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INNTERESTING

Deliverable 1.1: Technical, environmental and social requirements of the future wind turbines and lifetime extension

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[1] PU = Public
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DoA	In this task the technical, environmental and social requirements of the future wind turbines, and more precisely for bearings and gearboxes for large wind turbines will be defined. The requirements will be focused more deeply on pitch bearings and gearbox. The specifications will be technical (lifetime, structural integrity, environmental conditions, etc.), environmental performance, protection and footprint, economic issues, and social issues (effect on the population, public awareness on the topic, social acceptance). This task will also comprehend the analysis of the lifetime extension tendency of existing wind farms (mainly onshore). VITO, expert in social and environmental innovation, CSR and social impact assessment will carry out specific actions to foster social acceptance. Selected partners will be invited to join to the Stakeholders Working Group of the project. To become successful, a dialogue will be established at EU level, involving the relevant transnational organisations. A co-creation meeting with	

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		identified stakeholders will be carried out to include social requirements since the beginning of the project. This activity is completely linked with WP6 and WP7.	
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Abbreviations and Acronyms

Acronym	Description
AWE	Airborne wind energy
BAU	Business-as-usual
CAGR	Compound Annual Growth Rate
CAPEX	Capital expenditure
CS	Case Study
CSP	Combined Solar Power
DLC	Design load case
DOF	Degree of freedom
DTU	Technical University of Denmark
EMI	Electromagnetic interference
EU	European Union
IEA Wind TCP	International Energy Agency Wind Technology Collaboration Programme
IEC	International Electrotechnical Commission
IRENA	International Renewable Energy Agency
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCOE	Levelized Cost Of Energy
NGO	Non-governmental organisation
NREL	National Renewable Energy Laboratory (United States)
NIMBY	Not in my backyard
NORCOWE	Norwegian Centre for Offshore Wind Energy
OEM	Original Equipment Manufacturer
O&M	Operation and Maintenance
OPEX	Operational expenditure
PDP	Product Development Process
PMG	Permanent Magnet Generators
RSF	Ring Structural Failure
RWT	Reference Wind Turbine
PV	photovoltaics

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S-LCA	Social LCA
TRL	Technology Readiness Levels
VAWT	Vertical Axis Wind Turbine
WHO	World Health Organization
WP	Work package
WT	Wind turbine
WTG	Wind turbine generator

0. Executive Summary

In this deliverable (D1.1., WP1 in the INNTERESTING project), the technical, environmental, and social requirements of the future wind turbines (2030-2050), and more precisely for pitch bearing and gearbox for large wind turbines are described. These are the selected components for the development and application of the tools and methodologies to be developed in the project. The data, trends and definitions of the case studies outlined in this document will serve as a basis for the tasks carried out later within the different WPs.

Installed capacity evolution forecast and wind turbine size evolution forecast

The predictions define a large increase in the implementation of the wind energy in the following decades, reaching values close to 2000 GW of installed power in 2030 and up to 6000 GW in 2050 worldwide. In order to reach these values, it is necessary to increase the nominal power size of the installed turbines and the size of the wind farms. In addition, turbine costs must be reduced, and their reliability increased, reducing maintenance actions and maximizing their efficiency.

In section 2.2 a study has been carried out on the trends in the size of turbines for the following years. During the last decade, the increment of the average size for offshore wind turbines has gone from close to 3 MW in 2010, 4 MW in 2015, to a value close to 7,2 MW in 2019. The expected values of turbine sizes in the coming years are not easy to predict, but after analysing the existing literature and latest news on upcoming projects published by manufacturers with the largest market share, a horizon of 10-12 MW has been defined as the average installed size for 2030 and 20 MW for the 2050. For onshore, the average size of installed turbines has gradually increased from 1.8 MW in 2010 to 3.1 MW in 2019. By 2030 the installed average size can be increased up to 5MW and by 2050 the size can be doubled (up to 10 MW). Surely the nominal power values of the most ambitious projects for years to come will be much higher than those defined as average sizes. Large wind turbine manufacturers are today competing in the race to design and manufacture more powerful turbines and the results will be visible in the not too distant future. Maximum wind turbine sizes close to 20 MW are expected by 2030.

Section 2.8 provides a summary of the most important aspects of the turbine at present and the forecast for 2030 and 2050 (adding expected average and maximum values).

Pitch bearing evolution and forecast

In section 2.3 the requirement for future pitch bearings are described. The need to increase the size of the turbines and blades results in the fact that the pitch bearing also has to adapt to more demanding requirements. Both, the static and dynamic capacity of this component will have to be increased, ensuring its reliability throughout its lifetime. The generation of new pitch bearing concepts are in continuous evolution, trying to solve the problems that arise when defining larger wind turbines. For bigger turbines the bearing diameter will change from the current diameters of 2 - 5 meters (for the latest installed prototypes these diameters will be close to 6 meters), to larger values. However, this evolution seems to progress towards an asymptote: for turbines greater than 20 MW no diameters greater than 8-9 meters are expected.

Gearbox evolution and forecast

In section 2.4 the requirements for future gearboxes are described. The wind turbine size limit has not yet been reached, but logistically, the size of the components is already critical. New developments should focus on limiting the size and weight of gearboxes. The total value of

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torque per weight ratio can be an important parameter for finding the best option. In the last three decades this value has increased from 50 Nm/kg to 100-125 Nm/kg. Even though gearbox sizes have increased when turbines have been growing, relative gearboxes sizes have gone smaller and torque density has increased. Although the values of torque density that exist on the market are below 130 Nm/kg (otherwise gearboxes are too heavy and too large for transportation), the requirements in the future will be higher, reaching values between 150 to 200 Nm/kg.

Lifetime extension

In section 2.7 the lifetime extension concept is studied. When the wind turbine achieves its design lifetime, asset managers and owner-operators face the end-of-life scenario with three main choices: decommission and return the site to previous use, repower the site with modern turbines or extend the life of the existing installed asset. The option of extending the lifetime is getting rapidly more attractive since relevant energy production is achieved for a relatively low investment, which reduces the LCOE and increases the project revenue. From 2020 to 2030, and knowing that the current European fleet has an average power of around 2.5 MW, it can be estimated that lifetime extension concepts will be potentially applicable to around 25-30 thousand turbines. This scenario is encouraging wind turbine manufacturers to develop tools and methods to make decisions on the life extension or/and decommissioning of wind turbines close to the end of their design lifetime.

Environmental requirements

The following environmental aspects of wind turbines are considered in section 3: wind turbine noise, impact on flora and fauna, visual impact, electromagnetic interference effects, land-use impacts, and shadow flickering. For future large wind turbines in general, the turbine size can have a positive impact on bird interaction, and a negative impact on the visual impact and electromagnetic interference. Regarding future gearboxes, reducing noise emissions is an important requirement that needs to be considered, not only from an environmental point of view, but also as one of the most significant factors affecting social acceptance of wind energy. In addition to the abovementioned aspects, environmental impacts based on Life Cycle Assessment (LCA) are briefly discussed based on found literature, as an LCA is part of the work done in work package 6 (WP6).

Social requirements

Section 4 gives an overview of the key messages from the literature review on social acceptance towards wind energy, including the definition and aspects of, and influences on social acceptance. Key messages found are that:

- The overall acceptance at society level needs to increase, rather than at the level of individual projects.
- There is a lack of comprehensive and systematic review to identify common findings and outstanding research questions. Significant insights are produced, yet knowledge gaps remain.

Based on the literature review, no major difference is to be expected for social acceptance of the host community of a wind energy project with or without the solutions developed within INNTERESTING. Research on the influence of wind farm lifetime on social acceptance is lacking. There may be small improvements due to less maintenance and thus less idle time which may lead to a stronger acceptance. Further research to learn more about the difference in social acceptance of wind farms with an extended lifetime versus repowering is needed, as reports have shown that repowering can be highly effective in improving the social acceptance

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of a wind farm. In addition, section 5 provides some examples of good practices resulting from projects and research on social acceptance, providing an overview of different tools developed and abstracts of identified relevant recent research articles related to social acceptance.

Stakeholders

A high-level identification and mapping of stakeholders is included in section 7.2.The process is developed considering relevant target groups in the wind energy value chain. Rationale for each target group to be involved in INNTERESTING is analysed, which helps to understand why they would be interested in being part of the Stakeholder Group and how they could contribute to better understanding future technical, environmental and social requirements.

Definition of INNTERESTING CS

Section 6 details the case studies (CS) selected in the INNTERESTING project for the development of tools and methodologies to be implemented in the components of a wind turbine. In recent years, various reference wind turbines (RWT) have been defined, which have served as the basis for many research works. One of the great advantages of using these RWTs is that their description and many of their analyses are available to the public, provided by the institutions and projects that have developed them. In this project, these turbines will be the basis for the development of the CSs as starting data, turbine descriptions, etc. are public and usable by any person concerned.

CS1

For the **new pitch bearing concept** to be used in future larger wind turbines by 2030-2050, the selected nominal power is 20 MW (which is the expected maximum size by 2030 and the average size for 2050 for offshore). The WT will be installed in the NORCOWE reference wind farm with a size of 2.04 GW and 102 turbines. The design lifetime requirement is 40 years and the required pitch bearing diameter is 7 m.

CS2

For the **next generation wind turbine main gearbox GBX concept,** including novel gearing and bearing systems to increase torque density and reliability in the future, the selected nominal power is 10 MW (it is the expected maximum size by 2030 and the average size for 2050 for onshore). The WT will be installed in Germany, in a farm size of 100MW and 10 turbines. The design lifetime requirement is 30 years.

CS3

For the **pitch bearing reparation and stiffening concept**, the selected WT nominal power is 3,4 MW and it will be installed during 2020 in Spain. Considering a target life of 20 years, the pitch-hub bearing assembly design has been designed so that a crack initiation would arise on the bolt hole surface in some pitch bearings during the 4th year of lifetime, thus making the bearing fail prematurely. In this case study two scenarios will be developed:

- Reparation of failed bearings in order to slow crack propagation down.
- Stiffening of serviceable bearings in order to delay crack initiation.

