes of the International Patent Classification was almost 65%.

Table 14: Most prominent IPC groups indicated by applicants (2010-2019)

(Source: List of patent applications related to Maintenance, repair and replacement, Transcript of patent groups according to WIPO)

IPC Group	IPC patent group transcript	Share	IPCs assigned
F03D0001	Wind motors with rotation axis substantially parallel to the air flow entering the rotor	16,1%	1495
F03D0011	Components and accessories not elsewhere classified (cancelled in 2015, group F03D 80/00 applies instead)	11,1%	1024
F03D0013	Assembly, mounting or commissioning of wind motors; Arrangements specially adapted for transporting wind motor components	8,9%	823
F03D0080	Details, components or accessories not provided for in groups F03D 1/00-F03D 17/00 [2016.01]	7,5%	692
B66C0001	Load-engaging elements or devices attached to lifting, lowering, or hauling gear of cranes, or adapted for connection therewith for transmitting forces to articles or groups of articles	4,7%	440
B66C0023	Cranes consisting essentially a beam, boom or triangular structure acting as a cantilever and mounted for translatory or swinging movements in vertical or horizontal planes or a combination of such movements, e.g. jib cranes, derricks or tower cranes	4,5%	417
E04H0012	Towers; Masts or poles; Chimney stacks; Water-towers; Methods of erecting such structures	3,3%	302
F03D0017	Monitoring or testing of wind motors, e.g. diagnostics	2,9%	268
F03D0007	Controlling wind motors	2,6%	238
F03D0009	Adaptations of wind motors for special use; Combinations of wind motors with apparatus driven thereby; Wind motors specially adapted for installation in particular locations	1,7%	161

Within the next sub-chapters, there will be a further in-depth assessment of most common topics among inventors and an indication of most prominent development trends of techniques for the maintenance, repair and replacement of wind turbines:

1. Transport, assembly and servicing blades
2. Maintenance and repair of offshore wind installations
3. Condition monitoring and diagnostic techniques
4. Maintenance, repair and replacement wind turbine by manipulators
5. Other prominent techniques: cranes, oiling

5.2 Transport, assembly and servicing blades

The blade is the most critical and vulnerable part of the wind turbine, which has to cope with all external cyclic, mechanical, climatic, vibrational and other type of impacts, but also to be in constant motion during the operation of the wind turbine. In addition, this is one of the largest parts of a wind turbine, which cannot be assembled onsite in parts, unlike, for example, a tower, but must be delivered to the site of operation in a finished form and assembled entirely without disassembly. It is obvious that the transportation of such long parts, sometimes exceeding a hundred meters, as well as their installation on a turbine, is an extremely difficult technical undertaking. Correspondingly, diagnostics, repair or replacement of blades requires the highest qualifications of personnel, the availability of highly efficient technologies and tools for carrying out these operations. The capacity factor of wind turbines is primarily determined by the reliability of the blades of wind turbines, therefore, inventors have a keen interest in this topic.

In this sub-chapter, two main groups of technological operations related to the maintenance of the blades have been investigated:

1. Transportation of the blades;
2. Assembly, installation, fastening of the blades and maintaining them.

It should be noted that in the overwhelming majority of cases, the technical solutions associated with these processes are identical both for the case of the initial installation of wind turbines and for diagnostic or repair operations, and therefore were not specially separated.

Transportation of wind turbine blades

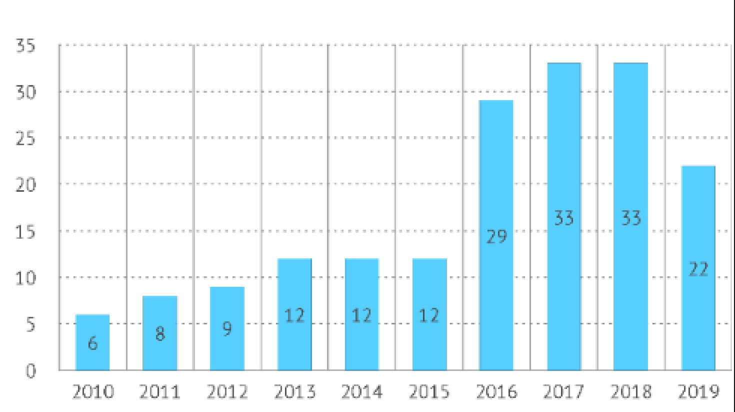
The selection of patent documents, which refer to the operation of transporting blades, was made from the AENERT database for the technological element *Maintenance, repair and replacement*, using the subgroups of IPC indices:

- F03D 13/40 Arrangements or methods specially adapted for transporting wind motor components
- B60P 3/40 Vehicles adapted to transport for carrying long loads

In total, over the period from 2010 to 2019, 176 patent applications were identified, which were submitted by 57 applicants from 11 different countries and registered in 19 patent offices around the world.

The general distribution of patent applications by year is shown in Fig. 22. From the data presented in the following graph, it follows that this topic may have passed the peak of inventive activity and presumably has a tendency to decrease.

Distribution of patent applications by year in area of *Blades transportation*



Searched keywords:

- Transport Vehicle for Wind
- Transporting and Storing Blades
- Lifter and Method for Handling a Rotor Blade,
- Transporting Blade
- Blades Packing System

Figure 22: Distribution of patent applications by year in area of Blades transportation

(Source: List of patent applications related to Maintenance, repair and replacement)

This development is also supported by such facts as: decrease in the share of applications in relation to patents in recent years; decrease in the annual share of newly registered patent applications to their average number over the past five years; the virtual absence of new patent offices where patent applications were registered (over the past five years - only 2 new offices).

On the other hand, in the last three years the share of single applications (not included in previously formed patent families) was very high - at the level of 40%, which indicates the desire of inventors to create new original technical solutions, and not to expand the use of those already created patent families.

The distribution of identified patent documents by patent offices, as well as by countries of residence of inventors is shown in Fig.23. Among the patent offices, the most popular were the Chinese CNIPA, as well as the American, European and Korean offices.

More than 60% of patent applications during the period under review were submitted by residents of Denmark and Germany, which indicates a potentially high level of concentration of research facilities and intellectual resources here.

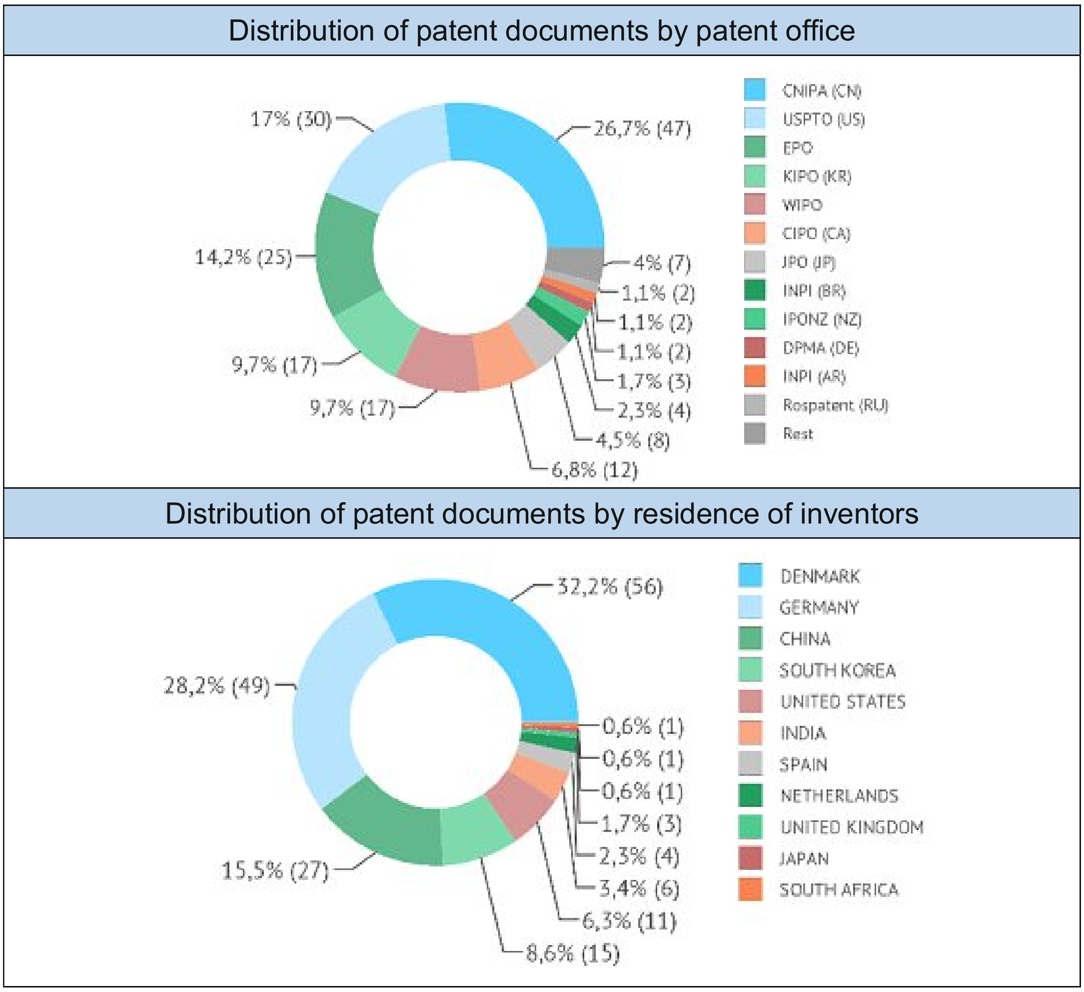


Figure 23: Patent documents distribution in area of Blades transportation

(Source: List of patent applications related to Maintenance, repair and replacement)

The list of top 10 leading applicants is shown in the Table 15. Among applicants, five positions are occupied by companies from Denmark and Germany, while Danish Vestas Wind Sytems A/S leads by a significant margin in terms of the number of registered patent applications.

Table 15: Largest patent applicants - Transport of blades (2010-2019)

(Source: List of patent applications related to Maintenance, repair and replacement)

Country	Applicant	Applications
DK	Vestas Wind Sytems A/S	38
DE	Wobben Properties GmbH	17
DE	Siemens AG	14
DE	Wobben Aloys	12
KR	Samsung Heavy Industries Co., Ltd	9
US	General Electric	7
CN	Nanjing High Accurate Drive Electromechanical Co Ltd	7
IN	Windcare India Pvt Ltd	5
KR	Doosan Heavy Industries & Construction	4
DK	LM WP Patent Holding A/S	4

As follows from the methodology for the selection of patent documents that consider the issues of transporting blades, they all contain specific IPC indices - F03D 13/40 and B60P 3/40. The first indicator was mentioned 114 times in 176 patent applications, and the second indicator was mentioned 65 times during 2010-2019.

Dynamics of applications by top 10 IPC indices referring to Transport of blades

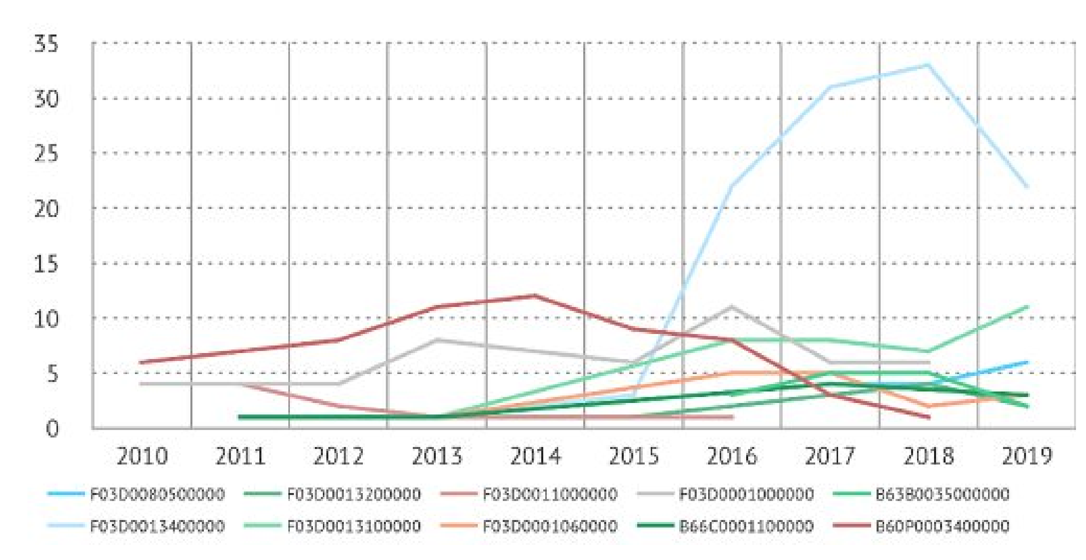


Figure 24: Assigned IPC subgroups for the top 10 IPC indices

(Source: List of patent applications related to Maintenance, repair and replacement)

As follows from Fig. 24, the assignment of the IPC index F03D 13/40 in recent years has increased many times and in fact, has become the most dominant index. The IPC index B60P 3/40, on the contrary, has significantly decreased. Thus, the focus of the inventors' interests shifted from technical solutions related to vehicles (index B60P 3/40) to devices and methods for transportation (index F03D 13/40).

Among individual patent applications and their groupings, it is necessary to highlight the patent documents with most prominent characteristics and unified indicators:

- In area of HCP / MRR / HWT / D, Wobben Properties GmbH (DE) has the largest representation with the following documents - BR112012024508A2, CA2792884A1, CL2012002803A1, EP2555947A1, EP2799224A32032ZA201317, RU2012147277A.
- In area of HCC, HOR / MRR / OFT / D, M, Vestas Wind Systems A / S (DK) was in the lead with the following documents - CN107923361A, EP3317512A1, JP2018523052A, KR20180022951A, US20180171982A1, WO2017000944A1,
- Finally, for MRR group HWT / D, M most productive was Windcare India Pvt Ltd (IN) - EP3359812A4, JP2017515048A, KR20160148682A, PH12018500779A1, WO2017060825A1.

The largest patent families were put together by:

- Wobben Properties GmbH - *Transport vehicle for rotor blades and/or tower segments of wind power plants and transport rack for a transport vehicle* with the root document WO2011124574A1 (25 patents and patent applications within 15 patent offices)
- Wobben Aloys - *Transport apparatus*, root document US8753050B2 (18 documents in 17 offices).

As noted earlier, the blades of a wind turbine are a lengthy product, sometimes exceeding 100 meters, so their transportation to the installation site in real geographic conditions is an extremely difficult task. In the group of patent documents prepared by Wobben Properties GmbH, the solution consists of a "*truck (400), as well as, for example, a semitrailer (300). A transport rack (200) is fixed to the saddle semi-trailer. A part of the rack is rotatable and is used to receive the rotor blade (100)."* (Global Dossier, 2011:6).