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1 INTRODUCTION

The INNTERESTING project aims to accelerate wind energy technology development and increase lifetime extension of wind turbine components. To this end, a novel hybrid methodology and breakthrough design tools will be developed to assess the reliability of critical components included in larger wind turbines. This will avoid the need for building larger test-benches in the future by overcoming size dependent issues during the design process and testing. These methodologies should be applied and addressed to the wind turbines of the future (2030-2050) and will be worthwhile in case studies that may represent emerging technologies. For this reason, in this first part of the project, a forecast of the requirements and new challenges for the wind energy of the future is defined.

In the first part of the document, market trends in the sector will be identified. These trends will mark the new cost targets, turbine sizes, durability requirements and emerging technologies that are forecasted. In the following points, the requirements related to the environmental and social part will be defined, which are crucial for the social acceptance of the new market trends. Within this work package and throughout the entire project, stakeholders will be identified, who will carry out an advisory and follow-up job throughout the entire development.

The INNTERESTING project pursues the validation of the developments through three different case studies (Figure 1) dealing with innovative pitch bearing concept (CS1), a new gearbox component design (CS2) and an innovative repairing solution for lifetime extension of existing pitch bearings (CS3). The future requirements for these case studies are collected in section 6 of this deliverable based on the projection of the dimensions and specifications that wind turbines will have in the future. This information will be essential for the subsequent detailed tasks of case studies and pre-dimensioning.

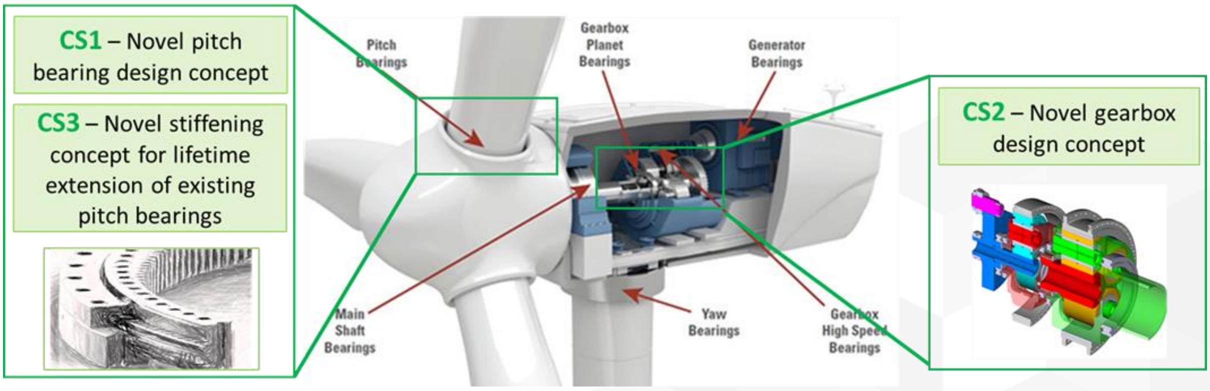

Figure 1: CS location on the wind turbine

In addition, another key objective of INNTERESTING is to greatly reduce environmental impact and improve social acceptance compared to current testing methodologies based on large scale component validation. Therefore section 6 of this document also includes requirements related to these two aspects for the case studies based on sections 6 and 4, which are crucial to evaluate the viability of the developments foreseen in this project

Within this work package and throughout the entire project, stakeholders are identified, who will carry out an advisory and follow-up job throughout the entire development. The final section

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of this document discusses the communication and relationship building actions that will be taken during the course of the INNTERESTING project.

In general, the information analysed as input for this document was obtained on three different main sources (Figure 2):

- the first is current data, predictions and publications about (the future of) wind energy
- the second is information of the partners of the consortium itself, especially those who work closest to the market
- final source, the results obtained during the first meeting with the project stakeholders.

Unfortunately, due to the health emergency of COVID19, the meeting with the stakeholders has been delayed to September 2020, so the inputs from that meeting will be included later as part of deliverable 7.3.

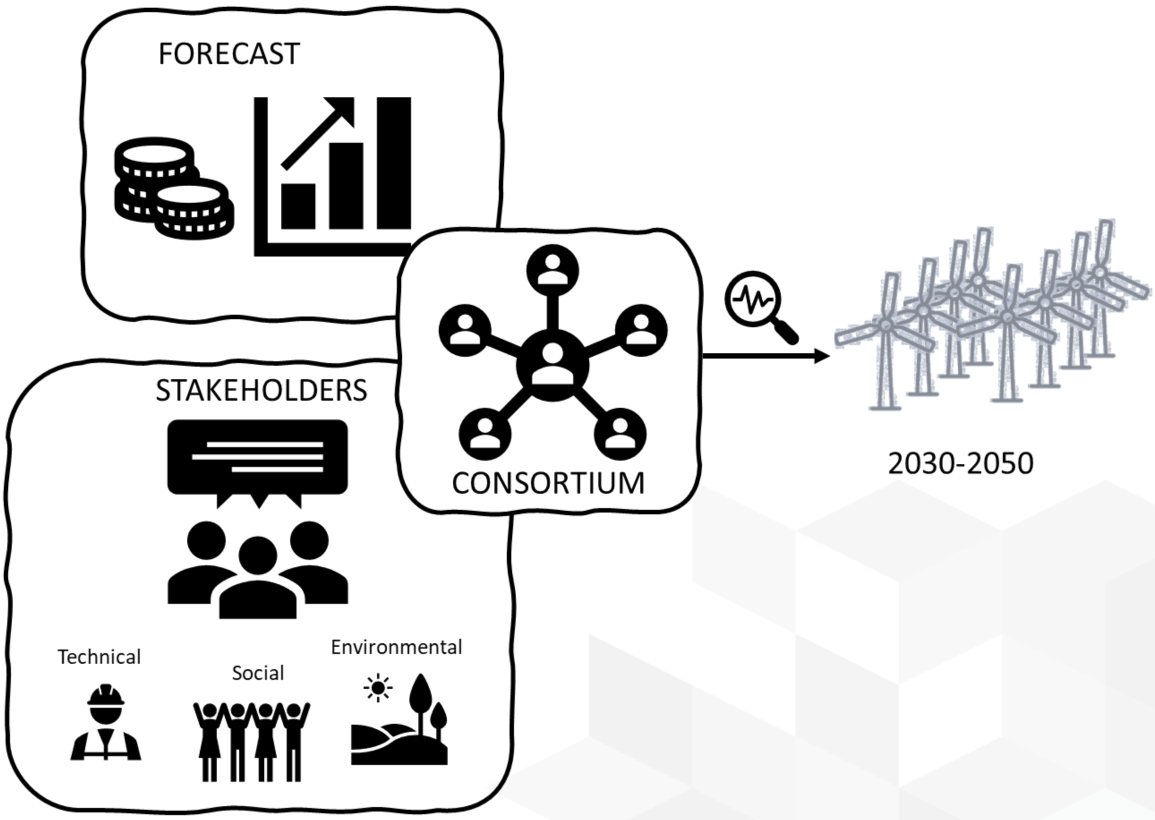

Figure 2: Information sources for the analysis (2030-2050)

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2 MARKET TREND ANALYSIS

This section details the market trends that have been identified for wind farms of the future. Each information source found gives an indicative value or range of prediction, therefore the sources are bundled in this section and the data have been evaluated as a whole. This chapter starts with the forecast of the evolution of energy consumption and the installed capacity by 2030-2050. Then, this evolution will be related to the expected increase in the size of wind turbines in the future. Consequently, the pitch bearing, and the gearbox will also increase in size and capacity, which will be discussed in the third and fourth subsection. The need to reach the installed capacity values will increase the lifetime requirements of wind farms. The evolutions on design lifetime requirements and lifetime extension will therefore also be discussed in this section, including an explanation of the current product development process. Finally, this section concludes with an overview of new technological concepts within the wind energy industry.

2.1 Energy consumption evolution and forecasts

In the last decades, energy consumption in the world has extremely increased. Additionally, in the last twenty years, renewable sources have become important (Figure 3) [2]. In the near future, renewable power capacity is set to expand by 50%, especially solar (60% of the expected growth) and onshore wind (25%).

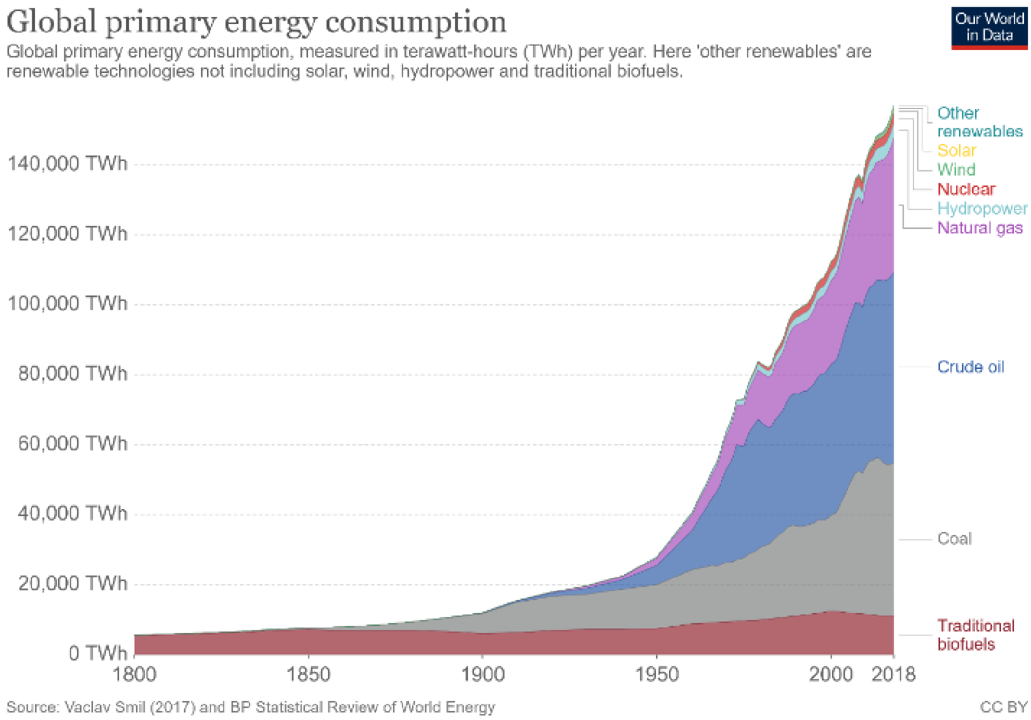

Figure 3. Global primary energy consumption[2].