Transport of blades according to WO2011124574A1

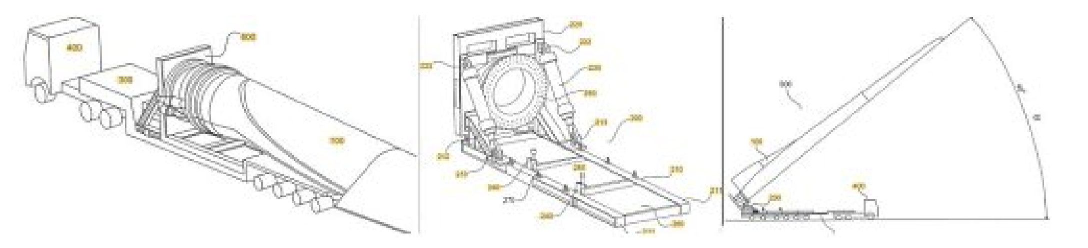


Figure 25: Solution for transportation of blades according to WO2011124574A1

(Source: Global Dossier, 2011:15)

The objective of the invention is to provide a "*transportation solution, in particular for rotor blades of wind power plants and/or tower segments, which provides more flexible transportation.*" (Global Dossier, 2011:2). The objectives of the invention are achieved due to the special design of a special transport rack, significantly expanding the possibilities of regulating the position of the load.

According to the authors, due to the special design of the rotary adjusting unit (in particular, due to the angle between the first and second rotation plane), "*it is possible to rotate the rotor blade mounted on the blade adapter or rotate the tower segment around its longitudinal axis by turning the first and second rotary bearings, so that an angle is formed between the transport rack and the rotor blade, or, respectively, the tower segment.*" (Global Dossier, 2011:17). Thus, it is possible to adjust the angle between the transport rack and the rotor blade, respectively, of the tower segment by turning the first and second rotary bearing. In addition, thanks to the adapter block, according to the inventors, it is possible to transport the rotor blades of the wind turbine or tower segments also at very narrow turns, since due to the tipping of the tipper, the entire rotor blade fixed to it can be turned upwards, and thereby there are no obstacles on a narrow bend.

Of the single entries, the highest rating according to AENERT methodology was calculated for the patent document entitled *Handling a wind turbine blade using an airship*, which is briefly described in Table 16 or in more details in Appendix 2.

Table 16: Patent overview - Handling a wind turbine blade using an airship
(Source: Global Dossier, 2018)

Patent parameters	Patent details
Title	**HANDLING A WIND TURBINE BLADE USING AN AIRSHIP**
Publication Number	WO2019001660
IPC	F03D13/20, F03D13/10, F03D13/40, F03D80/50
Inventors	LARSEN, Gerner, J.B.K. JENSEN, Ivar PEDERSEN, Gunnar K. Storgaard BAUN
Applicant	VESTAS WIND SYSTEMS A/S
Publication Date	03.01.2019
Technology categories	HWT Horizontal axis wind turbine in general
Technology elements	MRR Maintenance, repair and replacement
Problems	HCC High CAPEX / Plant construction
Technical solution types	D: Device; M: Method
Claims	23
Rate	14

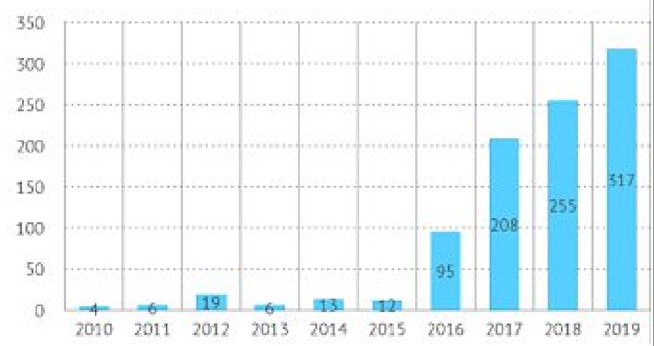
Assembly, installation, fastening of blades and keeping them in good condition

To select patent documents for the analysis of these technological operations, the following combination of subgroups of IPC indices was used:

- F03D 13/00 - F03D 13/40 Assembly, mounting or commissioning of wind motors
- F03D 80/50 Wind motors / Maintenance or repair

In total, during 2010 to 2019, 935 patent applications were identified, which were submitted by 332 applicants from 22 countries and registered at 22 patent offices. Thus, this is one of the most popular and demanded topics among inventors.

Distribution of patent applications by year in area of *Blades assembly*



- Searched keywords:
  Rotor blade and connecting device, Assembling blade
  Installing a rotor blade
  Mounting of wind turbine blades, Reinforcing a weakened area of a wind turbine blade,
  De-erection and re-erection of a blade, Attachment devices on a wind turbine blade, Mounting a rotor blade, Blade bearing removal, Connecting two rotor blade, blades lifting, Blade replacement, Assessment of rotor blades, Adjusting a rotor blade etc.

Figure 26: Distribution of patent applications by year in area of *Blades assembly*
(Source: List of patent applications related to Maintenance, repair and replacement)

The distribution of patent applications by year is shown in Fig. 26. From a brief assessment of the presented graph, it can be concluded that there has been a tremendous growth in patent activity over the past four years.

This topic also has a high representation of single applications that do not belong to patent families. Their share in recent years has ranged from 30 to 52%. Interestingly, during the past five years, patent applications have begun to be filed with 14 new patent offices, which were not previously seen for this technology group. In addition, the number of new applicants and IPC indices at the subgroup level has grown significantly.

The distribution of identified patent documents by patent offices, as well as by countries of residence of inventors is reflected in Fig.27. As in the previous case, the Chinese CNIPA was the most popular. In addition to it, the European and American national patent offices should be highlighted.

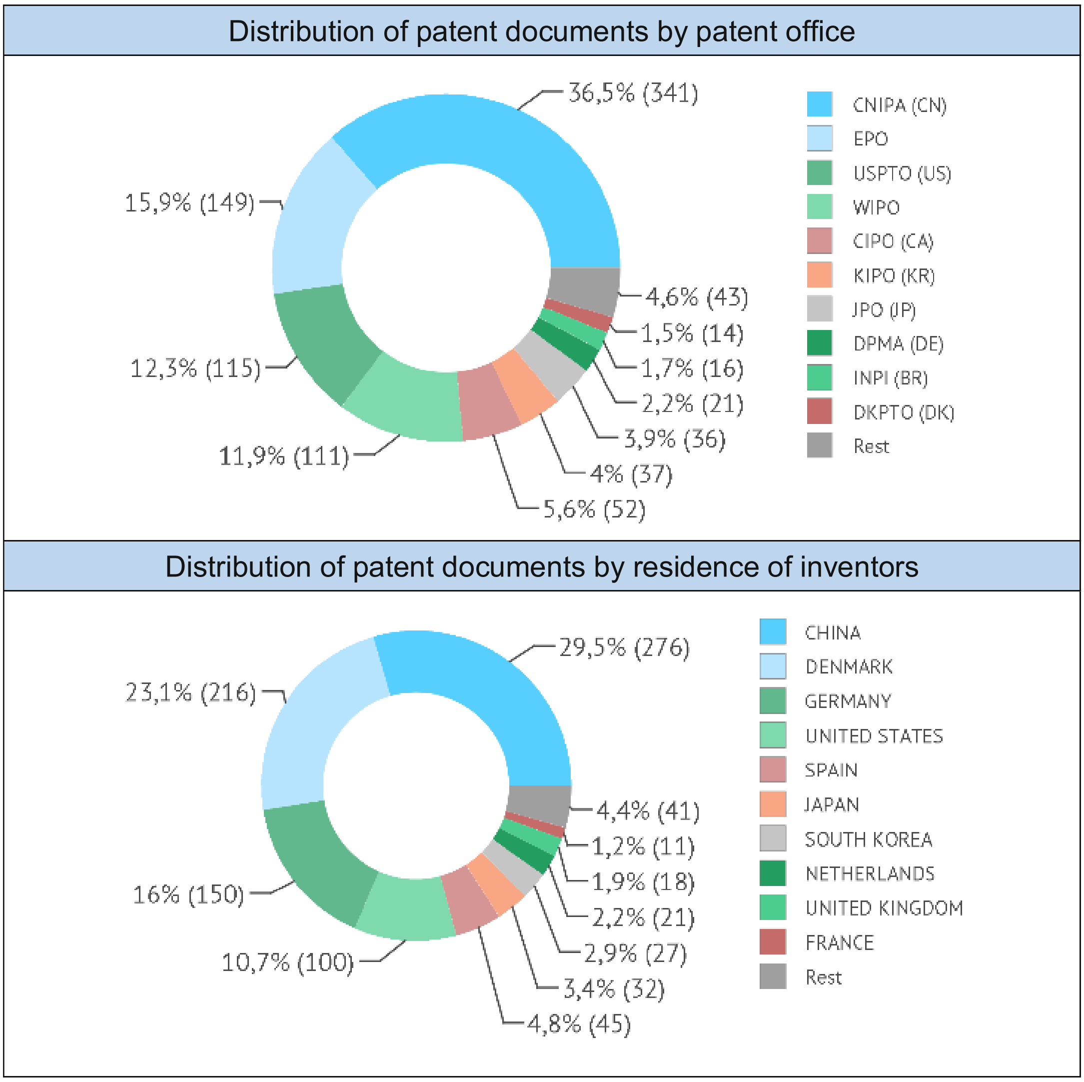


Figure 27: Patent documents distribution in area of Blades assembly

(Source: List of patent applications related to Maintenance, repair and replacement)

Also from Fig.27, it can be noticed that Chinese inventors were most active. Traditionally, residents of Denmark and Germany looked very representative as well. Table 17 shows the top 10 applicants by the number of registered patent applications during 2010 - 2019. Despite the fact that Chinese applicants dominated the total number of applicants, their representation in the top 10 is limited only by Beijing Goldwind Science & Creation Windpower Equipment Co Ltd. The Danish Vestas Wind Systems A/S was again the leader in the number of patent applications.

Table 17: Largest patent applicants - Assembly of blades (2010-2019)

(Source: List of patent applications related to Maintenance, repair and replacement)

Country	Applicant	Applications
DK	Vestas Wind Systems A/S	114
DE	Wobben Properties GmbH	62
US	General Electric	52
DK	Siemens Gamesa Renewable Energy A/S	28
DE	Senvion S.A.	25
CN	Beijing Goldwind Science & Creation Windpower Co Ltd	20
DE	Siemens AG	20
DK	MHI Vestas Offshore Wind A/S	19
ES	Gamesa Innovation & Technology S.L.	18
US	Wind Tower Technologies, LLC	14

The IPC index F03D 80/50 was found in more than 350 patent applications, and the indexes of the subgroup F03D 13/00 - F03D 13/40 were assigned in total to almost 800 documents.

Dynamics of applications by top 10 IPC indices referring to Assembly of blades

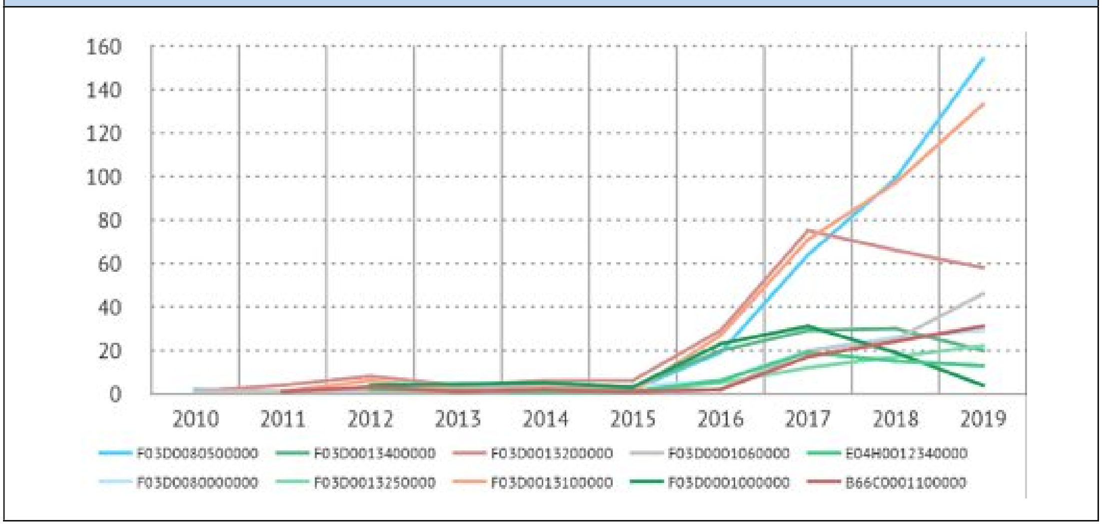


Figure 28: Assigned subgroups of IPC indices from among top 10 indices

(Source: List of patent applications related to Maintenance, repair and replacement)

The following patent applications and their group associations have the leading characteristics for technological processes related to the assembly, installation, fastening of blades and their maintenance in good condition:

- In area of HCC / MRR / HWT / D, M – Wobben Properties GmbH (DE) – has the largest representation with the following documents: BR112018013704A2, BR112018077442A2, CA3008500A1, CA3030056A1, CN108474351A, CN109477338A, DE102016113350A1, DE102016200160A1, EP3400385A1, EP3488060A1, JP2019509417A, JP2019527781A, KR20180100604A, KR20190028510A, US20190003459A1, US20190309532A1, WO2017118663A1 , WO2018015339A1;
- In area of HOR / MRR / HWT / D, M – General Electric (US) – CA2960487A1, EP3431752A1, EP3431757A1, EP3456957A1, US20170211547A1, US20180313332A1, US20180313336A1, US2018036219006A818A1, US2018036219006A8201
- In area of HCC / MRR, SE / WTU / D, M – Vestas Wind Systems A/S (DK) – CA2945418A1, CA2945422A1, CA2945861A1, CA2963586A1, CA2963587A1, CA3018672A1, CN106414998A, CN10646064784A, CAN1064602A, CN106460784A, CN1064602A EP3134643A1, EP3204576A1, EP3204641A1, US20170030101A1, US20170030102A1, US20170037651A1, US20170037830A1, US20170241153A1, US20170248126A1, US2017032035592A

Among patent families by the number of documents included in them, most prominent documents are briefly described in Table 18-20 and in more details in Appendix 3-5.

Table 18: Patent overview - Method and device for mounting a rotor of a wind energy system
(Source: EPO, 2017)

Patent parameters	Patent details
Title	**METHOD AND DEVICE FOR MOUNTING A ROTOR OF A WIND ENERGY SYSTEM**
Publication Number	EP3211217A1 (core document WO2013050569A2)
IPC	B66C1/10, F03D1/00, F03D13/10
Inventors	EYER WOLFGANG, KUIPER GERRIT
Applicant	WOBBEN PROPERTIES GMBH
Publication Date	30.08.2017
Technology categories	HWT Horizontal axis wind turbine in general
Technology elements	EE Electrical equipment and generators, MRR
Problems	HCP High CAPEX / Equipment production
Technical solution types	D: Device; M: Method
Claims	15
Rate	12

Table 19: Patent overview - Method for installing a rotor blade on a wind turbine

(Source: Canadian Intellectual Property Office, 2016)

Patent parameters	Patent details
Title	**METHOD FOR INSTALLING A ROTOR BLADE ON A WIND TURBINE**
Publication Number	CA2956875A1 Core document: US20170233228A1
IPC	F03D13/10, F03D13/40, B66C13/04, B66C13/46, B66C13/48
Inventors	CONERS Rolf, LAODA Fiona
Applicant	WOBBEN PROPERTIES GMBH
Publication Date	18.02.2016
Technology categories	HWT Horizontal axis wind turbine in general
Technology elements	MRR Maintenance, repair and replacement
Problems	ESI Environmental and social impact HCC High CAPEX / Plant construction
Technical solution types	D: Device; M: Method
Claims	17
Rate	13

Table 20: Patent overview - Method for installing a wind turbine rotor blade

(Source: Global Dossier, 2012)

Patent parameters	Patent details
Title	**WIND TURBINE ROTOR BLADE AND METHOD FOR INSTALLING A WIND TURBINE ROTOR BLADE**
Publication Number	US9759074B2 Core document: WO2012163918A1
IPC	F01D5/30, F03D13/10
Inventors	Hoffmann Alexander
Applicant	WOBBEN PROPERTIES GMBH
Publication Date	06.12.2012
Technology categories	HWT Horizontal axis wind turbine in general
Technology elements	MRR Maintenance, repair and replacement
Problems	HCC High CAPEX / Plant construction HOR High OPEX / Repair and replacement
Technical solution types	D: Device; M: Method
Claims	12
Rate	18

The solution provided by Wobben Properties *Wind turbine rotor blade and method for installing a wind turbine rotor blade* is further described below, on how the invention simplifies installation of the rotor blade of the wind-driven power plant.

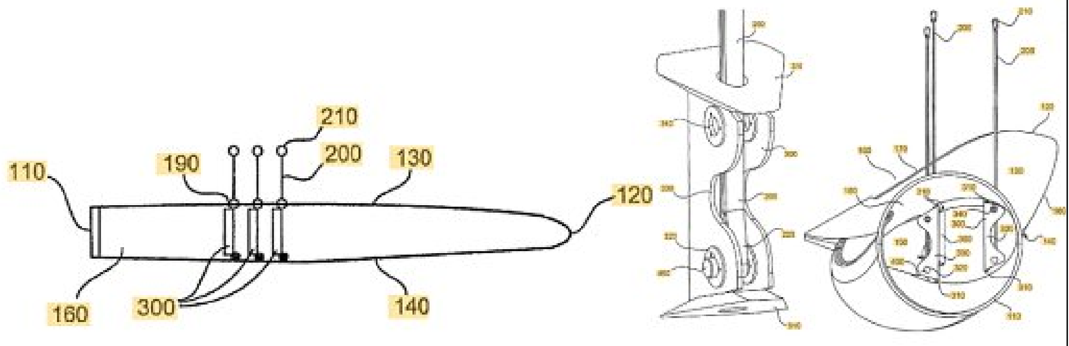
Assembly of blades according to WO2012163918A1


Figure 29: Solution for assembly of blades according to WO2012163918A1

(Source: Global Dossier, 2012:3)

The rotor blade 100 has a rotor blade shank 110, a rotor blade tip 120, a back side 130, a front side 140, a leading edge 160 of the rotor blade, and also, for example, three holes 190 in the outer shell 180 on the back side or the front side, which are provided in or around the canter of gravity. Using the reinforcement plates 310, the fastener is secured to the outer shell. A bolt is inserted into the first hole 320 in order to detachably secure the ropes 200. In this way, load or force distribution is initiated or envisaged to the downward pointing side. The ropes are secured to the fastener 300 with a bolt 400.

To summarize, the invention relates to the idea of mounting or dismounting, in particular, large rotor blades aligned no longer vertically, but horizontally. This is preferable, as this reduces the surface exposed to wind. In addition, the invention relates to the idea of the possibility of separating the manipulation tools necessary for mounting the rotor blades, without the need for the installer to bypass the mounted rotor blade from the outside, which can be done, for example, by means of a cradle with a person on a crane. Moreover, the invention relates to the idea of securing the manipulation means inside the rotor blade in such a way that they can also be removed again inside the rotor blade. This can occur, for example, by means of a bolt, which can be removed after the installation of the rotor blade. Then through the hole can be removed means of manipulation (for example, ropes). For this, none of the installers is required on the outside of the rotor blade.

5.3 Maintenance and repair of offshore wind installations

Maintenance and repair of offshore wind turbines is one of the most popular topics among inventors in recent years. For the purposes of this study, about 700 patent applications were selected, both related to wind power maintenance or related operations and offshore wind turbines.

The distribution of selected patent applications for the period from 2010 to 2019 on this topic is shown in the Fig.30:

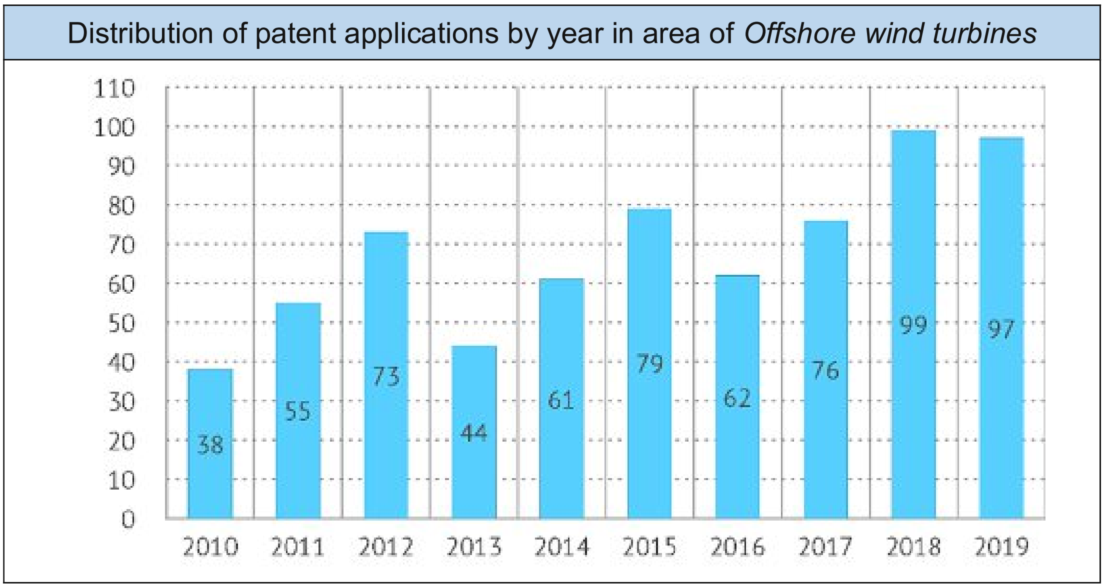


Figure 30: Distribution of patent applications in the area of Offshore wind turbines

(Source: List of patent applications related to Maintenance, repair and replacement)

As follows from the above graph, there is a steady upward trend with small statistical drops. Most of the patent applications registered at that time were concentrated in previously formed patent families, however, the share of single documents was quite high - more than 11%.

In addition, over the past three years, the share of single applications on average has increased significantly and exceeded 30% of the total number for this period of time. Statistically, this indicates a very high interest of inventors in this topic and, as a result, in the desire to eliminate or mitigate the impact of existing technical and organizational problems in this segment of wind energy.

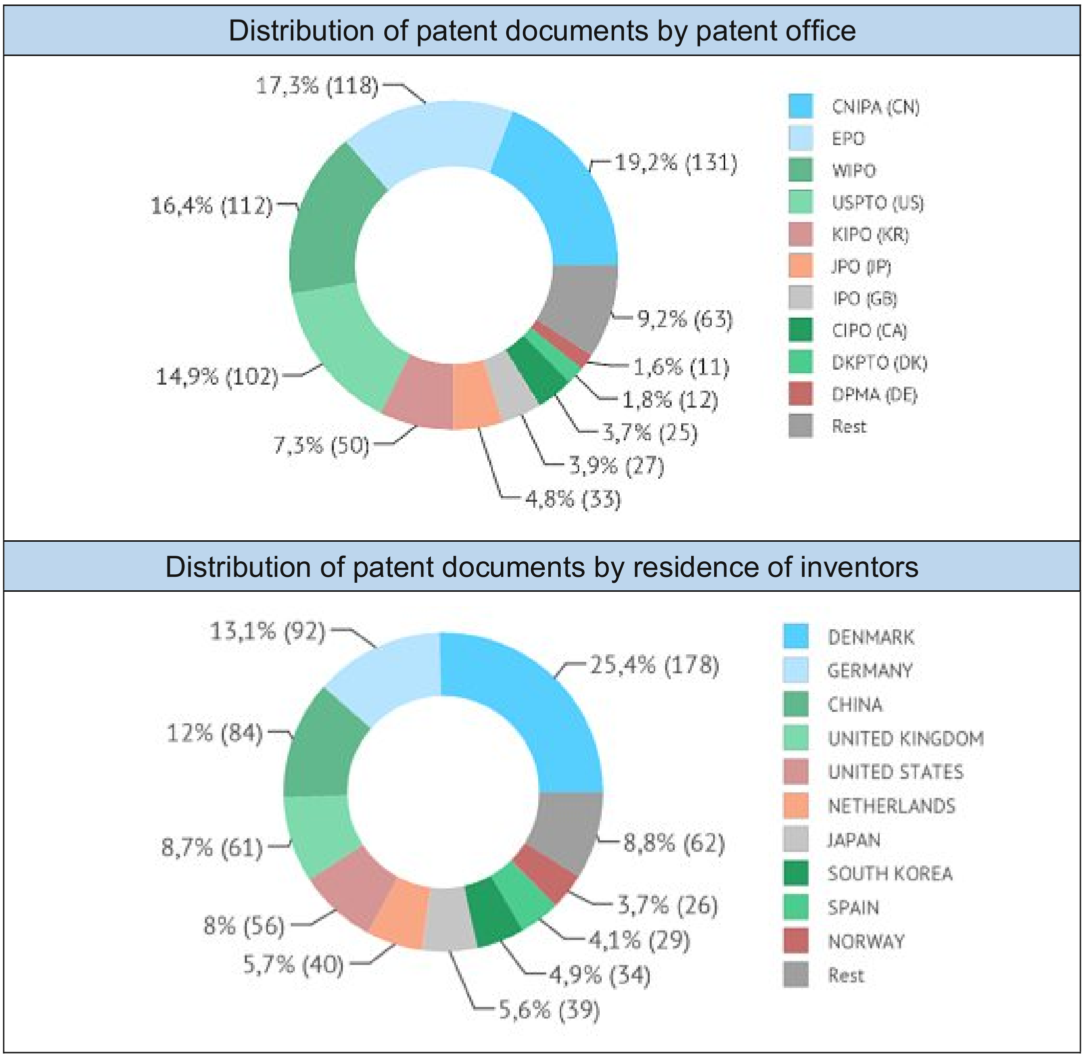


Figure 31: Patent documents distribution in area of Offshore wind turbines

(Source: List of patent applications related to Maintenance, repair and replacement)

The majority of patent applications were approximately equally filed at four patent offices - CNIPA, EPO, WIPO and USPTO. Their combined share was almost 70%. The most productive among the applicants were representatives of Denmark (over 25%), Germany, China, Great Britain and the USA. In total, 273 applicants from 17 countries took part in the creation of these inventions.

As indicated in Table 21, Vestas group of companies has shown the greatest patent activity in this sector of inventive activity. Among other applicants, more than twenty patent applications were filed by Germany's Siemens AG and Japan's Mitsubishi Heavy Industries.

Table 21: Largest patent applicants - Offshore wind turbines (2010-2019)

(Source: List of patent applications related to Maintenance, repair and replacement)

Country	Applicant	Applications
DK	Vestas Wind Systems A/S	76
DK	MHI Vestas Offshore Wind A/S	30
DE	Siemens AG	30
JP	Mitsubishi Heavy Industries, Ltd.	24
DK	PP Energy APS	19
KR	Samsung Heavy Industries Co., Ltd.	18
BE	High Wind N.V.	17
US	General Electric	14
DK	Envision Energy (Denmark) APS	12
JM	Chin Howard M	11

Of the 292 subgroups of the IPC classifications assigned to patent applications from this patent selection, the following were distinguished:

- F03D 80/50 Wind motors. Maintenance or repair (4.5%);
- F03D 13/10 Assembly of wind motors; Arrangements for erecting motors (4.1%);
- F03D 13/25 Assembly, mounting or commissioning of wind motors; specially adapted for offshore installation (3.2%);
- B66C 23/18 Cranes specially adapted for use in particular locations or for particular purposes (3.8%);
- B63B 35/00 Vessels or similar floating structures specially adapted for specific purposes and not otherwise provided for (3.7%);
- F03D 1/06 Wind motors with rotation axis substantially parallel to the air flow entering the rotor / Rotors (3.4%).

The dynamics of changes in the number of mentions of IPC subgroups over a ten-year period is shown in Fig. 32.