Wind and solar energy will also lead the way in the transformation of the global electricity sector. Wind power would supply more than one-third of total electricity demand by 2050 and

[2] BP Statistical Review of Global Energy. June 2019

is well aligned with energy transformation scenarios defined by government policies, clearly highlighting the importance of scaling up the wind power generation share in order to decarbonise the energy system in the next three decades. In the context of total installed capacity by 2050, a larger capacity expansion would be needed for solar photovoltaics (8 519 GW) as compared to wind (6 044 GW) (Figure 4) [3].

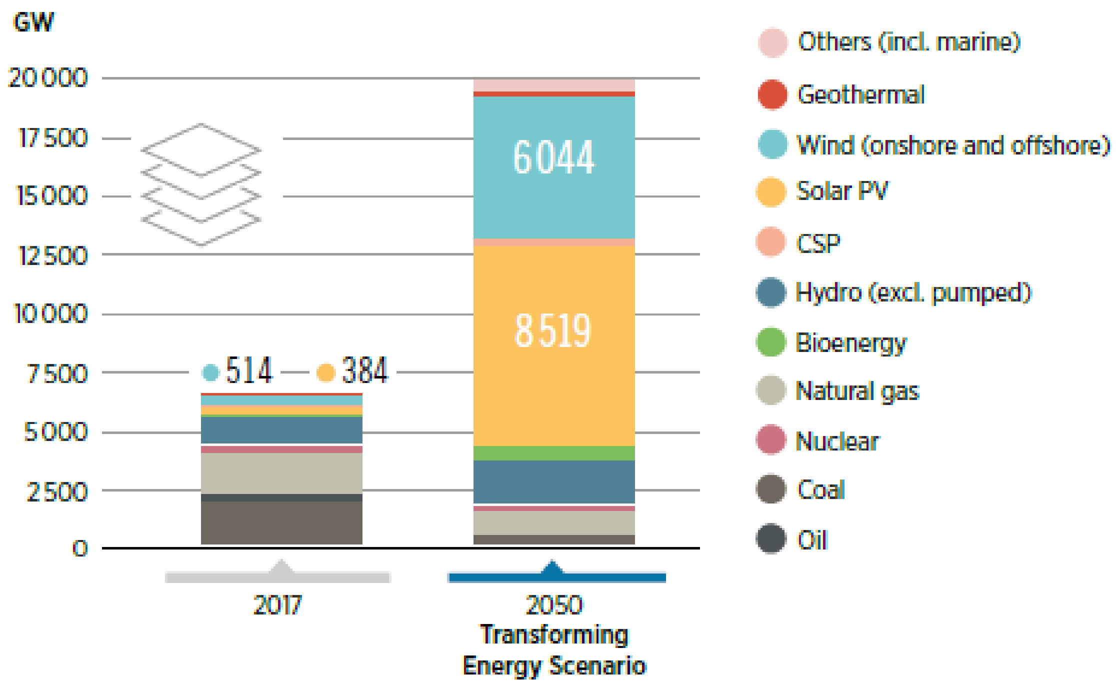

Figure 4.Total installed power capacity (GW) (source IRENA)

Regarding Europe, in January 2014, the European Commission proposed a new policy framework for climate and energy to expand the EU objectives from the year 2020 to the year 2030. In October 2014, the European Council reached an agreement resulting in three higher EU-wide targets to be achieved by 2030. The targets were revised upwards in 2018[4]: 1) a 40% cut in greenhouse gas emissions compared to 1990 levels, 2) at least 32% of renewable energy in gross final energy consumption, and 3) at least 32.5% energy savings compared with the business-as-usual scenario (BAU).

In this scenario, the study about the Renewable energy prospects for the EU by the International Renewable Energy Agency (IRENA) analyses the expected deployment of renewables in the EU by 2030 under a reference case scenario (which assumes the continuation of existing and planned policies) and through REmap Options (i.e. realisable renewable-based technology potential). According to this, the total installed power generation capacity generated by renewable sources in the EU-28 is expected to increase from 864 GW in 2010 to 1 079 GW in the reference case and 1 237 GW in REmap by 2030. Capacity additions come from renewable technologies, which would grow from 266 GW installed in 2010

[3] Global Renewables outlook. IRENA 2020

[4] https://ec.europa.eu/clima/policies/strategies/2030_en#:~:text=Renewables%20%E2%80%93%20increasing%20to%20at%20least,was%20revised%20upwards%20in%202018.

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to 608 GW under the reference case and 814 GW under the REmap case. The installed capacity of non-renewable sources would decrease significantly, especially coal and nuclear (Figure 5)[5].

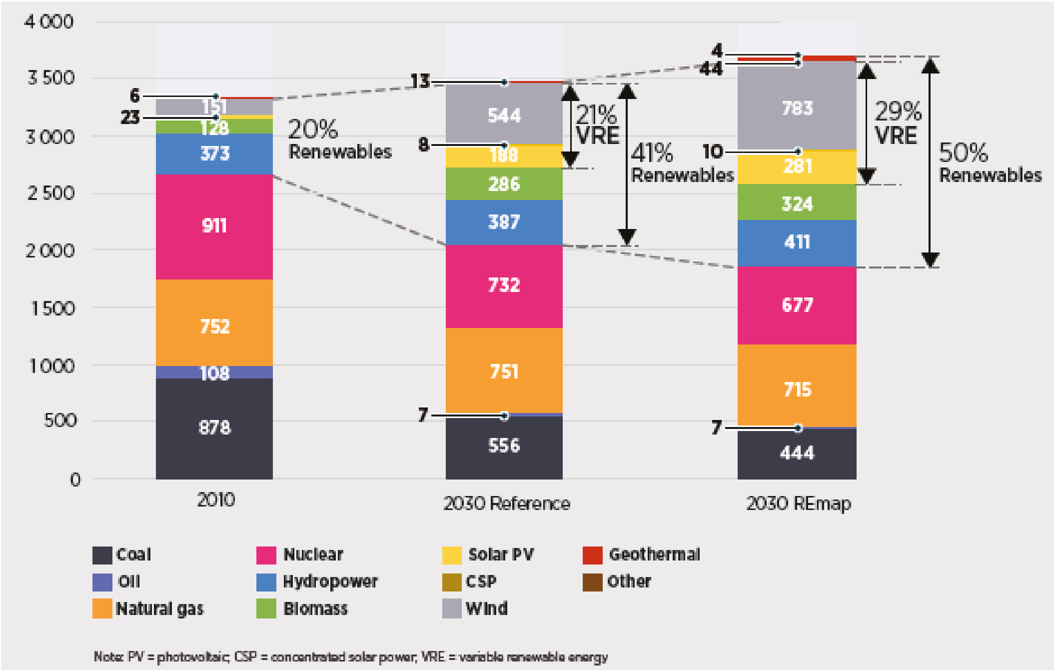

Figure 5. Installed power generation capacity by source in the EU-28 in 2010 and 2030 under the Reference Case versus REmap (GW)[6].

By 2050 the objective of Europe is to achieve net-zero greenhouse gas emissions. This comes promoted by the Paris Agreement that has the objective to hold global temperature increase to well below 2°C and to pursue efforts to limit it to 1.5°C. The road to reach a net-zero greenhouse gas economy is based on joint action along different strategic lines. One of them is to maximise the deployment of renewables and the use of electricity to fully decarbonise Europe's energy supply. The goal is to achieve an energy system where primary energy supply would largely come from renewable energy sources and reducing the actual use of oil and gas from 55 to 20% by 2050. To compensate this reduction, by 2050, more than 80% of electricity will be coming from renewable energy sources, which seems an achievable goal considering that currently more than half of Europe's electricity supply is free from greenhouse gas emissions [7].

2.1.1 Present and future installed capacity of wind energy

Among all renewable energy technologies, wind power, after hydropower, has dominated the renewables industry for the last decades. In 2019, more than 60 GW were installed reaching a total installed capacity of 624 GW. The outlook for 2030 foresees an increment to 1455 GW and 2434 GW in 2050[8] .

[5] Renewable Energy Prospects for the European Union. IRENA. 2018
[6] Renewable Energy Prospects for the European Union. IRENA. 2018
[7] A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. EU Commision. 2018
[8] Global Renewables outlook. IRENA 2020

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To date, China has been the leader in the onshore market, which covers a total of 620 GW installed, with a total of 230 GW, followed by US (>100 GW) and India (56 GW). Regarding offshore, the total installed capacity at the end of 2019 was 29.1 GW being the United Kingdom, Germany and China as the main contributors. Over 355 GW of new onshore capacity is expected to be added in the next five years, what means 71 GW of new installations each year until 2024. Regarding the global offshore market, the capacity is expected to increase in 57 GW the capacity, with annual growth from 6 GW in 2019 to 15 GW 2024[9].

Considering the ample resource availability, large market potential and cost competitiveness, onshore wind is expected to drive overall renewables growth in several regions over the next three decades. To meet the goals specified, it is necessary to have a year-on-year compound annual growth rate (CAGR) of more than 7%. This implies that the total installed capacity of onshore wind would grow more than three-fold by 2030 (to 1.787 GW) and nearly ten-fold by 2050, nearing 5.044 GW. The total land area required for global onshore installation of 5 044 GW by 2050 is between 1.008.800 square kilometres (km²) (around the size of Ethiopia) and 1.664.520 km² (around the size of Iran). Asia would continue to lead global onshore wind power installations, with the region accounting for more than half (2.656 GW) of the total global capacity by 2050.

Concerning the offshore market, it would grow significantly over the next three decades, with the total installed offshore wind capacity rising to 228 GW in 2030 and near 1.000 GW in 2050. Offshore wind would represent nearly 17% of the total global installed wind capacity of 6 044 GW in 2050. China would dominate offshore wind installations, outpacing Europe in less than two decades from now[10].