Dynamics of applications by top 10 IPC indices referring to *Offshore wind turbines*

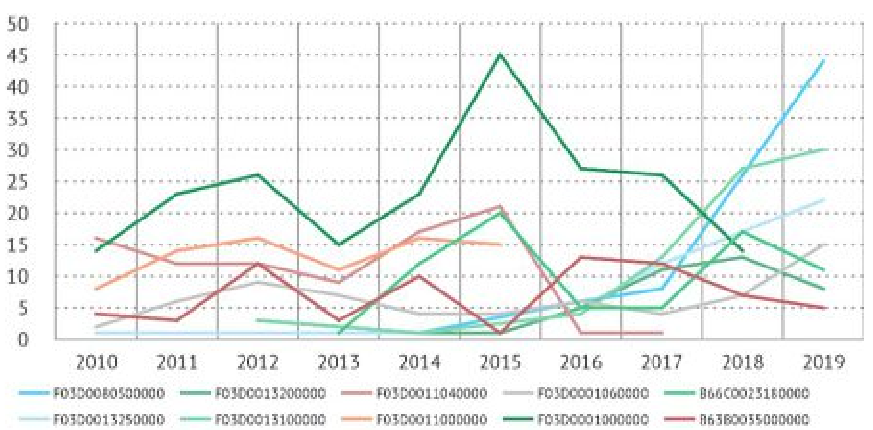


Figure 32: Dynamics of changes in the number of mentions of the most popular IPC subgroups for Offshore wind turbines

(Source: List of patent applications related to Maintenance, repair and replacement)

In the second half of assessment period, the subgroups F03D 80/50, F03D 13/10 and F03D 13/25 showed a sharp increase, a noticeable increase also has F03D 1/06 and B66C 23/18.

It should be accentuated that the subgroups F03D 11/ 00-11/04 have ceased to exist since 2016, and IPC indices from the F03D 80 group began to be assigned instead. The subgroup F03D 1/06 has a largely generalized nature, which does not correspond to the purposes of detailed analysis in this work. However, the aforementioned subgroups F03D 80/50, F03D 13/10, F03D 13/25, B66C 23/18 and B63B 35/00 generally have a deep level of detail and can be seen as reflecting the real interests of inventors in the area of offshore wind turbines maintenance and repair.

The patent applications selected for the analysis were clearly dominated by two problems that the pending patent applications were aimed at solving: *High CAPEX / Plant construction*, which is mentioned in more than 40% of documents and *High OPEX / Repair and replacement* (33%). In addition, *Environmental and social impact* issues were mentioned quite often. It should be noted that in the first case, the described problems are considered not to be formally related to the topic of *Maintenance, repair and replacement.* However, it should be noted that technical solutions from patent applications related to *Plant construction*, in their essence, in the overwhelming majority of cases, can also be attributed to *Repair and replacement* area and, therefore, were considered here together.

Specialized floating vessels equipped with devices for installation, maintenance and repair are essential for the maintenance of offshore wind turbines. The importance of this matter is determined by the conflicting requirements for the operation of offshore wind turbines. On the one hand, their placement in offshore zones is advisable to extract a larger volume of wind energy, however, on the other hand, the operation of these facilities in areas of high wind speeds is difficult due to frequent and unsafe sea waves, less stability of installation equipment, additional vibration impact and the need to comply with special safety regimes for personnel.

In this work, about 90 patent applications were identified that are directly related to the *Vessels or similar floating structures specially adapted for specific purposes and not otherwise provided for* and have an IPC index of B63B 35/00. More than half of them were registered in the last four years, while in 19% of cases they did not complement the previously formed patent families but offered new technical solutions. This indicates the high patenting activity of inventors in this matter.

Inventors from South Korea (more than 23% of the total number of applications) and, in particular, Samsung Heavy Industries Co., Ltd. were the most dominant applicants. Obviously, this is due to the developed industrial network for the construction of sea vessels in this country.

The most popular problems addressed by technical solutions in patent applications, were related to the reduction of the cost of operations for the construction of offshore wind turbines and their maintenance. For example:

- Samsung Heavy Industries Co., Ltd. registered a series of such patent applications with the Korean Patent Office, including KR20140000374A, KR20140000385A, KR20170109094A, KR20180003214A;
- MHI Vestas Offshore Wind A/S registered with various international offices such patent applications EP3237750A1, KR20170101951A, US20170370346A1, WO2014139532A1, WO2016101957A1.

The largest patent families were created by the following applicants:

1. Tianjin University *Method for transporting an offshore wind turbine in a floating manner*, core document: US9297355B2, size: 13/13, offices: 7;
2. Nordic Yards Holding GmbH *Ship and method for transporting and setting up offshore structures*, core document: EP2436593A1, size: 11/11, offices: 7;
3. Stx France SA *Transport vessel of a wind turbine to an offshore site and method for its implementation*, core document: EP2495162A1, size: 11/11, offices: 6.

Among the patent applications registered in the period under review and not part of the previously created patent families, it is necessary to highlight the following ones with the highest bibliographic rating:

- *Vessel for transporting and installing sea wind power generator,* core document: KR20190128432A; applicant - Korea Electric Power Corp, Xinnos Co Ltd, Sm Instr Co Ltd., Ilho Seatech Co Ltd.;
- *Method and apparatus for installing wind turbine*, core document: KR20190098496A by Doosan Heavy Ind & Construction Co Ltd.;
- *Floating structure*, core document: KR20160098745A by Samsung Heavy Ind.

As an example of a noticeable technical solution, the patent application EP2436593A1 from Nordic Yards Holding GmbH will be further described. The invention notes that the construction of offshore wind turbines is a high-cost operation, especially *"... For the construction of the Alpha-Ventus offshore wind farm, the wind turbines were set using the Thialf platform of the Dutch company Heerema. This is a very large tool that is typically used for the construction of oil rigs. The implement remains for longer periods at the installation site. Building an offshore wind turbine, however, takes only one to two days and then the platform has to be towed to another location. The use of this implement for the construction of wind turbines is too expensive and expensive."* WIPO (2012:2)

During the transportation of heavyweight offshore structure, the inventors focused on ship's strength by designing a *U-shaped cross-section of the ship's hull*. According to the inventors, this is particularly advantageous *"…for ship hydrodynamics and the connection of the two structures that the lifting support systems can be integrated into the side walls. When setting up the offshore structures, the ship can be fixed by lowering the jacks to the seabed. As a result, the ship is kept in a stable reference position, which is independent of swell, current and wind influences. This is advantageous for the installation of wind turbines, because the masts must be aligned very precisely vertically. Furthermore, the U-section has the advantage that the upper edges of the side walls can be used as a basis for the movable crane. As a result, the crane can be moved above the offshore structures loaded on the ship."* (WIPO, 2012:3)

This invention can be applied not only for the primary installation of a wind turbine, but also for its complete replacement or for replacement of large-sized elements, for example, blades, other rotor elements or generators.

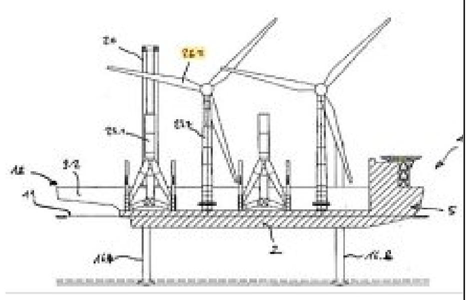
Transporting offshore structures during installations and replacements, according to EP2436593A1	
	*The ship according to the invention for transporting and setting up offshore structures has:* • *a hull having a U-shaped cross-section which has an open stern and overhangs of the side walls projecting aft beyond the trailing edge of the ship's floor;* • *in the hull integrated Hubstützensysteme (Jack systems) with jacks, which are movable in the vertical direction with their lower ends in positions below the ship's bottom and a movable on the upper edge of at least one side wall crane.*

Figure 33: Solution for transporting offshore structures according to EP2436593A1

(Source: WIPO, 2012)

Another major challenge in offshore wind turbine maintenance is the availability of highly efficient wind turbine mounting or attachment devices and the appropriate technology. These inventions are most often marked with the IPC group index F03D 13 and are further detailed with special subgroups, for example, F03D 13/10 Assembly of wind motors; Arrangements for erecting wind motors.

In the general patent selection related to *Maintenance, repair and replacement*, about 200 patent applications were identified that include IPC indexes of the F03D 13 group. 96 applicants from 16 countries took part in the creation of these inventions during 2010 - 2019. The overall distribution of patent applications over a ten-year period has been characterized by an explosive upward trend in recent years. Suffice it to say that only 13 patent applications were found for the period from 2010 to 2015, and 171 applications were found for the period from 2016 to 2019, and a significant part of them (more than 30%) were not a continuation of previously formed patent families. This indicates the great interest of inventors in this topic. The largest number of technical solutions was proposed here by representatives of Denmark (about 30%) and China (about 25%). The most popular office for filing patent applications was CNIPA. As in the case already described beforehand, the most popular problems in inventions were - reducing the cost of operations for the construction of offshore wind turbines and their maintenance. The group of Danish affiliated companies Vestas Wind Systems A/S and MHI Vestas Offshore Wind A/S clearly dominated here in terms of the number of patent applications - a total of 43 pieces.
The largest patent families were created by the following applicants:

- Howard M. Chin, Kimberly A. Carraha *Weather maintenance system for an offshore wind turbine maintenance program*, core document: US20160068373A1, size: 19/19, number of offices: 5;
- Nabrawind Technologies SL *Wind turbine assembly system and related method*, core document: EP3130796A1, size: 6/6, number of offices: 4;

In the patent family by Howard and Carraha, they proposed an original invention, aimed at improving the efficiency and safety of maintenance of offshore wind turbines. The main element of the invention is a working chamber, which allows for the safe transportation of personnel with a working tool from the ship to the offshore wind turbine and back: *"…The present invention in its preferred form includes as its basic components a maintenance capsule which would carry a group of repair personnel and their equipment for maintaining an offshore wind turbine on a wind turbine tower and for returning repair personnel and equipment to a maintenance vessel such as a* *ship or boat. The equipment comprises tools and replacement parts. The maintenance capsule is conveyed from and to a wind turbine tower apparatus by means of such a maintenance vessel. The maintenance vessel would carry a number of maintenance capsules configured as required and they would each be transferred to a wind turbine tower apparatus by means of an appropriate crane apparatus or assembly which is also part of the invention."* (USPTO, 2016:9).

Another group of inventions related to special-purpose cranes is essential for the repair and maintenance of wind turbines in offshore zones. Patent applications for this case were searched by using the IPC subgroup B66C 23/18 *Cranes specially adapted for use in particular locations or for particular purposes*. In total, a little more than 70 applications were found during 2010 to 2019. The distribution of patent applications over a ten-year period is highly volatile, with no clear upward or downward trend.

The representatives of the Netherlands and Belgium were most active here (in total, about 45% of applications). The most active in terms of the number of registered patent applications was the Belgian High Wind N.V. - 16 documents.

Obviously, it should be mentioned that it is in the waters of these countries that the world's largest offshore wind turbine from General Electric is located - Haliade-X has a tower height of 260m above sea level, a rotor diameter of 220m, and each blade is 107m long. This turbine is capable of generating 67 GWh of electricity annually and has a unique capacity factor of 63 %.

In almost 20% of cases, applications were registered at the European Patent Office. 85% of the applications were dominated by issues related to numerous variations in the high cost of building or maintaining wind turbines, 14% of applications mentioned the problem of Environmental and social impact.

Among the holders of the most developed patent families, it is necessary to highlight:

- Lynderup Henrik Fomsgaard, Moeller Jesper M*ethod and device for mounting of wind turbine blades*, core document: US8966753B2, size: 21/21, offices: 6;
- Chin Howard M, Carrera Kimberly A. *Crane assembly for a maintenance system for a wind turbine maintenance program*, core document: US20160068373A1, size: 19/19, offices: 5
- Wobben Properties GmbH *Tower crane for erecting a wind turbine and method for erecting said tower crane*, core document: US20170334685A1, size: 16/16, offices: 12.

In most cases, patent applications of this group propose designs of special cranes and technologies for their use for mounting and replacing wind turbine blades.

5.4 Maintenance of wind turbine by manipulators

Maintenance of wind turbines by means of controlled manipulators or robots is at the same time one of the most attractive, but also very difficult tasks. On the one hand, the dimensions of wind turbines and the unstable climatic conditions of their operation presuppose serious difficulties in conventional maintenance technologies, on the other hand, the same reasons require the development of the latest and complex manipulator designs, as well as the creation of special control systems for them. It is difficult to find a compromise in this process and therefore, this area has not received significant development in recent years.

To assess patent activity in the area of control and maintenance methods in wind energy, patent applications were selected from the general list of patent documents related to *Maintenance, repair & replacement* during 2010-2019. The selection was carried out according to the presence in the patent application of the group IPC B25J Manipulators. In total, 34 documents were found that were registered by inventors from 9 countries at 12 patent offices.

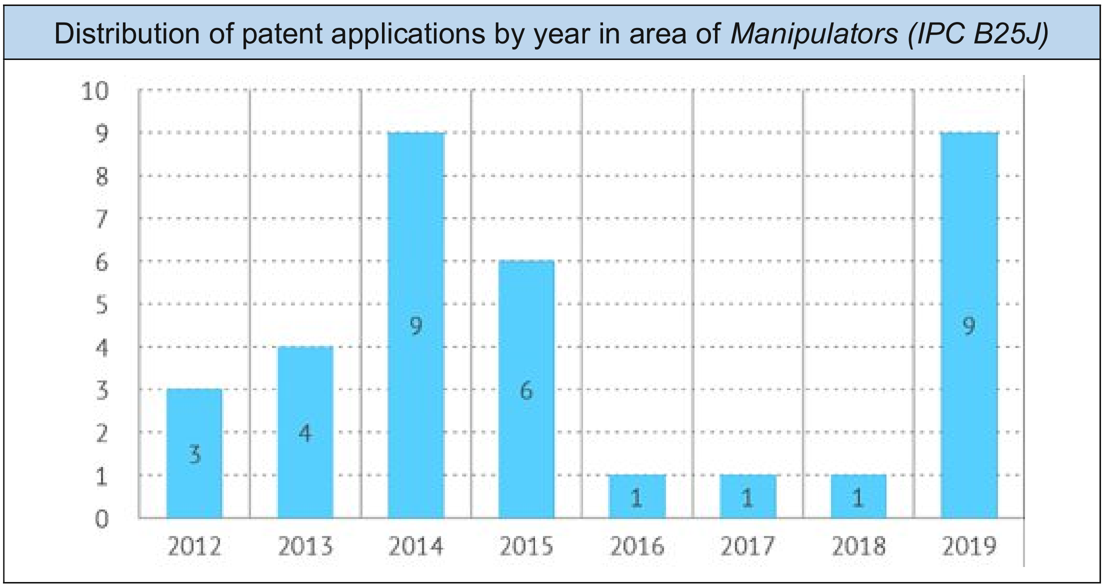


Figure 34: Distribution of patent applications by year in area of Manipulators

(Source: List of patent applications related to Maintenance, repair and replacement)

It should be noted that despite the previously conducted preliminary selection of patent documents by analysing their texts to the level of individual technological elements, further selection of applications based on the IPC indices has certain drawbacks. The main reason here is that in many patent families contain patents and applications with identical technical solutions, but they are registered at different patent offices, where examiners are often assigning different IPC subgroups, which can distort the statistical results obtained. Based on this explanation, all patent families were selected for assessment if the group B25J was assigned to at least one document in them. In total, 21 patent families were discovered in this way.