Focusing in Europe, 15.4 GW of new wind power generation capacity was added in 2019. Thus, the continent's installed wind power capacity was 205 GW by the end of 2019. Of the 15.4 GW added in 2019, 11.8 GW came from onshore wind parks, while the offshore segment accounted for the remaining 3.6 GW. The biggest contributor was the UK where 2.4 GW of on- and offshore wind farms went live, closely followed by Spain with 2.3 GW of newly commissioned plants, all of them onshore [11].

For the near future, according to WindEurope, Europe could install 90 GW of new wind energy capacity over the next five years if governments adopt clear and ambitious national energy and & climate plans and resolve their current issues around wind farms, thus permitting and continuing to invest in grid infrastructure. This would give Europe a total of 277 GW installed wind capacity by 2023. Most of the new installations are expected to be onshore[12].

In the coming decades, Europe is likely to be the third largest market for onshore wind, after China and the US. The installed onshore capacity is expected to increase to 215 GW in 2030 and 483 GW in 2050 (Figure 6). Germany, France, Denmark, Spain, Italy, Sweden, Norway, Poland and Ireland would remain the top wind markets, where the largest share of new onshore installations would take place. On the other hand, the foreseeable increase for the offshore is 78 GW in 2030 and 193 GW in 2050 (Figure 7). Regarding the ambitious goal for offshore, apart from the EU actions and efforts, the different countries have also established their objectives. For example, Germany defined a total installed offshore wind energy capacity

[9] GWEC. Global Wind Report 2019. March 2020.
[10] FUTURE OF WIND: Deployment, investment,technology, grid integration and socio-economic aspects. IRENA. October 2019.
[11] Wind Energy in Europe in 2019. WindEurope. February 2020.
[12] Wind Energy in Europe: Outlook to 2023. WindEurope. October 2019.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851245.

expansion target of 15 GW by 2030. The Netherlands set an offshore wind generation target of more than 49 terawatt-hours (TWh), which implies a total installed capacity of 11.5 GW by 2030 and the United Kingdom confirmed a deal with the offshore wind industry to help the sector reach 30 GW of installed capacity in UK waters by 2030.

New operation and maintenance technologies are going to be key to a faster evolution of new wind farm facilities. New digitalisation techniques for monitoring that proactively identify failures will help to reduce costs. The use of drones for visual inspections for example can simplify the costly intensive inspections.

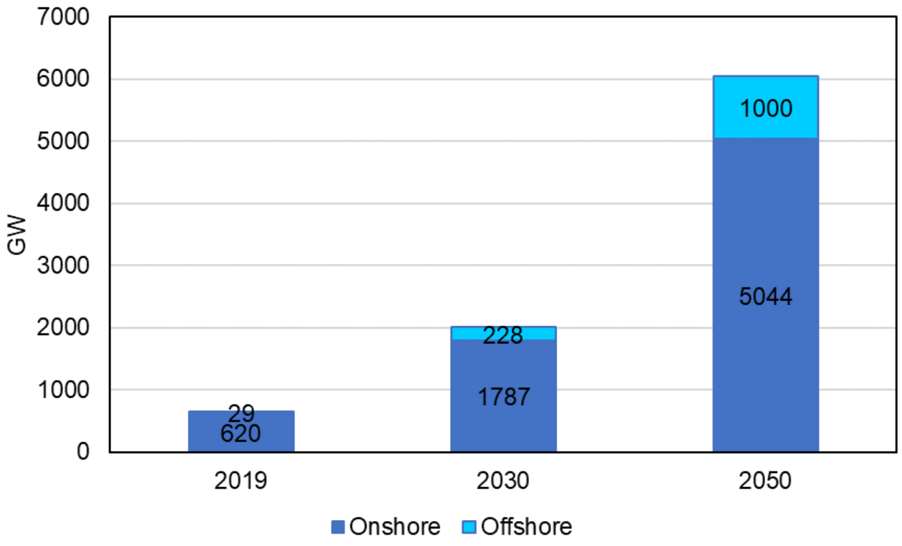

Figure 6: Worldwide installation prediction for wind energy (data from Table 1).

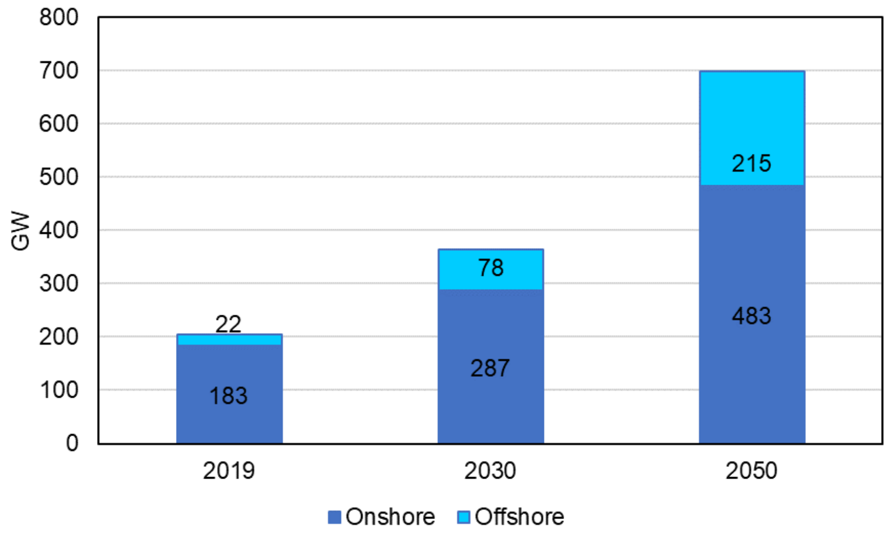

Figure 7: European installation prediction for wind energy (data from Table 1)

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2.1.2 Wind turbine manufacturers

More than half of the Global Wind turbine OEM market is divided between four main manufacturers (data source 2018[13]): Vestas (21%), Goldwind (14%), Siemens Gamesa (12%) and GE Renewable Energy (10%). In 2018 these four companies represented 55% of the total market: Vestas led the supplier list with 9,6 GW, followed by Siemens Gamesa with 8.8 GW, the Chinese Goldwind was in the third position with 8.3 GW and GE Renewable Energy with 7,4 GW.[14]

The updated data for 2019 (Figure 8) show that Vestas became the first wind turbine manufacturer to install more than 10 GW of wind capacity in a single year (2019) (according to a new analysis by Wood Mackenzie)[15]. Siemens Gamesa Renewable Energy moved up to second place (from the third place in 2018), achieving more than 1 GW of onshore installations in Spain and US; and adding 1.9 GW to the offshore market in the UK. GE increased by 60% its global market with new projects in Greece, Oman, Jordan, Kazakhstan and Chile reaching 8.7 GW and the third position in the ranking (from the fourth in 2018).

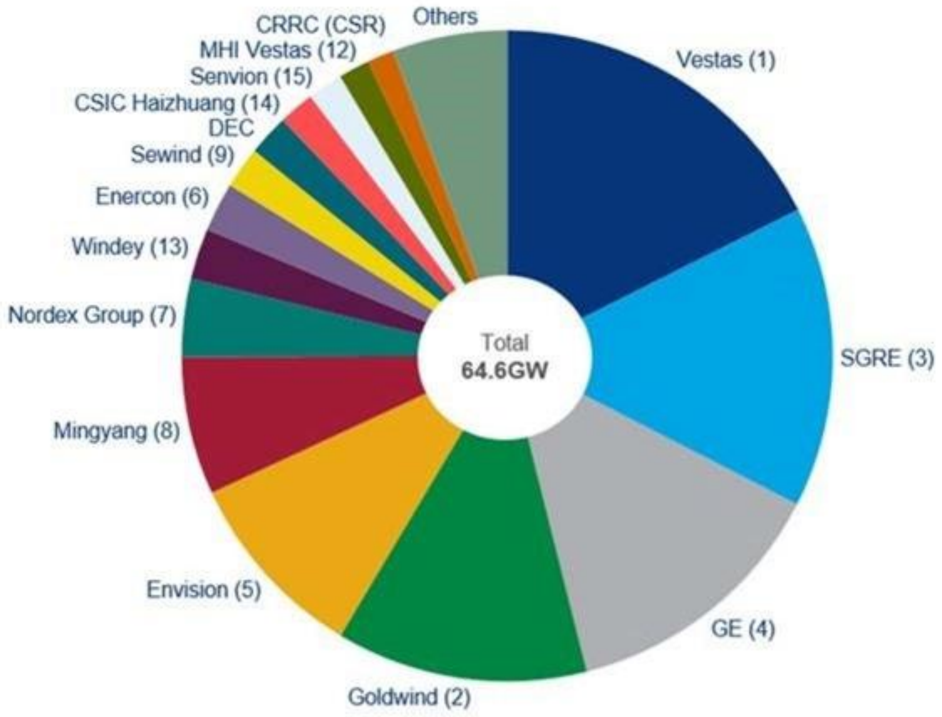

Figure 8: Wind turbine manufacturer ranking 2019 (source: Wood Mackenzie)

This scenario leaves the development of the turbines of the future mostly in the hands of a few wind turbine manufacturers, being these manufacturers the ones that will somehow set the pace of advancement and development of future wind turbines.

[13] Navigant research 2018
[14] https://www.greentechmedia.com/articles/read/bnef-vestas-keeps-turbine-crown-for-2019
[15] https://www.evwind.es/2020/05/12/vestas-sets-a-record-for-wind-turbines-and-dominates-onshore-wind-energy/74705

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2.2 Turbine size evolution and forecast

Large wind turbine manufacturers are today competing in the race to design and manufacture more powerful turbines. In this race, GE has been able to put the first prototype of the Haliade-X 12 MW offshore wind turbine into operation in the Rotterdam port (Netherlands). Vestas developed the V164-7.0MW and went through a series of upgrades until they reach the capacity of 9,5 MW (Figure 9). Siemens Gamesa developed an 8MW turbine and the prototype was installed at Denmark's National Test Centre for Large Wind Turbines in 2018, and now is moving to a 14 MW concept (SG14[16]). For the onshore market, GE developed Cypress, a 5 MW onshore wind turbine platform, ready to operate for capacities between 4.8 and 5,3MW. A great advantage of this onshore turbine is the revolutionary two-piece wind turbine blade design, which can improve logistic problems due to transportation[17].

Larger wind turbines will probably have a much higher CAPEX per MW (for only the turbine), but they will still reduce the cost of energy by increasing energy production with lower investments in foundations and installation. For the same reference capacity wind farm, the fact of having fewer turbines reduces maintenance costs (fewer turbines to inspect), improves safety and even has fewer foundations with a lower environmental cost.

Figure 9: HaliadeX 12MW prototype[18] (Rotterdam) and MHI Vestas 9.5MW[19] wind turbines.

The predictions defined in this document are based on reports of specialists in the wind energy sector and the news obtained recently from manufacturers in different media. New ambitious

[16] https://www.siemensgamesa.com/es-es/products-and-services/offshore/wind-turbine-sg-14-222-dd
[17] https://www.ge.com/renewableenergy/wind-energy/onshore-wind/4-5-mw-platform-cypress
[18] https://www.ge.com/renewableenergy/wind-energy/offshore-wind/haliade-x-offshore-turbine
[19] https://mhivestasoffshore.com/category/v164-9-5-mw/

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projects from wind turbine manufacturers and wind-power operators, and forecast for experts are regularly published; always trying to lead the race towards a machine of greater power and size:

- "*Iberdrola open the doors to invest in offshore wind turbines in Brasil. The presented project for 2027-2030 includes four wind farms, divided equally: 750 MW with 50 wind turbines with a nominal power of 15 MW*"[20].
- *"Siemens Gamesa is also moving to a "1X" offshore design concept (14-16 MW range). Siemens Gamesa applied for a patent to protect components in a new offshore wind turbine model 14-megawatt to 16-MW range"*[21].
- "*Offshore wind turbine 20MW generator ready 'within three years': Rare-earth-free permanent magnet generators (PMG) for offshore wind turbines with nameplates of 20MW are expected to be a reality "within three years", following trials of a new-generation concept at the UK Offshore Renewable Energy (ORE) Catapult facility*".[22]
- *"DNV GL believes that the turbine size is bound to increase in the coming decades. Some developers have that 10 MW offshore turbines, with a hub height of 130 metres and a rotor diameter of 200m, will be commercially available in the early 2020s. For 2030-2050, the average size could grow to sizes of 10-15 MW and up to 20 MW for new installations in the later part of the period "*[23]
- *"The world's largest wind turbine about to enter serial production is the 12MW GE Haliade-X turbine, but manufacturers are actively developing ever-larger turbines with the hope of delivering 20MW turbines by the end of the decade", "Germany's Fraunhofer Institute for Wind Energy Systems (IWES) is gearing up to launch a mobile grid test simulator that will assess the impact of mammoth wind turbines with outputs of as much as 20MW"*[24]
- *"The industry is targeting even larger 15-20 MW turbines for 2030. This increase in turbine size and rating has put upward pressure on capital costs as larger turbines pose construction challenges and require larger foundations, but it has also reduced operation and maintenance costs, ultimately leading to lower levelized costs of electricity* (Figure 10)*"*[25]
- *"The new turbine model has a 14 MW capacity, reaching up to 15 MW using the company's Power Boost function, a 222-metre diameter rotor, 108-metre long blades, and a 39,000 m2 swept area. The turbine prototype is expected to be ready in 2021, and the model will be commercially available in 2024, Siemens Gamesa said. "*[26]
- *"During the first quarter of 2020 construction workers have assembled the nearly 28 meters high building to host LORC's new 25 MW nacelle test facility. The test bench will from January 2021 test the next generation of prototypes of the world's largest offshore wind turbines to make sure that the enormous energy giant can withstand the scenarios out on the ocean."* [27]

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[20] https://www.eleconomista.es/energia/noticias/10288973/01/20/Iberdrola-abre-las-puertas-a-invertir-22500-millones-en-eolica-marina-en-Brasil.html
[21] https://www.smartbrief.com/branded/C0D1F99F-3D33-45EC-90B9-B926C64391E0/7B1CC3FA-C343-4863-A787-DD7AB2E072B1
[22] https://www.rechargenews.com/wind/offshore-wind-turbine-20mw-generator-ready-within-three-years/2-1-711845
[23] https://www.dnvgl.in/technology-innovation/broader-view/electrifying-the-future/third-generation-wind-power.html
[24] https://reneweconomy.com.au/germany-gears-up-to-test-20mw-wind-turbines-79007/
[25] Offshore Wind Outlook 2019, World Energy Outlook Special Report, IEA
[26] https://www.offshorewind.biz/2020/05/19/siemens-gamesa-cranks-it-up-to-15-mw-with-offshore-behemoth/
[27] https://www.lorc.dk

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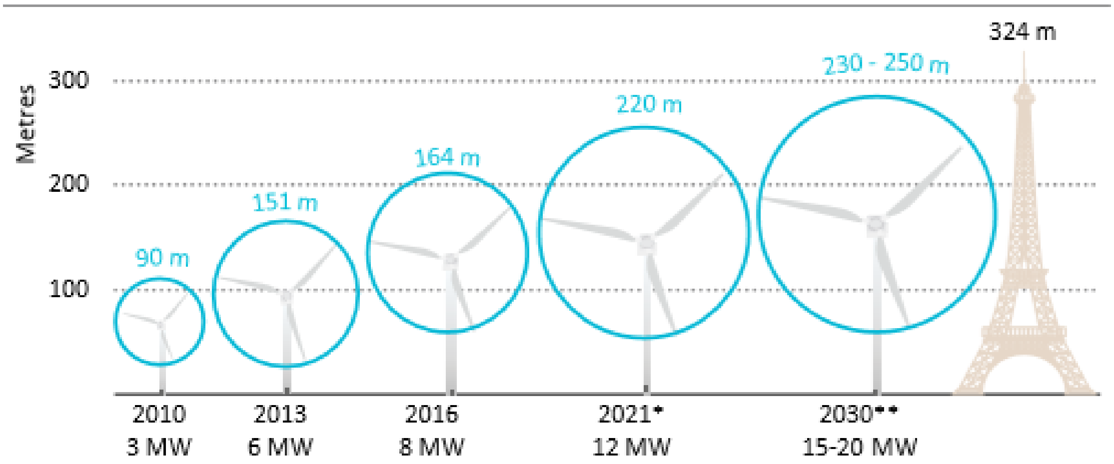

Figure 10: Evolution of the largest wind turbines[28]

Considering the analysed information,in the last decade, the increment of the average size for offshore wind turbines has gone from 3 MW in 2010 and 4 MW in 2015, to a value close to 7,2 MW[29] in 2019. The expected values of turbine sizes in the coming years are not easy to predict, but after analyzing the existing literature in this study, a horizon of 10-12 MW has been defined as the average size for offshore in 2030 and 20 MW in 2050. Regarding onshore, the average size of installed turbines has gradually increased from 1.8 MW in 2010 to 3.1 MW in 2019. By 2030 the installed average size can be increased up to 5MW (close to the actual maximum size) and by 2050 the size can be doubled (up to 10 MW) (Figure 11).

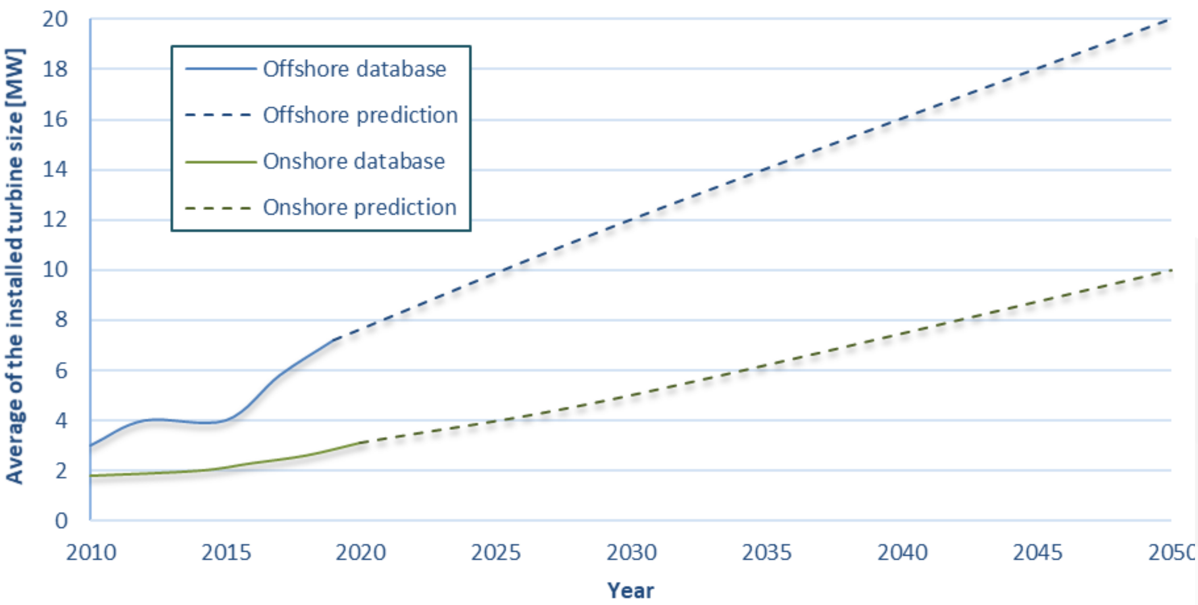

Figure 11: Average offshore-onshore installed turbine size from literature and evolution prediction.

[28] Offshore Wind Outlook 2019, IEA
[29] Wind Energy in Europe in 2019: Trends and statistics.