As follows from the Fig. 34, the patenting process is cyclical with significant time delays. In addition, the vast majority of applications in this figure are from patent families, sometimes quite large. Thus, patenting activity in this technological area is unstable and very modest. Among the patent documents of this group, the following IPC indices were most often assigned:

- B25J 11/00 Manipulators not otherwise provided for (13.3%);
- B25J 5/00 Manipulators mounted on wheels or on carriages (10.9%);
- B25J 13/08 Controls for manipulators / by means of sensing devices (3.9%);
- B25J 19/00 Accessories fitted to manipulators, Safety devices combined with or specially adapted for use in connection with manipulators (3.1%).

The top ten applicants for in area of *Manipulators* are presented in the following table:

Table 22: Largest patent applicants - Manipulators (2010-2019)

(Source: List of patent applications related to Maintenance, repair and replacement)

Country	Applicant	Applications
KR	Samsung Heavy Industries Co., Ltd	9
DE	Krampe Susanne	4
DK	Rope Robotics Aps	4
GB	Rotos 360 Limited	3
DK	Bovin Jonas	2
KR	Ha Young Youl	2
SE	Jagd Lars	2
DK	Johst Kenneth	2
DE	Krampe Nina Katharina	2
DE	Krampe Timothy	2

The largest number of applications were filed with the patent offices in South Korea, (KIPO), US (USPTO) and WIPO, with the most active inventors from South Korea, Germany and Denmark.

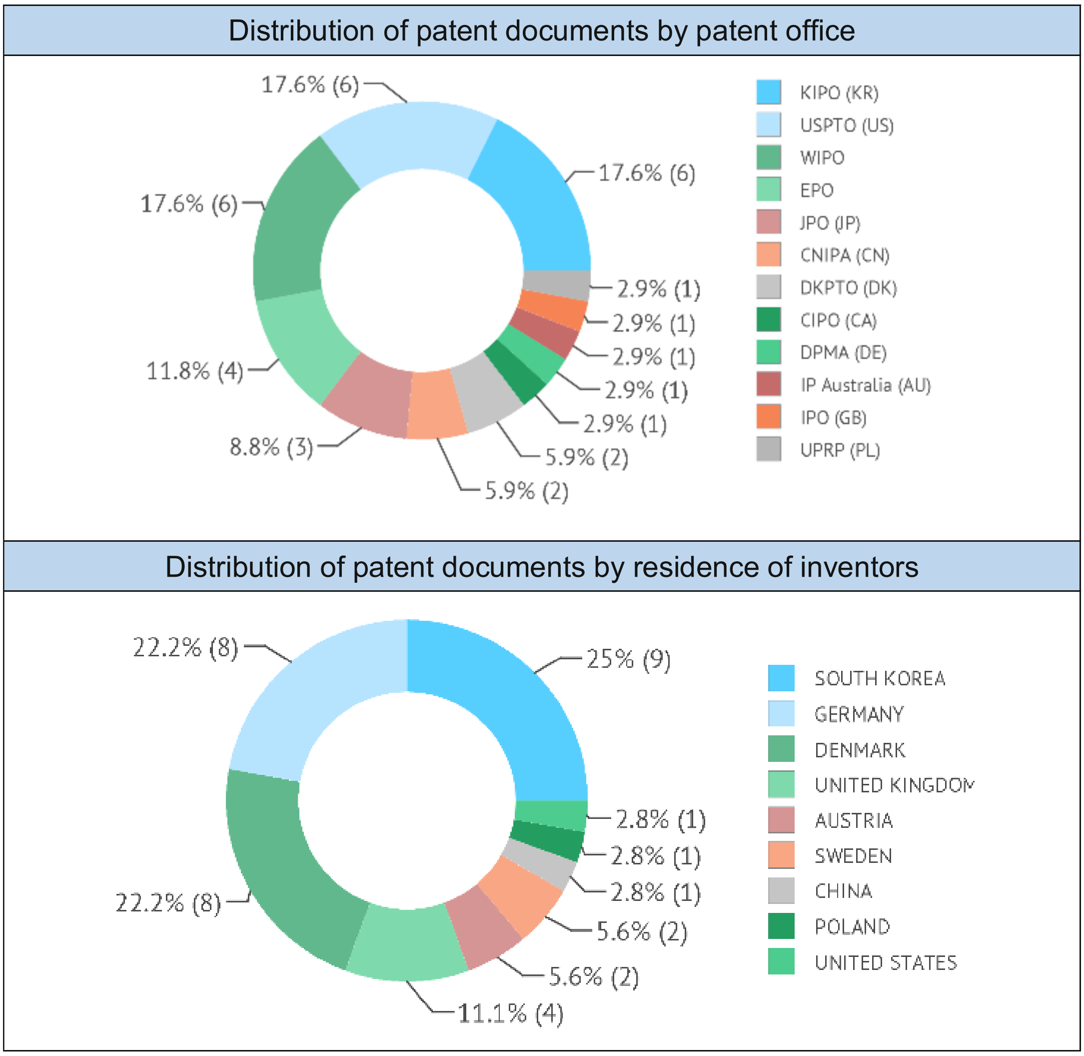


Figure 35: Patent documents distribution in area of Manipulators

(Source: List of patent applications related to Maintenance, repair and replacement)

Interestingly, the restraint of the Chinese patent office and Chinese inventors is noticeable for this technological direction.

The most popular problems, the solution of which was reflected in technical solutions, were:

1. High OPEX / Repair and replacement;
2. High OPEX / Operational maintenance;
3. Environmental and social impact.

The largest patent families in this group were:

- Wobben Properties GmbH with root document: *Method for the automated surface treatment of a profiled large component of a wind turbine, treatment device and treatment system*: Publication no.US20150283665A1, 24 documents;

- *Robot for inspecting rotor blades of wind energy installations*: Publication no.US20150267688A1 by inventors: Krampe Susanne, 11 documents;
- *Bolt tightening robot for wind turbines*: Publication no. US9212651B2 by inventors Johst Kenneth, Jagd Lars, Bovin Jonas, 11 documents.

The prominent publication no. US20150267688A1 *Robot for inspecting rotor blades of wind energy installations* states that *"... In general, the service of wind energy installation blades at high altitudes poses a challenge to the workforce and to industry. In the case of optical in situ inspection of the rotors at least two skilled workers are necessary, wherein per day the blades of only one or maximally two wind energy installations can be inspected. It is possible to automate the rotor blade service by the flying robot according to the invention which can also be referred to as service copter."* (USPTO, 2015:1). The brief essence of the invention is described in Fig.36:

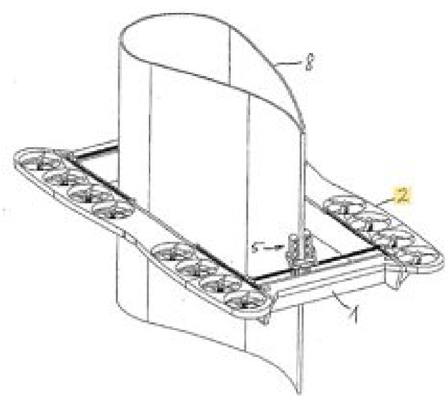
Robotized solution for inspecting rotor blades according to US20150267688A1	
	*The robot (service copter) according to the invention can be positioned, for example in accordance with drawing, at the upper portion of a rotor blade (8) of a wind energy installation and can be moved along the rotor blade in the vertical direction and, where necessary, additionally or alternatively in the horizontal or inclined direction. The robot comprises a carrier module (1) including aerodynamic drive technology, a drive unit (2) including propellers and a control, a guiding and docking system (5), a rotor blade state detection system and a cable which is connected either fixedly or detachably.*

Figure 36: Solution for inspecting rotor blades according to US20150267688A1

(Source: USPTO, 2015)

In the series of documents *Bolt tightening robot for wind turbines* with the root number US9212651B2, it is a proposed solution to a rather complex problem of automating the tightening of wind turbine bolts. The inventions in this series state that *"... During the erection of the wind turbine the bolt nuts are today typically applied and retightened manually. This is followed by a manual procedure that applies the specified preload to the nut bolts. During this procedure a hydraulic high torque wrench is typically used. The tightening of every bolt is typically done manually, and a high level of quality is needed in order to ensure the stiffness and strength of the wind turbine."* (USPTO, 2014:1). The invention is seeking to alleviate the physical deterioration and work-related illnesses that the monotonous and repetitive job with vibrating equipment is resulting in. A more detailed solution description is provided in the Fig.37:

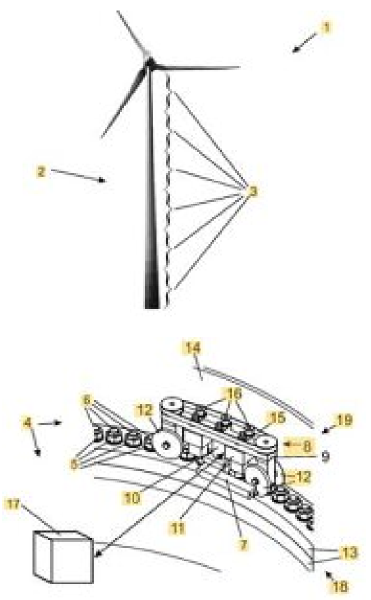
Automating the tightening of wind turbine bolts according to US9212651B2	
	*5 - nut bolts* *6 - bolts* *7 - wrench* *10 - clamp system* *11 - position sensors* *12 - wheels* *13 - flange & 14 - wall* *15 - belt & 16 - adjustable rollers, robot control system 17* *A robot to bolt down a series of nut bolts in a joint circular flange connection of a wind turbine, which robot comprises at least two wheels and a drive to transport the robot along the series of nut bolts and a tool to bolt down a nut bolt with a predefined torque and a position sensor to position the tool above the nut bolt to be bolted down and a robot control system to control the tightening process and document parameters relevant for the stability of each bolted down nut bolt.*

Figure 37: Solution for automation of bolt tightening according to US9212651B2

(Source: USPTO, 2014)

Highest rating was calculated for patent application *System and method for removing or installing rotor blade hardware of a wind turbine* with root document no. US20190024639A1. Here a technical solution is proposed for a very important problem of removing or installing equipment for wind turbine rotor blades and more detailed patent application overview is presented in Table no. 23 and Appendix 7.

Table 23: Patent overview - System and method for removing or installing rotor blade hardware of a wind turbine

(Source: WIPO, 2020)

Patent parameters	Patent details
Title	**SYSTEM AND METHOD FOR REMOVING OR INSTALLING ROTOR BLADE HARDWARE OF A WIND TURBINE**
Publication Number	US20190024639A1
IPC	F03D80 / 50, F03D13 / 10, F03D1 / 06, B25J11 / 00, B25J15 / 15 00
Inventors	Davidson Paul Howard, Willman Stephanie Lohberg
Applicant	General Electric Company
Publication Date	24.01.2019
Technology categories	HWT Horizontal axis wind turbine in general
Technology elements	MRR Maintenance, repair and replacement
Problems	HOR High OPEX / Repair and replacement
Technical solution types	D: Device; M: Method
Claims	20
Rate	15

5.5 Monitoring and diagnostics of the technical condition of wind turbines

Monitoring and diagnostics of the condition of individual components of wind turbines, including primarily the blades, transmission, control systems and electrical equipment, is essential for the successful operation of wind turbines. Continuous and high-quality diagnostics and monitoring allows to timely identify the occurrence and intensification of dangerous defects, prevent uncontrolled equipment malfunction, set the required maintenance schedule or deliver the necessary parts for replacement. It is obvious that the development of a reasonable schedule of maintenance and repair should be alligned with the operating modes to minimize shutdowns in the operation of wind turbines. This can be achieved both by effective administration of operations and by choosing the best and modern methods and devices for diagnostics and repair. A significant amount of information to address these issues is concentrated in the patent literature. Among them, the most popular are the following thematic sections related to monitoring and diagnostics:

- Testing static and dynamic balance of machines or structures;
- Measuring force or stress;
- Investigating or analysing properties of materials;
- Measuring electric or magnetic variables.

Testing static or dynamic balance of machines or structures

Below is a brief analysis of patent applications published during 2010-2019 on monitoring and diagnostics operations. The selection of documents for analysis was carried out from the general patent database of *Maintenance, repair & replacement patents application* by using the IPC indexes of the same name.

Distribution of patent applications by year in area of
Testing static or dynamic balance of machines or structures (IPC subclass G01M)

Figure 38: Distribution of patent applications by year

(Source: List of patent applications related to Maintenance, repair and replacement)

In total, according to this criterion, 126 patent applications were identified, published at 21 patent offices and prepared by 54 applicants from 15 countries. As follows from Fig. 38 as a whole, there is an upward trend, although the peak values were reached in 2015. The share of single applications that are not part of the previously created patent families, and therefore carry completely new technical solutions, steadily decreased 2010-2015, and then stabilized at the level of 18-30% of the total number of new ones. This indicates that this topic has been fuelled by new ideas in recent years, and at a relatively representative level. Obviously, due to this particular group of applications, a cautious upward trend is maintained in general.

Figure 39 show the distribution of patent applications by offices and countries. Among the national patent offices, the leaders were the Chinese CNIPA and the European EPO, as well as the international office of WIPO.

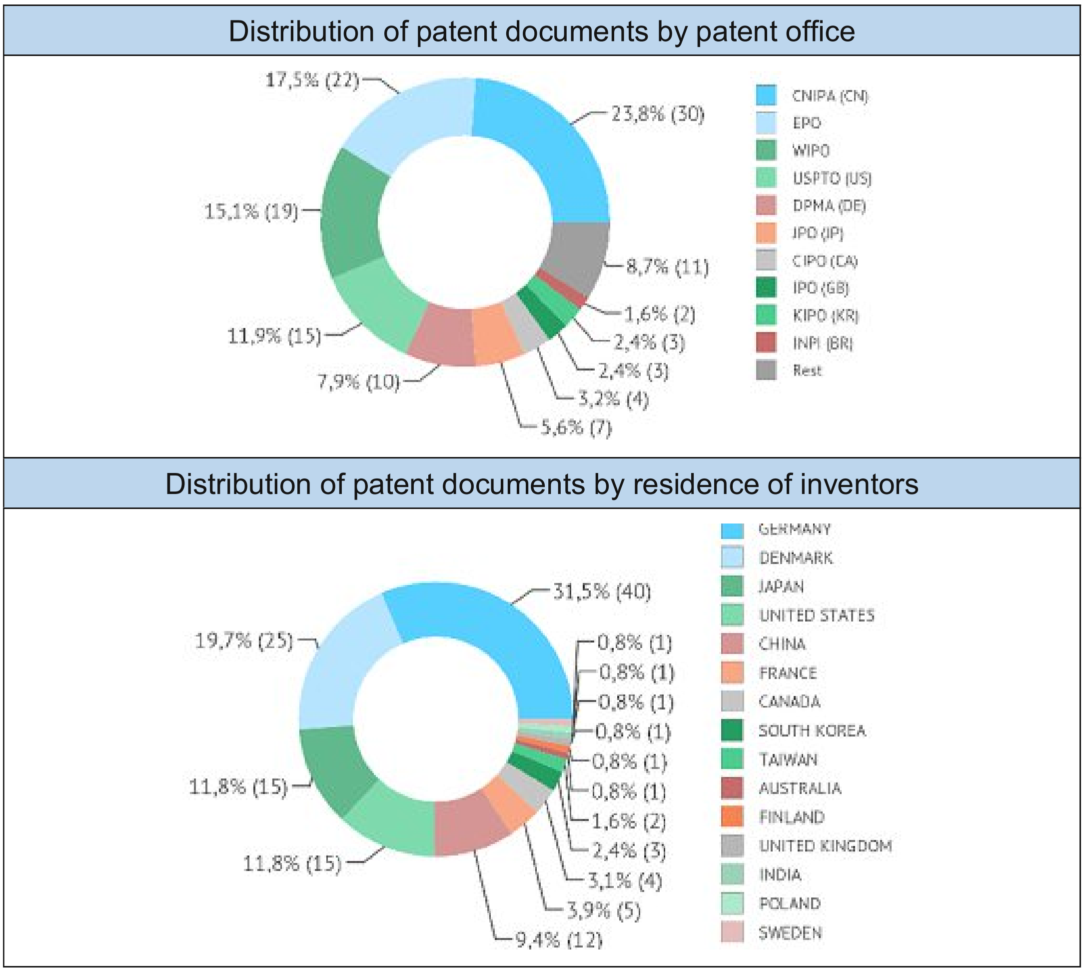


Figure 39: Patent documents distribution in area of Testing static or dynamic balance of machines or structures (IPC subclass G01M)

(Source: List of patent applications related to Maintenance, repair and replacement)

As in many previous cases of patent analysis, residents of Germany and Denmark were in the lead among applicants, their combined share in this topic exceeded 50%. The third and fourth share among the applicants were residents of Japan and the USA. The Danish Vestas Wind Systems A/S and the German Wobben Properties GmbH, as in most previous cases, were the most productive among the 54 patent applicants (Table 24).

Table 24: Largest patent applicants - Testing static or dynamic balance

(Source: List of patent applications related to Maintenance, repair and replacement)

Country	Applicant	Applications
DK	Vestas Wind Systems A/S	22
DE	Wobben Properties GmbH	17
US	General Electric	7
DE	Siemens AG	7
US	Mts System Corp	6
DE	Senvion S.A.	6
FR	Astrium SAS	5
CA	Collineo Inc	4
JP	Hitachi, Ltd.	4
DE	Imo Holding GmbH	4

The most prevalent methods for diagnostics of wind turbine parts among inventors were the following:

- Diagnostics of gearbox, transmission mechanisms;
- Diagnostics of the condition of bearings;
- Measuring rate of loss or gain of fluid, lubricating oil, coolants, brake fluids;
- Investigating the elasticity of structures.

The largest patent family was put together by Wobben Properties GmbH - *Monitored component connection, wind power system, method for monitoring a component connection for inadvertent loosening of the component connection in the connected state* with core publication number US20150159633A1. The family includes 10 patents and 17 patent applications registered in the USA, Europe, Japan, South Korea, Russia, Taiwan and other countries.

As an example of most prominent invention on this subject, a patent application by Vestas Wind Systems A/S is given in Table 25:

Table 25: Patent overview - Fatigue testing of a wind turbine blade

(Source: EPO, 2019)

Patent parameters	Patent details
Title	**FATIGUE TESTING OF A WIND TURBINE BLADE**
Publication Number	US20190094104A1
IPC	G01M5/00
Inventors	Penn Katherine, Stuart Guy, Richards William David
Applicant	Vestas Wind Systems A/S
Publication Date	28.03.2019
Technology categories	WTU
Technology elements	MRR Maintenance, repair and replacement
Problems	HOM High OPEX / Operational maintenance HOR High OPEX / Repair and replacement
Technical solution types	D: Device; M: Method
Claims	31
Rate	15

The abstract of the invention summarizes its essence: *"The application relates to an apparatus (100) for fatigue testing a wind turbine blade specimen (10). The apparatus (100) comprises first and second support assemblies (120, 130) and an actuator (140) for cyclically deflecting the specimen (10) in a first transverse direction."* (EPO, 2019:1).

Testing of a wind turbine blade according to US2019094104A1

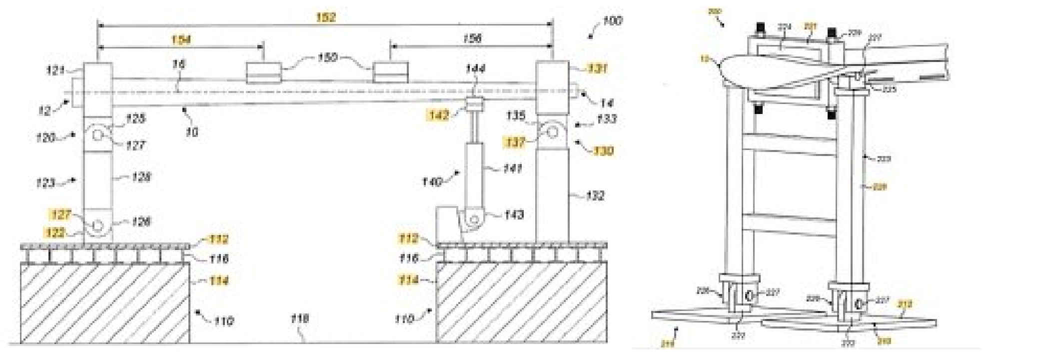


Figure 40: Solution for testing wind turbine blade according to US2019094104A1

(Source: EPO, 2019)

In the text of the invention, the authors note that *"... Wind turbine blades are subjected to cyclical loading during use as a result of inertial loads and aerodynamic loads, such as lift and drag. These loads are experienced in both the edgewise and flapwise directions of the blade. Such cyclical loading may cause weakening of the blades over* *the duration of their service life, potentially eventually leading to fatigue failure in the absence of appropriate design. Fatigue testing is used to determine whether a particular blade design can withstand the expected cyclical operating loads without fatigue failure for the duration of the desired service life of the blade."* (EPO, 2019:10).

The main advantages of the invention, according to the authors, are as follows: *"The present invention has particular benefit for fatigue testing of wind turbine blade sections or wind turbine blade subcomponents, as opposed to entire wind turbine blades. At start-up, the cyclical deflection force generated by the actuator 140 is steadily increased from zero until it reaches its operating frequency at a resonance frequency of the blade specimen 10, at which it remains for the duration of the test. By exciting the blade specimen 10 at a resonance frequency the energy requirements of the apparatus 100 are lower than for forced vibration testing apparatuses. It also means that the mean and peak loading on the first and second supports 120, 130 during the test are lower."* (EPO, 2019:5)

Other methods for diagnosing the state of wind turbines

A noticeable number of inventions during 2010-2019 were devoted to methods and devices for the study or analysis of materials by determining their chemical or physical properties (IPC subclass G01N). A total of 88 patent applications were identified for this area. Most of them were focused on investigating the presence of flaws, defects or contamination. The most productive applicants here were the German Wobben Properties GmbH, as well as the American General Electric and Digital Wind Systems Inc.

Several patent applications (16 in total) were related to the measurement of forces, stress and torque (IPC subclass G01L, measuring force or stress). Here the apparatus for, or methods of, measuring force, work, mechanical power, or torque, specially adapted for specific purposes, measuring force or stress using resistance strain gauges and measuring torque, work, mechanical power, or mechanical efficiency were mentioned more often than others. Imo Holding GmbH has the largest number of patent applications on these topics.

32 patent applications contained IPC subclass G01N - measuring electric or magnetic variables. The inventors paid attention mainly to the following issues - testing dynamo-electric machines, AC power supplies and testing of circuit interrupters, switches or circuit-breakers. The German Repower System AG was the most active here.

5.6 Other prevalent areas of inventive activity related to maintenance, repair & replacement

The regulated format of this Master Thesis does not consent to consider in detail all possible groupings of patent applications related to *Maintenance, repair & replacement*, therefore, this part provides brief statistical information about them.

- One of these groupings refers to various ***lifting mechanisms*** used in the construction of wind turbines or when replacing their individual elements (cranes, winches). This is one of the most popular topics, with at least 673 patent applications assigned the IPC index of the same name B66C. Most inventions consider the use of special cranes or other lifting mechanisms for the installation of large-sized elements on wind turbines - blades, nacelles, generators and gearboxes. Mostly these are special-purpose cranes, the main element of which is a beam, jib or triangular structure acting as a cantilever (Cranes comprising essentially a beam, boom or triangular structure acting as a cantilever specially adapted for use in particular locations or for particular purposes). The annual peak for patent applications of this group fell in 2015, then there is a quantitative stabilization at an average of 70 patent applications per year. The leaders in the number of inventions are residents of Germany and Denmark (together - 60% of applications), in particular the German Wobben Properties GmbH, Siemens AG, Areva Wind GmbH and the Danish Vestas Wind Systems A/S. In almost 90% of cases, the main problem to be solved by technical solutions in these inventions was High OPEX/Repair and replacement, as well as the adjacent High CAPEX / Plant construction.
- About one hundred patent applications during 2010 - 2019 were devoted to the improvement of existing or development of new designs of ***working platforms*** for repair or diagnostic work. Due to the fact that the existing IPC indexes do not reflect this topic, the selection of patent documents was carried out by keywords[8] within the database related to *Maintenance, repair & replacement*. A total of 94 patent applications were selected. The most productive applicants here were Areva Wind GmbH, Wobben Properties GmbH, Vestas Wind Systems A/S, Siemens Gamesa Renewable Energy A/S, General Electric Company, Nordex Energy GmbH, Senvion S.A., Envision Energy, Helicopters and others. The main technological interests of the inventors were concentrated in such areas as the

[8] WORKING GALLERY, WORKING PLATFORM, PORTABLE TERMINAL, HANDY TERMINAL, ACCESS PANEL, SERVICE FLOOR, HELICOPTER PLATFORM, HELIPLATFORM

creation of multifunctional or modular platforms (Multifunctional Platform, Modular Servicing Platform), effective methods of fastening or installing repair platforms on the elements of a wind turbine, special helipads, working platforms on offshore wind turbines.

- In recent years, inventors have increased their interest in creating new technical solutions related to ***bearing or lubricating arrangements*** (IPC index F03D80/70). Here most of patent applications were submitted by residents of the United States and China. Specifically, the leading applicants were the American General Electric, the Japanese Hitachi, Ltd. and Danish Siemens Gamesa Renewable Energy A/S. The main problems that were solved in the inventions are High OPEX/Operational maintenance and Repair and replacement.
- Another topic of undoubted interest in connection with the expansion of the geography of the spread of wind energy is related to the ***detection of ice*** and the elimination of icing of parts of wind turbines and, above all, of the blades (IPC index F03D80/40). In total, about 100 patent applications were identified, mostly in the last four years. Most of inventors originated from Germany and Denmark, which accounted for almost 70% of patent applications. Moreover, almost half of them were registered with the national patent offices of China and Canada. Among the leading applicants, as most often were previously presented - Wobben Properties GmbH and Vestas Wind Systems A/S, as well as Siemens Gamesa Renewable Energy A/S and Senvion S.A. The main problems that the inventors tried to solve in their patent applications were Low efficiency caused by secondary natural factors and High OPEX/Operational maintenance and Repair and replacement.

6. Conclusions

This chapter contains a summary of the results gained, but also answers the research questions of the current state of techniques for wind turbines maintenance and the latest development trends based on patent analysis. Suggestions for further studies and recommendations are also presented.

In this thesis a patent analysis methodology, developed by AENERT was assessed. The main goal of this methodology was to evaluate more thoroughly the wind energy patents by determining the development trends, characteristics of leaders in area of *Maintenance, repair and replacement*, evaluation of cooperative and technological relations between participants and monitoring of quantitative patent statistics for all constituents of technological processes.

The analysis of the statistical indicators of the development of wind energy and the analysis of patent applications in area of *Maintenance, repair and replacement* allows to draw the following conclusions:

1. Wind energy is a rapidly developing area of modern energy, which plays an increasingly important role in the global energy supply. As of the end of 2019, the volume of installed wind turbine capacity in the world exceeded 600 GW, and electricity generation amounted to 1270 TWh at the end of 2018, i.e. about 5% of the global electricity generation (Global Wind Energy Council, 2020);
2. It is assumed that by 2050 the share of wind energy in global production will reach 36%, or almost 15000 TWh (IRENA, 2019a);
3. To ensure further large-scale developments in this area, it is crucial to solve a number of serious technological and organizational problems. One of such problems is the relatively low capacity factor, which in real practice of wind turbines rarely exceeds 30%. As a result, material-intensive and expensive structures of wind turbines stand idle for a considerable time without generating electricity, reducing the investment attractiveness of the industry, preventing a decrease in selling prices for electricity and limiting the competitiveness of this industry;
4. Currently, the main paths to solve the problem of increasing the capacity factor are - improving site selection for wind farms, based on improved wind data and site-specific measurement, scaling of wind turbines and automation of wind turbine control;
5. There is a large group of subjective factors that impede the extraction of the maximum possible capacity factor. These include, for example, ineffective

equipment condition monitoring, especially remote monitoring, poor-quality technical overhauling, untimely delivery of component parts, suboptimal organization of transportation or repair work, lack of high-performance tools for maintenance, which leads to unexpected shutdowns of wind turbines. The solution to these problems can provide additional reserves for the use of power and represents the most promising way to improve the efficiency of the wind energy industry in general.