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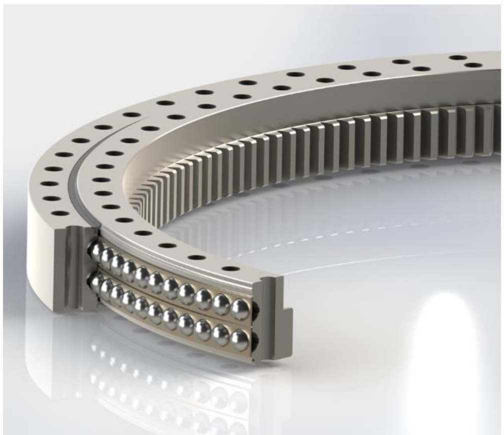
2.3 Pitch bearing evolution and forecast

The capacity factor of a wind turbine is highly influenced by the size of the blades to define larger swept areas for a given wind resource. In the development of new bigger blades, the key issues are the optimisation of the designs, the materials and the improvement of their environmental behaviour. The requirement to increase the blade size has also resulted in the need to work on new and increasingly innovative concepts of pitch bearings (case studies 1 and 3 of the INNTERESTING project, Figure 12). This subsection gives the evolution analysis on this specific component: first on the types of pitch bearings, followed by a forecast on the diameter.

Figure 12: Pitch bearing in a wind turbine (source Laulagun)

2.3.1 Pitch bearing types

The most used pitch bearings so far have been four-point contact 2 row ball bearings and three row roller bearings (Figure 13). In recent years, the number of patents related to new pitch bearing designs has increased: most of them looking for higher static and dynamic capacity values, but in other cases trying to solve problems related to transportation or mounting.



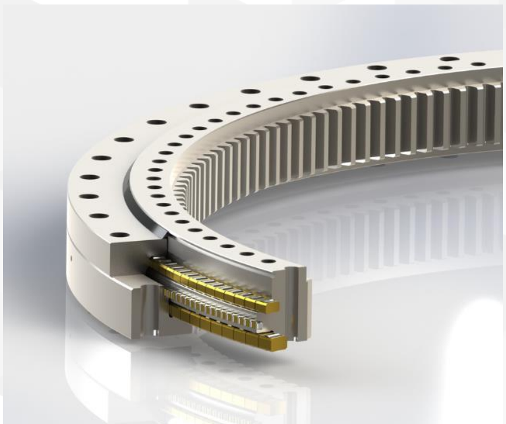


Figure 13: Four-point contact 2 row ball bearings and 3 Row Roller bearings (Laulagun).

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The research and generation of new pitch bearing concepts are in continuous evolution, trying to solve the problems that arise when defining larger wind turbines. For example:

- The T-SOLID design developed by IMO[30]: where axial load is carried out by two rows of balls contacting in the bearing axis direction (90º) and where radial loads are supported by radial rollers (Figure 14).
- GE patented a pitch bearing with two single row radial bearings separated by a cylindrical part; this dual pitch bearing configuration avoids having transmitting tilting moments in those bearings[31](Figure 15).
- GE also patented a pitch bearing that, according to the description provided, can withstand higher loads without the need for larger balls or more expensive roller bearings. The bearing is based on the design of four rows of balls with two contact points[32] (Figure 16).

Figure 14: T-solid from IMO

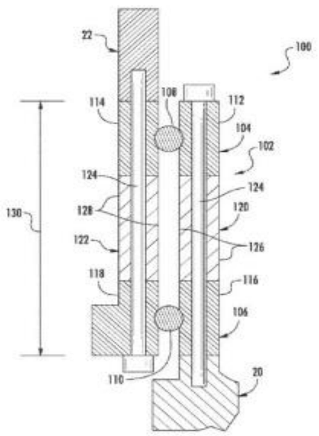

Figure 15: GE patent dual pitch bearing configuration[34]

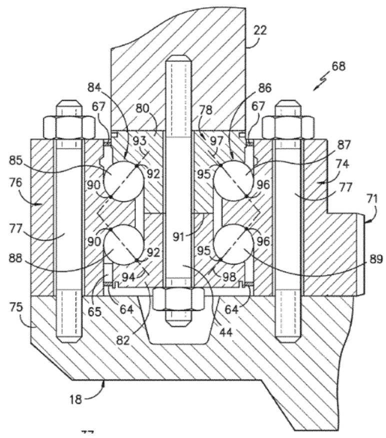

Figure 16: GE patent 4 rows of balls with 2 contact points[35]

In addition, there are other concepts that develop new ways of joining the blade to the bearing, without using screws and reducing weight[36]. There are also patented bearings with machined teeth to a given height of the ring, not the entire height, so the material above the teeth is retained, stiffening he ring[37]. Some other patents are more oriented to define methods to reinforce current pitch bearings[38,39,40,41,42,43], trying to increase the capacity of the bearings by stiffening them in their most demanding zones.

[30] https://www.t-solid.de/us/the-story
[31] US2017321662A1
[32] US 2018/0283362 A1, 2018
[33] https://www.t-solid.de/us/the-story
[34] US2017321662A1
[35] US 2018/0283362 A1, 2018
[36] AU2017359582 (A1), 2018
[37] US20180274519 A1, 2018
[38] EP2933476A1, 2014
[39] US2018112645A1
[40] CN109113938A
[41] https://patents.google.com/patent/EP3112669A1/ar
[42] ES 201730868, 2017 (LAULAGUN)
[43] WO2019162541 (LAULAGUN)

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2.3.1.1 Current pitch control methods

The pitch control adjusts the angle of the wind turbine's rotor blades in order to optimize the loading and the power generation of the turbine. For this purpose, the pitch actuator must exceed the bearing torque under external loads to apply a relative movement between the rings of the bearing. This movement can be generated by an electric motor and gears or using hydraulic cylinders (Figure 17, and Figure 18). The use of electric pitch forces to one of the rings to be geared; which can be the inner or outer ring, depending on the overall design of the rotor. In the case of the hydraulic actuator, a pitch plate with a joint is necessary to transform the linear movement of the cylinder in a rotation movement between rings.

Figure 17: Hydraulic pitch control (source: www.windpowerengineering.com)

Figure 18: Electric pitch control (source: www.fv-bearing.com)

The use of one type of actuator or another type of pitch control depends on the turbine manufacturer. There is no clear market trend on this issue. The traditional single pitch actuator is being replaced in some cases by multiple smaller actuators. In this case, if there is a failure with one of the actuators, the turbine can continue generating energy (at least at low winds) until it is repaired.

2.3.2 Pitch bearing diameter evolution

The pitch bearing diameter can be considered similar to the diameter defined as the blade chord. Due to the importance of the aerodynamic loads and blade design, this diameter is predefined by the blade design and is usually an input for pitch bearing manufacturers. In order to define a guideline diameter range for each turbine size, data from different sources has been collected. Juan Pablo Sanchez[44] created in 2013 a wind turbine database where rotor diameters were linked to the rotor chord values (adding information from turbines on the market). The analyzed data defines a trend: as the blade size increases, the increase in the diameter of the chord rotor is reduced, tending towards an asymptote Based on this data and the information obtained for defining the reference wind turbines (RWT), in this deliverable, the pitch bearing diameters (considered similar to chord diameters) have been linked to the wind

[44] Juan Pablo Sanchez, *Wind turbine database: Modelling and analysis with focus on upscaling*, Master's thesis, Chalmers University of Technology, Sweden 2013.

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turbine nominal power (Figure 19). For 3.4 – 5 – 10 – 15 and 20 MW reference turbines, the chord diameter of the blade is obtained from research works developed based on their specifications.

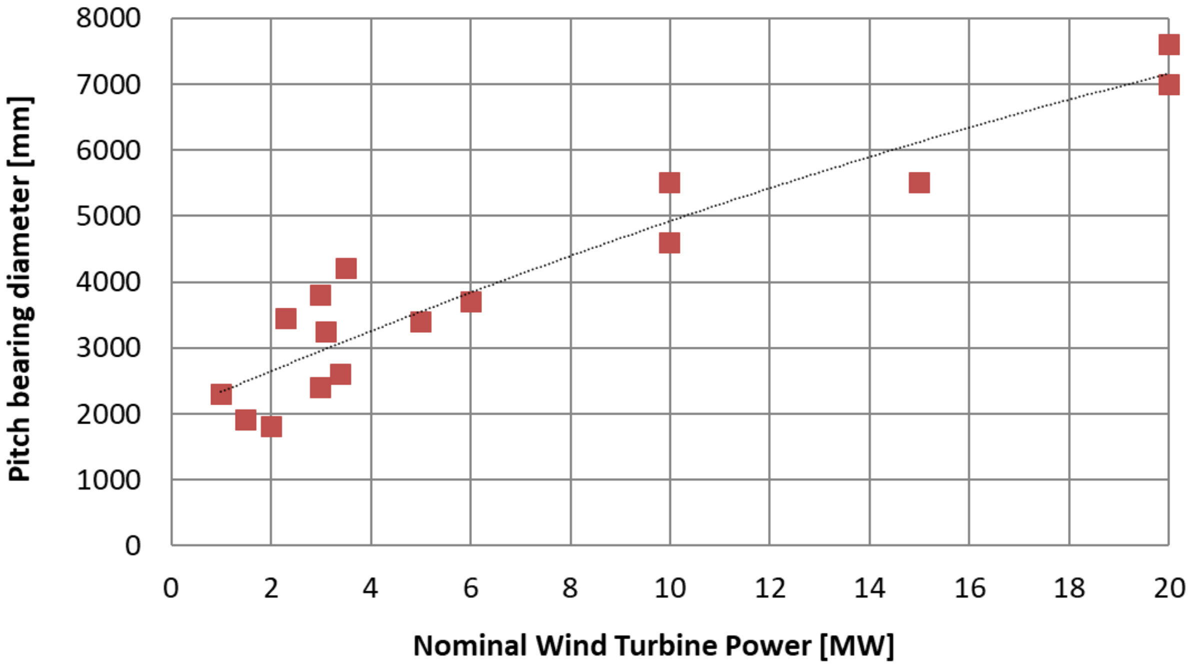

Figure 19: Pitch bearing diameter tendency for several turbine sizes

For RWTs, depending on the research work and the optimization carried out on the blade design, the blade chord diameter might vary, this is the reason why for 10 and 20 MW two different diameters are defined. The graph seems to progress towards an asymptote, hence from diameters greater than 20 MW. No diameters greater than 8-9 meters are expected.