6. A significant amount of information on modern highly efficient methods of *Maintenance, repair and replacement* in wind energy is provided by patent information;
7. Over the past decade, from 2010 to 2019, there has generally been a steady upward trend in the number of newly registered patent applications related to *Maintenance, repair and replacement*. Among the national patent offices, the largest volume of patent applications was filed with CNIPA (China), the European office of the EPO and the US office of the USPTO. More than 55% of global patent applications were published at these offices during this mentioned decade.
8. The most productive applicants during this period were residents of Germany (over 30% of applications), Denmark (about 20%), China (about 15%) and the United States (over 10%). Among individual applicants, the highest patent activity in terms of the number of published patent applications was demonstrated by the German Wobben Properties GmbH, Siemens AG, Danish Vestas Wind Systems A / S, American General Electric, Japanese Mitsubishi Heavy Industries, Ltd.
9. According to the analysis in this thesis, inventors paid the greatest attention to the following technological aspects of *Maintenance, repair and replacement*:
   - Assembly of blades (the most popular topic, found in every fourth document, tremendous growth in the number of patent applications in recent years);
   - Transport of blades (moderate growth);
   - Offshore wind turbines, including special vessels for transporting parts, methods and devices for assembling products (a fairly popular topic, found in about every fifth document, a steady growing trend);
   - Testing static or dynamic balance of machines or structures (steady growth);
   - Measuring electric or magnetic variables (small amount of patenting);
   - Investigating the presence of flaws, defects or contamination (moderate nature of patenting);
   - Hoisting mechanisms, including cranes (serious interest in the topic, a slight decrease in the volume of patenting after a peak in 2015);

- Construction of working platforms for repair or diagnostic work (sustainable patent activity);
- Bearing or lubricating arrangements (tremendous growth in the number of patent applications in recent years);
- Ice detection, de-icing means (tremendous growth in the number of patent applications in recent years);
- Automatic manipulators or robots (cyclical nature of patenting).

For all these technical operations, the main statistical indicators were determined, and the most noticeable patent applications and their combinations were identified by the value of the calculated patent rating, by the size of the formed patent families or groups with identical individual unified indicators.

10. There are reasonable grounds to believe that in the coming years, *Maintenance, repair and replacement* patent activity will be largely dominated by applications related to: Assembly of blades, offshore wind turbines, automatic manipulators or robots, testing static or dynamic balance of machines or structures, investigating the presence of flaws, defects or contamination, structures of working platforms for carrying out repair or diagnostic work.

11. The data obtained can help to identify further the most vulnerable technical operations in the general list of operations related to *Maintenance, repair and replacement*. This can further determine the boundaries of the technical capabilities of the proposed options for technical solutions, to get closer to understanding the prospects for their practical development and effective influence on the problem of extracting the maximum possible capacity factor.

The goal of this thesis was to apply the targeted methodology and create a systematic review of recent patent documents published from 2010 to 2019 and dedicated to the maintenance, repair, replacement of parts of industrial wind turbines with a horizontal axis of rotation. The assessment of wind energy patents leads to the conclusion that application of such patent methodology is an adequate solution, especially for young inventors, managers of moderate-size companies who lack experience in understanding sophisticated patent texts or interpreting analytical findings. Such methodology does not handle only bibliographical data of patents and applications, however, rather facilitates the development of lists of unified technical and subject-related indicators for patent documents, by combining multiple phraseological semantic variants from patent document texts into unambiguous, understandable and easily recognizable items. In addition, through a novel configuration between patent document combinations and their unified indicators and conventional bibliographical data, it allows detailed analytical conclusions with regard to, inter alia, individual inventions, and new useful types of batch patent document lists to be composed.

Based on this methodology and the outcome of patent assessment, results of high added value are generated for the targeted stakeholders.

The challenge, however, is that it is probably not possible to conduct a complete patent assessment, due to the continuous growth in number of patents, expansion of their geographical diversity and the ever-growing mutual penetration of various technical disciplines during the development of new inventions. Such factors indeed cause substantial difficulties for proper and timely acquisition of essential patent information.

Therefore, it is important to further follow patent data development through the foundation of Global Dossier, which is an important attempt of systematisation and towards the achievement of harmony between the suppliers and the consumers of patent data. However still, this does not result in the reliable data and precise assessment. There is a need for further modernization of patent classification methods and increase the volume of patent documents from national patent offices provided with high quality translation into the English language.

BIBLIOGRAPHY

Accenture (2017): *The future of onshore wind operations and maintenance*. Editors: Stark M., Narich C.

AENERT (2020): *Map of wind database.* http://aenert.com/technologies/renewable-energy/wind-energy/map-of-wind-database/ - retrieved on 2020-11-08

AENERT (2020): *Patent Analysis Methodology.* https://aenert.com/research-analysis/methodology/ - retrieved on 2020-12-06

AENERT, interview no.1 (2020): *Interview no. 1 "Patent document processing methodology" with AENERT,* 2020-12-06

AENERT, interview no.2 (2020): *Interview no. 2 "Unified indicators for the analysis of patent documents" with AENERT*, 2020-12-13

AENERT, interview no.3 (2020): *Interview no. 3 "Rating evaluation of patent documents" with AENERT*, 2020-12-19

Archer C.L., and Jacobson M.Z. (2005): Evaluation of global wind power. In: *Journal of Geophysical Research 110 (D12110)*, pp. 1-20

Barnard M. (2014): *Vertical Axis Wind Turbines: Great In 1890, Also-rans In 2014*. Clean Technica. https://cleantechnica.com/2014/04/07/vertical-axis-wind-turbines-great-1890-also-rans-2014/ - retrieved on 2020-10-18

Black & Veatch (2012): *Cost and Performance Data for Power Generation Technologies.* https://refman.energytransitionmodel.com/publications/1921 - retrieved on 2020-12-27

Burton T., Bossanyi E., Jenkins N., Sharpe D. (2001): *Wind Energy Handbook.* John Wiley and Sons, Chichester

Canadian Intellectual Property Office (2016): *CA2956875A1 - Method for installing a rotor blade on a wind turbine*

COVID-19 Wind Industry Report (2020): *COVID-19 Wind Industry Report*. OnyX Insight. https://onyxinsight.com/covid-19-wind-industry-report/?utm_source=Referral&utm _medium=press%20release&utm_campaign=C19%20report#download - retrieved on 2020-11-15

Cleveland C., and Ayres R. (2004): *Encyclopedia of Energy, Volume 6*. Elsevier Academic Press

Danish Wind Industry Association (2003): *The Wind Turbine Yaw Mechanism*

ECN (2014): *O&M Cost Reduction of Offshore Wind Farms - A Novel Case Study*. Editors: Asgarpour M., van de Pieterman R., Petten

ETIPWind (2020): *ETIPWind Roadmap Operations & maintenance.* ETIPWind Executive Committee

European Patent Office (2013): *EP2870354B1 - Monitored component connection, wind power system, method for monitoring a component connection for inadvertent loosening of the component connection in the connected state*

European Patent Office (2016): *EP3088735A1 - Method and arrangement to transport a tower of a wind turbine on a vessel*

European Patent Office (2017*): EP3211217A1 - Method and device for mounting a rotor of a wind energy system*

European Patent Office (2019): *US2019094104A1 - Fatigue testing of a wind turbine blade*

European Patent Office (2020): *Simple patent family*. https://www.epo.org/searching-for-patents/helpful-resources/first-time-here/patent-families/docdb.html - retrieved on 2020-10-03

European Wind Energy Association (2009): *The Economics of Wind Energy*. Editor: Søren Krohn, Brussels

Five IP Offices (2019): *Key IP5 statistical indicators 2019.* https://www.fiveipoffices.org/statistics - retrieved on 2020-11-21

Fraunhofer ISE (2018): *Levelized Cost of Electricity – Renewable Energy Technologies* https://www.ise.fraunhofer.de/en/research-projects/stromgestehungskosten-erneuerbare-energien.html - retrieved on 2020-12-27

GE Renewable Energy (2018): *GE announces Haliade-X, the world's most powerful offshore wind turbine.* https://www.ge.com/news/press-releases/ge-announces-haliade-x-worlds-most-powerful-offshore-wind-turbine - retrieved on 2020-11-01

Global Data (2016): *Global Wind Operations and Maintenance Market Review.* https://store.globaldata.com/report/gdae0257vpt--global-wind-operations-and-maintenance-market-review/ - retrieved on 2020-11-15

Global Dossier (2011): *WO2011124574 - Transport vehicle for rotor blades and/or tower segments of wind power plants and transport rack for a transport vehicle*

Global Dossier (2012): *WO2012163918A1 - Wind turbine rotor blade and method for installing a wind turbine rotor blade*

Global Dossier (2018): *WO2019001660 - Handling a wind turbine blade using an airship*

Global Wind Atlas (2020): *Global Wind Atlas - Key Features.* https://globalwindatlas.info/about/KeyFeatures - retrieved on 2020-11-07

Global Wind Energy Council (2016): *Global Wind Energy Outlook - 2016*. Editors: Fried. L, Shuklas S., Sawyer S., Teske S., Brussels

Global Wind Energy Council (2020): *Global Wind Report - 2019*. Lead Authors: Lee J., Zhao F., Brussels

Herreshoff H.C. (2001): *Het handboek voor de zeiler*. Konemann

Huang W., Liu X., Gill E. (2017): Ocean Wind and Wave Measurements Using X-Band Marine Radar: A Comprehensive Review. In: *Remote Sensing 2017, 9 (1261)*, pp. 1-39

IRENA (2019): *Future of Wind - Deployment, investment, technology, grid integration and socio-economic aspects*. Editor: Mastny L., Abu Dhabi

IRENA (2019): *Global energy transformation: A roadmap to 2050*. Editor: Carey J., and Mastny L., Abu Dhabi

IRENA (2019): *Renewable Power Generation Costs in 2018*. Editor: Govett. J, Abu Dhabi

IRENA (2020): *Renewable energy statistics 2020*. Prepared by: Whiteman A., Rueda S., Akande D., Elhassan N., Escamilla G. and Arkhipova I., Abu Dhabi

Khare V., Khare C., Nema S. (2019): *Tidal Energy Systems. Design, Optimization and Control.* 1st ed., Elsevier

Letcher T. (2017): *Wind Energy Engineering - A Handbook for Onshore and Offshore Wind Turbines*. 1st ed., Academic Press

Makinwa, K.A.A., J.H. Huijsing and A. Hagedoorn (2001): Industrial design of a solid-state wind sensor. In: *Sensors for Industry Conference. Proceedings of the First ISA/IEEE. Cat. No.01EX459*, Rosemont, IL, USA, 2001, pp. 68-71

Oxford Dictionary of National Biography (2004): *James Blyth*

Royal Meteorological Society (2018): *The Beaufort Scale*. https://www.rmets.org/resource/beaufort-scale - retrieved on 2020-11-20

Shankleman J., Parkin B., and Hirtenstein A. (2017): *Gigantic Wind Turbines Signal Era of Subsidy-Free Green Power*. BloombergNEF. https://about.bnef.com/blog/gigantic-wind-turbines-signal-era-of-subsidy-free-green-power/ - retrieved on 2020-11-09

Siemens Gamesa - Offshore turbines (2020): *SWT-6.0-154 - Offshore wind turbine.* https://www.siemensgamesa.com/en-int/products-and-services/offshore/wind-turbine-swt-6-0-154 - retrieved on 2020-11-01

Simley E., Pao L. (2013): *LIDAR Wind Speed Measurements of Evolving Wind Fields*, NREL Technical Monitor: Alan Wright, University of Colorado

Swedish Wind Power Technology Centre (2019): *Triblade rotor blades preliminary study*. Chalmers University. https://www.chalmers.se/en/centres/SWPTC/Pages/default.aspx - retrieved on 2020-09-05

U.S. Energy Information Administration (2020): *Annual Energy Outlook 2020 with projection to 2050,* Office of Energy Analysis, Washington

U.S. Energy Information Administration (2020): *Capacity Factors*. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b - retrieved on 2021-01-05

U.S. Energy Information Administration (2021): *Cost and Performance Characteristics of New Generating Technologies*, *Annual Energy Outlook 2020,* Office of Electricity, Coal, Nuclear and Renewables Analysis, Washington

U.S. Energy Information Administration (2021): *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2020,* Office of Energy Analysis, Washington

UK - Renewables Advisory Board (2010): *Value breakdown for the offshore wind sector.* https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/48171/2806-value-breakdown-offshore-wind-sector.pdf - retrieved on 2020-12-27

US Patent and Trademark Office (2014): *US9212651B2 - Bolt tightening robot for wind turbines with the root number*

US Patent and Trademark Office (2015): *US20150267688A1 - Robot for inspecting rotor blades of wind energy installations*

US Patent and Trademark Office (2016): *US20160068373A1 - Weather maintenance system for an offshore wind turbine maintenance program, core document*

US Patent and Trademark Office (2020): *Who comprises Global Dossier?* https://www.uspto.gov/patents-getting-started/international-protection/global-dossier-initiative - retrieved on 2020-12-20

WindEurope (2017): *Wind energy in Europe, Scenarios for 2030*. Editor: Pierre Tardieu, Brussels

WIPO (2012): *EP2436593A1 - Ship and method for transporting and setting up offshore structures*

WIPO (2019): *World Intellectual Property Indicators: Filings for Patents, Trademarks, Industrial Designs Reach Record Heights in 2018*. https://www.wipo.int/pressroom/ en/articles/2019/article_0012.html - retrieved on 2020-11-15

WIPO (2020): *US20190024639A1 - System and method for removing or installing rotor blade hardware of a wind turbine*

World Meteoroligical Organization (2018): *WMO Guide to Meteorological Instruments and Methods of Observation (WMO-No. 8, the CIMO Guide).* https://www.wmo.int/pages/prog/www/IMOP/CIMO-Guide.html - retrieved on 2020-10-24

List of abbreviations and symbols

Abbreviation	Explanation
AENERT	Advanced Energy Technologies
CNIPA	China National Intellectual Property Administration
CAPEX	Capital Expenditure
CIPO	Canadian Intellectual Property Office
CPC	Cooperative Patent Classification
DPMA	Deutsches Patent- und Markenamt
EIA	U.S. Energy Information Administration
EPO	European Patent Office
GIS	Geographic information system
GWEC	Global Wind Energy Council
HAWT	Turbines with a horizontal axis
IEA	International Energy Agency
INPI	National Institute of Industrial Property
IP	IP Australia
IPC	International Patent Classification
IRENA	The International Renewable Energy Agency
JPO	Japan Patent Office
KIPO	Korean Intellectual Property Office
LCOE	Levelized Cost of Energy
MRR	Maintenance, repair and replacement
NCEI	National Centers for Environmental Information
NEMS	National Energy Modeling System
NREL	National Renewable Energy Laboratory
O&M	Operations and Maintenance
OPEX	Operational Expenditure
VAWT	Turbines with a vertical axis
USPTO	United States Patent and Trademark Office
WIPO	World Intellectual Property Organization
WMO	World Meteorological Organization

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APPENDICES

APPENDIX 1

Wind Resources by Class and Country At 50m

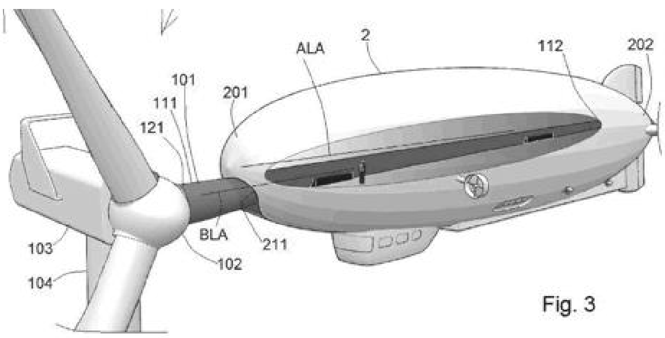
(Source: National Renewable Energy Laboratory: https://openei.org/doe-opendata/dataset/wind-resources-by-class-and-country-at-50m, accessed 2020-11-20)

Country	Total Resource Area (km^2) at 50m, Classes 3-7	Rank	Resource Area (km^2) at 50m, Class 3	Resource Area (km^2) at 50m, Class 4	Resource Area (km^2) at 50m, Class 5	Resource Area(km^2) at 50m, Classes 6&7
Brazil	3225342	1	1 225 289	754 534	517 807	727 712
Canada	2712417	2	1 357 662	635 789	294 430	424 536
United States	2237436	3	1 215 534	644 207	192 476	185 218
Russia	1152810	4	740 568	331 982	77 476	2 784
Peru	671212	5	79 164	143 342	142 913	305 793
China	650882	6	366 922	167 383	66 893	49 684
Argentina	418022	7	142 223	173 992	89 152	12 655
Australia	417658	8	339 143	78 515	0	0
Ecuador	229084	9	35 678	43 593	62 212	87 601
Norway	211749	10	29 864	42 850	116 142	22 894
Mongolia	160906	11	130 881	20 802	6 406	2 816
Greenland	151028	12	146 771	4 257	0	0
United Kingdom	146936	13	32 208	34 405	56 567	23 755
Chile	134210	14	61 670	42 732	19 103	10 704
Sweden	127205	15	37 202	39 863	40 226	9 914
Afghanistan	75619	16	44 008	15 193	6 633	9 785
Pakistan	69226	17	42 864	18 106	5 218	3 038
Iceland	60199	18	29 969	14 184	15 467	580
Colombia	57995	19	17 360	12 075	25 393	3 168
Svalbard	40162	20	1 834	11 077	23 312	3 939
Mexico	38688	21	24 003	6 815	3 184	4 685
Denmark	38464	22	7 604	11 717	12 678	6 465
France	26678	23	9 862	16 815	0	0
Bolivia	26611	24	20 736	5 875	0	0
Ireland	26253	25	12 945	3 998	6 720	2 590

APPENDIX 2

Patent overview - Handling a wind turbine blade using an airship

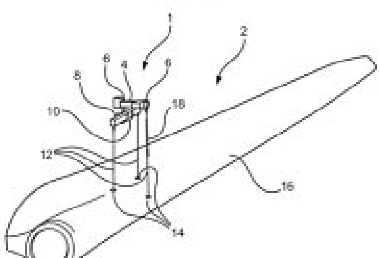
(Source: Global Dossier, 2018)

Patent parameters	Patent details
Title	**HANDLING A WIND TURBINE BLADE USING AN AIRSHIP**
Publication Number	WO2019001660
IPC	F03D13/20, F03D13/10, F03D13/40, F03D80/50
Inventors	LARSEN, Gerner, J.B.K. JENSEN, Ivar PEDERSEN, Gunnar K. Storgaard BAUN
Applicant	VESTAS WIND SYSTEMS A/S
Publication Date	03.01.2019
Technology categories	HWT Horizontal axis wind turbine in general
Technology elements	MRR Maintenance, repair and replacement
Problems	HCC High CAPEX / Plant construction
Technical solution types	D: Device; M: Method
Claims	23
Rate	14
Abstract	*Method for handling a wind turbine blade using an airship (2), comprising arranging the blade (101) at least partly inside the airship (2)*  Fig. 3

APPENDIX 3

Patent overview - Method and device for mounting a rotor of a wind energy system

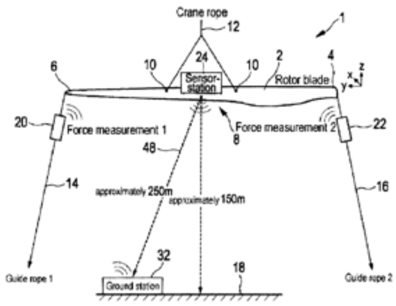
(Source: EPO, 2017)

Patent parameters	Patent details
Title	**METHOD AND DEVICE FOR MOUNTING A ROTOR OF A WIND ENERGY SYSTEM**
Publication Number	EP3211217A1 (core document WO2013050569A2)
IPC	B66C1/10, F03D1/00, F03D13/10
Inventors	EYER WOLFGANG, KUIPER GERRIT
Applicant	WOBBEN PROPERTIES GMBH
Publication Date	30.08.2017
Technology categories	HWT Horizontal axis wind turbine in general
Technology elements	EE Electrical equipment and generators, MRR
Problems	HCP High CAPEX / Equipment production
Technical solution types	D: Device; M: Method
Claims	15
Rate	12
Abstract	*The invention relates to a lifting beam (1) for lifting and handling a rotor blade (2) of a wind energy plant, comprising a fastening means (6) for fastening the lifting beam to a crane, at least one fastening means (12) for fastening the lifting beam to the rotor blade (2), a longitudinal pivoting means (18) for pivoting the rotor blade (2) which is supported by the lifting beam (1)* EP 3 211 217 A1  Fig. 2

APPENDIX 4

Patent overview - Method for installing a rotor blade on a wind turbine

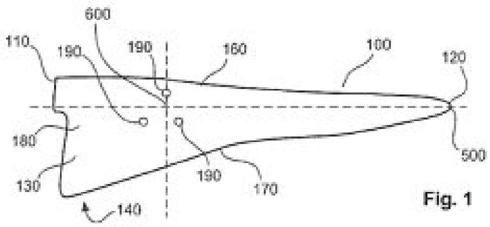
(Source: Canadian Intellectual Property Office, 2016)

Patent parameters	Patent details
Title	**METHOD FOR INSTALLING A ROTOR BLADE ON A WIND TURBINE**
Publication Number	CA2956875A1 Core document: US20170233228A1
IPC	F03D13/10, F03D13/40, B66C13/04, B66C13/46, B66C13/48
Inventors	CONERS Rolf, LAODA Fiona
Applicant	WOBBEN PROPERTIES GMBH
Publication Date	18.02.2016
Technology categories	HWT Horizontal axis wind turbine in general
Technology elements	MRR Maintenance, repair and replacement
Problems	ESI Environmental and social impact HCC High CAPEX / Plant construction
Technical solution types	D: Device; M: Method
Claims	17
Rate	13
Abstract	*The invention relates to a method of installing a rotor blade (2) on turbine, wherein the rotor blade comprises: a blade root (4) on a hub; a blade tip (6) facing away from the blade root; and a longitudinal axis running from the blade root to the blade tip.* 

APPENDIX 5

Patent overview - Method for installing a wind turbine rotor blade

(Source: Global Dossier, 2012)

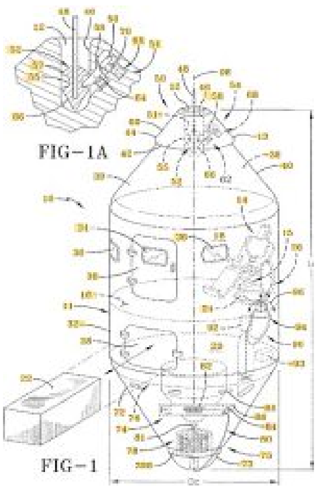
Patent parameters	Patent details
Title	**WIND TURBINE ROTOR BLADE AND METHOD FOR INSTALLING A WIND TURBINE ROTOR BLADE**
Publication Number	US9759074B2 Core document: WO2012163918A1
IPC	F01D5/30, F03D13/10
Inventors	Hoffmann Alexander
Applicant	WOBBEN PROPERTIES GMBH
Publication Date	06.12.2012
Technology categories	HWT Horizontal axis wind turbine in general
Technology elements	MRR Maintenance, repair and replacement
Problems	HCC High CAPEX / Plant construction HOR High OPEX / Repair and replacement
Technical solution types	D: Device; M: Method
Claims	12
Rate	18
Abstract	*The invention relates to a wind turbine rotor blade (100), comprising a rotor blade root (110), a rotor blade tip (120), a rotor blade front edge (160), a rotor blade rear edge (170), a pressure side (140), and a suction side (130). The rotor blade (100) further comprises a rotor blade outer shell (180) having at least one opening (190) in the pressure side and/or the suction side for accommodating handling means (200) for installing or removing the rotor blade (100).*  Fig. 1

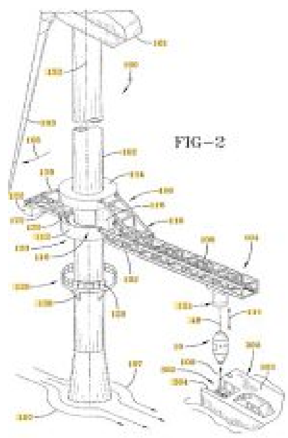
APPENDIX 6

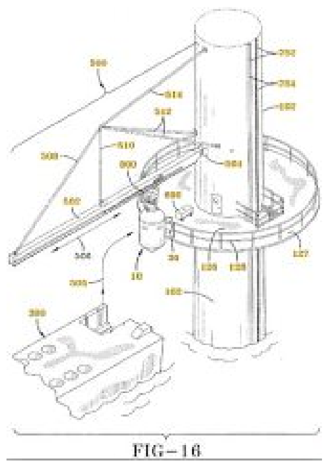
Patent overview - Weather maintenance system for an offshore wind turbine maintenance program

(Source: USPTO, 2016)

Transportation solution of personnel with a working tool from the ship to the offshore wind turbine and back, according to US20160068373A1







In a very brief summary, the essence of the invention is as follows:

- *An all-weather system for an offshore wind turbine maintenance program includes a vertical tower (102)*
- *A wind turbine mounted on the tower and a nacelle (550), an access platform (126), a vertical track system (720) and a cargo elevator assembly having a cable (724) and a device (733) raising and lowering the cable*
- *The maintenance system comprising a cargo elevator (700) for receiving a tool and / or parts storage box (600) for delivery to or reception from the nacelle*
- *The cargo elevator comprising a cable attachment structure (709) for securing the cargo elevator to the cable*

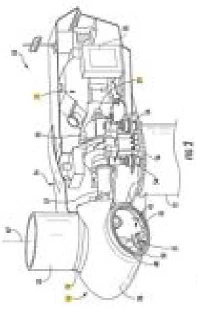
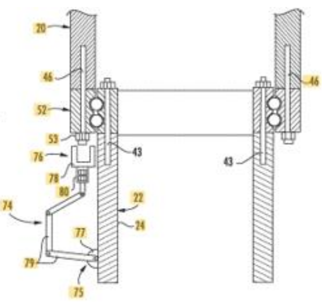
Some details of the invention are presented in the figures from the patent application:

- *Fig. 1 is a perspective, partially cut-away, schematic view of a maintenance capsule according to a preferred embodiment of the invention*
- *Fig. 2 is a partial, schematic, perspective view of a preferred embodiment of a crane assembly which is shown on a portion of a wind turbine tower apparatus transporting a maintenance capsule to or from a maintenance vessel, according to a preferred embodiment of the invention. Fig. 16 is a schematic, perspective view of the lower portion of a turbine tower incorporating aspects of the preferred embodiment of the invention showing a maintenance vessel transferring a maintenance capsule to the turbine tower and for lifting a wheeled equipment box up the tower.*
-

APPENDIX 7

Patent overview - System and method for removing or installing rotor blade hardware of a wind turbine

(Source: WIPO, 2020)

Patent parameters	Patent details
Title	**SYSTEM AND METHOD FOR REMOVING OR INSTALLING ROTOR BLADE HARDWARE OF A WIND TURBINE**
Publication Number	US20190024639A1
IPC	F03D80 / 50, F03D13 / 10, F03D1 / 06, B25J11 / 00, B25J15 / 15 00
Inventors	Davidson Paul Howard, Willman Stephanie Lohberg, Murcia Santiago, Klinghagen Joshua Adam, Thomas Gregory Clarence, Johnson Michael Royce, Johnson Don Conrad, Neumann Ulrich Werner, Davis Adam Sean, Roney Dean Thomas, Bentzel Kathleen Lynne
Applicant	General Electric Company
Publication Date	24.01.2019
Technology categories	HWT Horizontal axis wind turbine in general
Technology elements	MRR Maintenance, repair and replacement
Problems	HOR High OPEX / Repair and replacement
Technical solution types	D: Device; M: Method
Claims	20
Rate	15
Abstract	*The rotor (18) includes a rotatable hub (20) and at least one rotor blade (22) coupled to and extending outwardly from the hub (20).* *Rach root attachment assembly (42) may include a barrel nut (44) mounted within a portion of the blade root (24) and a hub bolt (46) coupled to and extending from the barrel nut (44) so as to project outwardly from a root end (48) of the blade root (24).* *More specifically, the uptower location may include the blade root (24) of the rotor blade (22), the hub (20), the pitch bearing (52), an external support structure mounted uptower, or any other suitable uptower structure. Further, as shown, the mechanical arm (74) includes a torqueing tool (78) at a distal end (76) thereof.* *Thus, the torqueing tool (78) is configured to locate each of the hub bolts (46) via the mechanical arm (74) and torque each of the hub bolts, nuts, washers, and similar so as to loosen the rotor blade from the hub.*   

APPENDIX 8

Patent overview - Monitored component connection, wind power system, method for monitoring a component connection for inadvertent loosening of the component connection in the connected state

(Source: EPO, 2013)

Patent parameters	Patent details
Title	Monitored component connection, wind power system, method for monitoring a component connection for inadvertent loosening of the component connection in the connected state
Publication Number	US20150159633A1/ EP2870354B1
IPC	F03D11/00, G01M13/00
Inventors	Jepsen Torsten, Kelling Ralf
Applicant	Wobben Properties GmbH
Publication Date	11.06.2015
Technology categories	HWT Horizontal axis wind turbine in general
Technology elements	MRR Maintenance, repair and replacement R Rotors and components thereof
Problems	HOR High OPEX / Repair and replacement
Technical solution types	D: Device; M: Method
Claims	26
Rate	12