Increasing the bearing diameter makes the manufacturing process difficult and highlights the need to tackle new technological challenges in the near future. The manufacture of forged bearing rings with diameters greater than 5-6 meters s with the required mechanical properties is challenging. However, some companies can already supply forged hoops up to 15meters in diameter[45]. The dimensions of the rolling elements can also be limiting which can lower the number of suppliers that can keep meeting the market requirements and can also increase the market prices.

[45] www.iraeta.com

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2.4 Drive train and gearbox evolution and forecast

Case study 2 of the INNTERESTING project revolves around the gearbox. This subsection therefore provides the evolution analysis of the drivetrain and gearbox. The types of turbine drivetrain may be categorized as follows (Figure 20):

- ***Drivetrain with two main bearings***: the bearings support the bending and forces coming from the rotor.
- ***Drivetrain with one main bearing***: the bending moments and forces from the rotor are supported by the main bearing and the gearbox structure.
- ***Integrated solutions***: the rotor bearings and the main shaft are integrated into the gearbox structure. The loads are transmitted through the gearbox structure.
- ***Gearless solutions, "Direct Drive, Drive train without gearbox***: direct drive wind turbine needs no gearbox or speed increaser, the rotor rotation is directly connected to the generator.

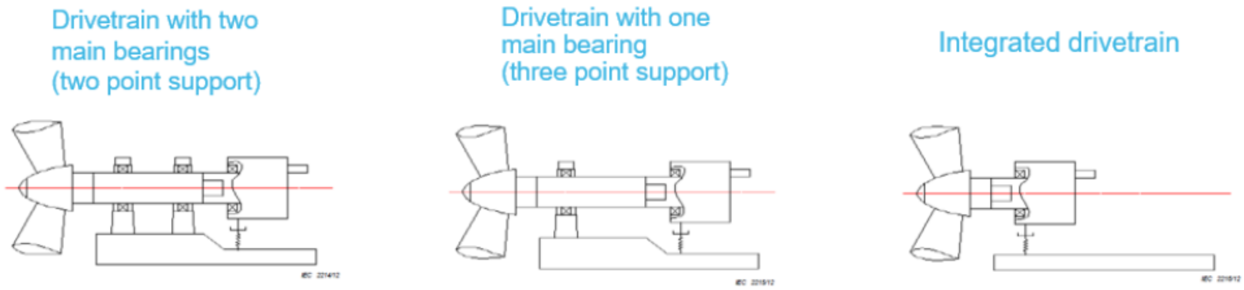

Figure 20: Drivetrain architectures (source: Moventas)

Geared wind turbine systems solutions are nowadays preferred based on the market size. Conventional high-speed geared systems (69.7%) and medium-speed turbines (3.7%) covered the three-quarters of the market (data from 2018)[46] and direct drive technology covers the rest of the market (26.6%).

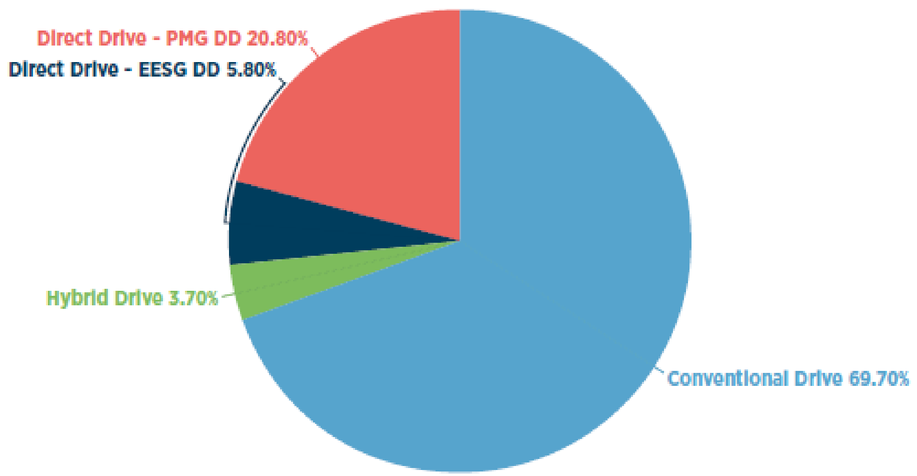

Figure 21: Drivetrain systems based on market data (source: IRENA)

[46] Future of wind 2019, IRENA, October 2019

This document focuses on the first three designs (Figure 20), where the gearbox is part of the solution (as in CS2 of the INNTERESTING project). The gearbox connects the low-speed shaft attached to the turbine blades to the high or medium-speed shaft attached to the generator (Figure 22).

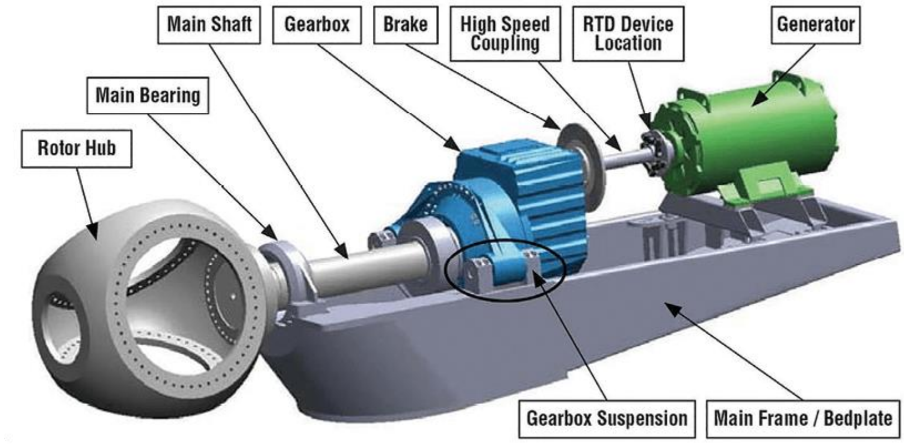

Figure 22: Drivetrain with one main bearing (source: NREL[47])

The nominal torque for different wind turbine sizes is showed in Figure 23, where onshore and offshore turbines are defined based on existing wind turbines. The forecast of future potential onshore wind turbine ranges are included with increases between 12 to 39 % in nominal torque values.

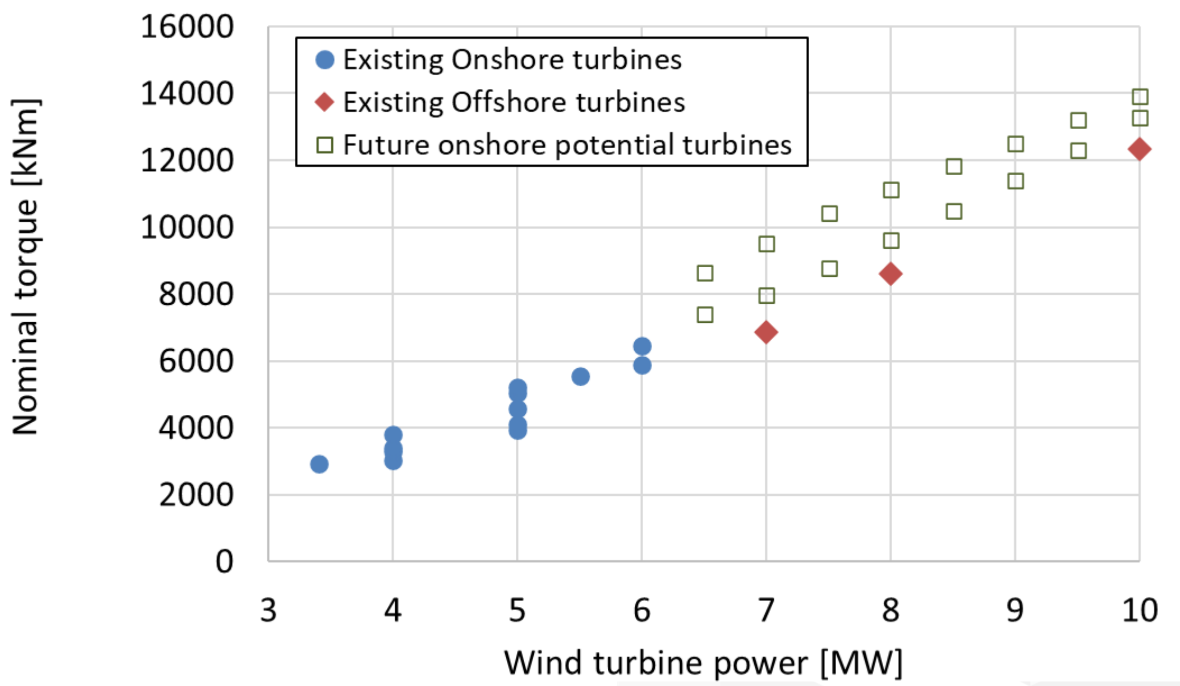

Figure 23: Nominal torque requirements for existing turbines[48,49,50] and future forecast

[47] www.windpowerengineering.com/extreme-torsional-loads-damage-more-than-wind-turbine-gearboxes/
[48] Existing turbine data found from Internet, web-pages of turbine OEM's
[49] https://en.wind-turbine-models.com/turbines/1124-adwen-ad-8-180
[50] Development of a 5 MW Reference Gearbox for Offshore Wind turbines, A. Rasekhi, Wind Energy, DOI: 10.1002/we

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During the WindEurope 2019 event, a meeting was held to discuss about the future of gearboxes and their limitations[51]. Different entities, representing various stages in the supply chain, participated in the discussion. One of the clear conclusions was that the turbine size limit has not been reached, but logistically, the size of the components is already critical. New developments should focus on limiting the size and weight of gearboxes. From now on, technological breakthroughs are expected, especially on the development of new materials as well as digitalisation.

Nowadays, based on current knowledge, it is difficult to predict the percentage in which the market is going to decide for medium or high speed gearboxes. In the current market both variants can be found. The medium speed drivetrain requires larger generator, but the size and weight of the gearbox are reduced. The total value of torque per weight ratio can be an important parameter for finding the best option. In the last three decades this value has increased from 50 Nm/kg to 100-125 Nm/kg. Even though gearbox sizes have increased when turbines have been growing, relative gearboxes sizes have gone smaller and torque density has increased (Figure 24). Although the values of torque density that exist on the market are below 130 Nm/kg (otherwise gearboxes are too heavy and too large for transportation), the requirements in the future will be higher, reaching values between 150 to 200 Nm/kg (Figure 25).

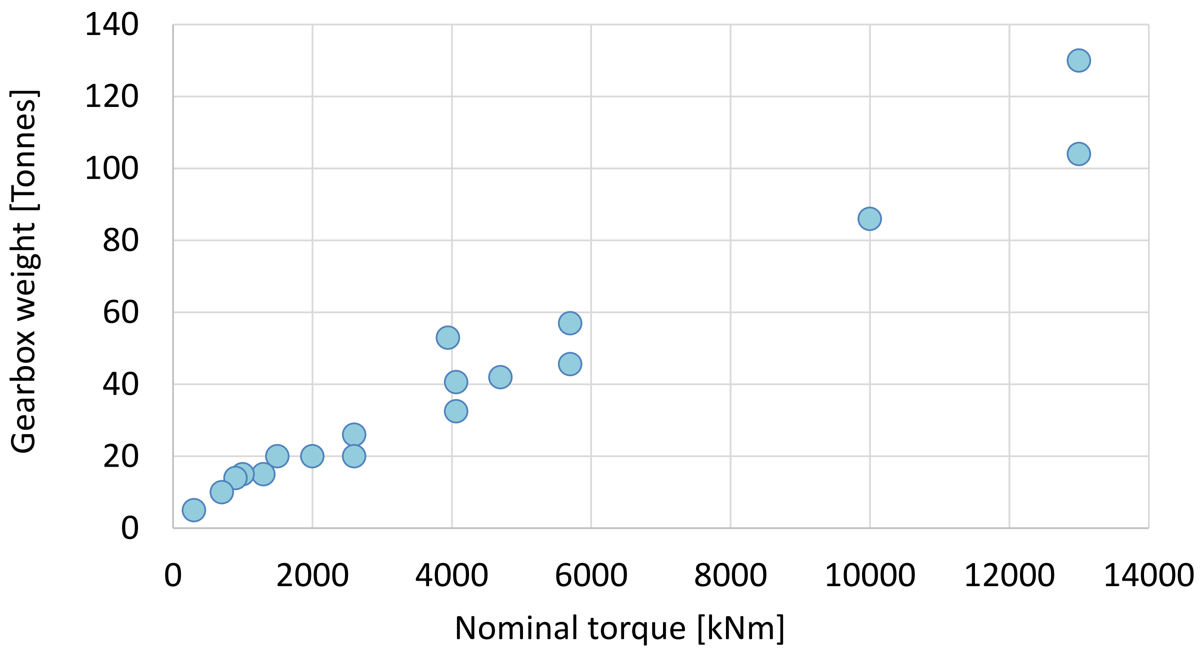

Figure 24: Gearboxes nominal torque and mass relation. [52,53,54,55,]

[51] https://www.windpowermonthly.com/article/1584161/future-gearboxes-happens-next
[52] Development of a 5 MW Reference Gearbox for Offshore Wind turbines, A. Rasekhi, Wind Energy, DOI: 10.1002/we
[53] https://en.wind-turbine-models.com/turbines/1124-adwen-ad-8-180
[54] S. Wang, A..R. Nejad, T. Moan, On design, modelling, and analysis of a 10-MW medium-speed drivetrain for offshore wind turbines, WIND ENERGY, 2020, https://doi.org/10.1002/we.2476
[55] Existing turbine data found from Internet, web-pages of turbine OEM's

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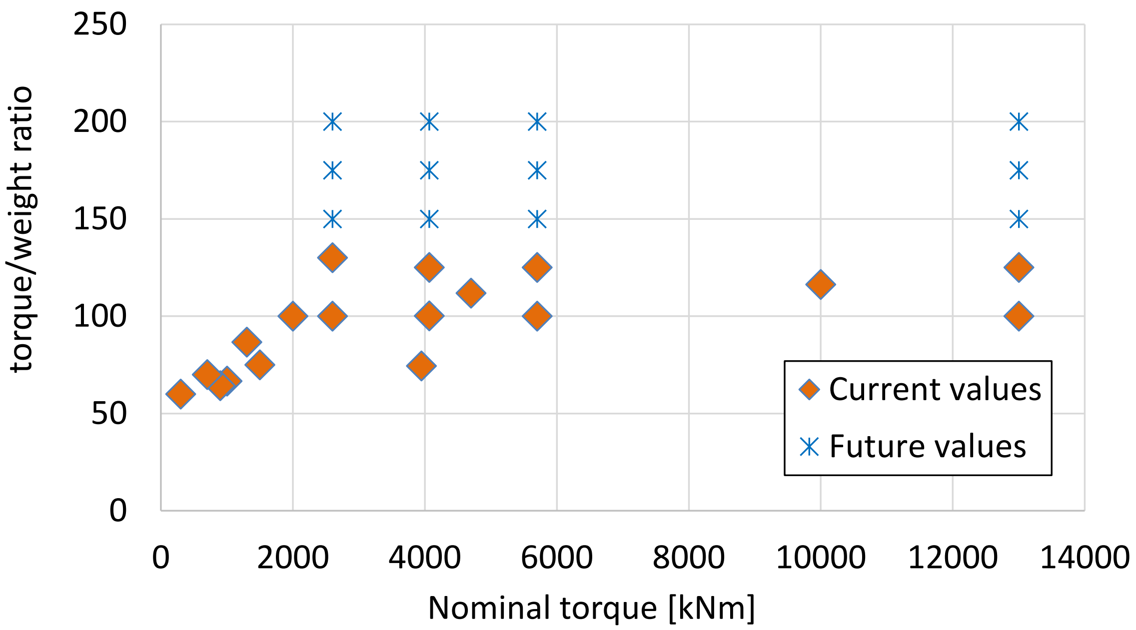

Figure 25: Torque density (kNm/Tons) for nominal torque [56].

The reliability of the components is crucial to improve performance and reduce maintenance costs in the WT and the gearbox is a critical component. The gearbox represents the 5% of the total failure rate in onshore and the 8,3% in offshore. But in terms of downtime, the gearbox represents the 24,2 % in onshore and the 33,3 % in offshore; similar values to other components like blades or generator. The failures per turbine per year for gearboxes is close to 0.7 for offshore and 0.2 for onshore[57]. Based on it, it is clear that there is a need to increase the reliability of this component to reduce failures and downtimes to achieve a LCOE increase.

2.5 Current product development process and time to market

The product development process (PDP) of an actual pitch bearing, and gearbox can be divided into different steps (Figure 27):

- **Predesign:** in the predesign stage, the wind turbine manufacturer must provide the component specifications (loading, dimensions, environmental requirements, etc). Regarding the pitch bearing, the diameter is an input conditioned by the dimensions and the design of the blade (the bolted connection position diameter between the blade and the pitch bearing). The fatigue and extreme loads are necessary for the rolling element dimensioning and the ring structural design. Concerning the gearbox, the nominal torque, loading conditions, gearbox ratio and space/weight limitations are necessary inputs in the predesign phase.
- **Design evaluation using existing design tools**: the developed component design must be evaluated for different failure modes using existing design tools (analytical evaluation, finite element method etc). The geometry is optimized for avoiding any failure during the

[56] Existing turbine data found from Internet, web-pages of turbine OEM's
[57] Dao C., Kazemtabrizi B., Crabtree C., Wind turbine reliability data review and impacts on levelized cost of energy, Wind Energy. 22:1848–1871, 2019.

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lifetime. These virtual models are represented in the current testing pyramid (Figure 26) in the *virtual testing* part.

- **Full-scale prototype and full-scale testbench design and construction**: when it is not possible to test the pitch bearing or egarboxes in existing testbenches (due to loading limitations, size, etc) a new full-scale testbench must be developed: Collecting requirements, detailed design, manufacturing and commissioning the new test bench are time-consuming and costly tasks. For new component concepts, the manufacturer must face these new challenges when manufacturing prototypes for testing . An increase in size, for example, can imply different manufacturing methods. Consequently, all requirements must be validated again. These physical test models are represented in the current testing pyramid (Figure 26) in the *virtual testing* part (component or full structure test).

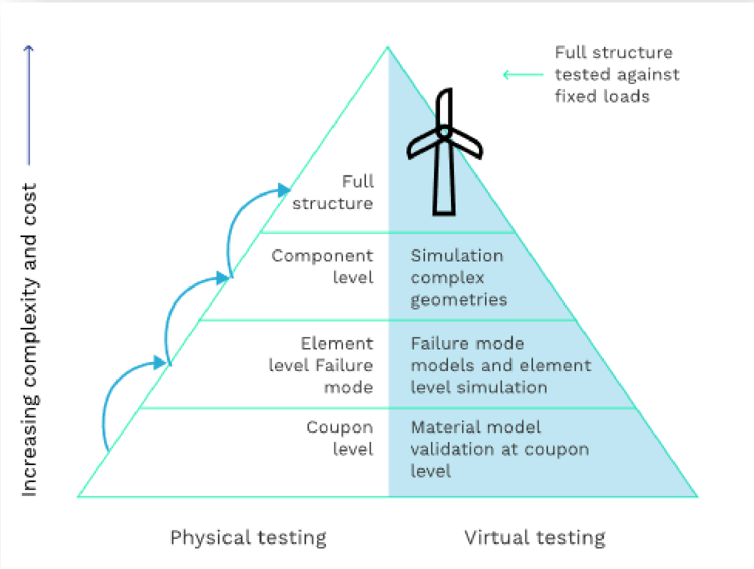

Figure 26: Current testing pyramid used during PDP process (BAU scenario)

- **Full scale test campaign**: to validate the viability and reliability of the components, it is necessary to have tests campaigns that can last up to 3-4 months.

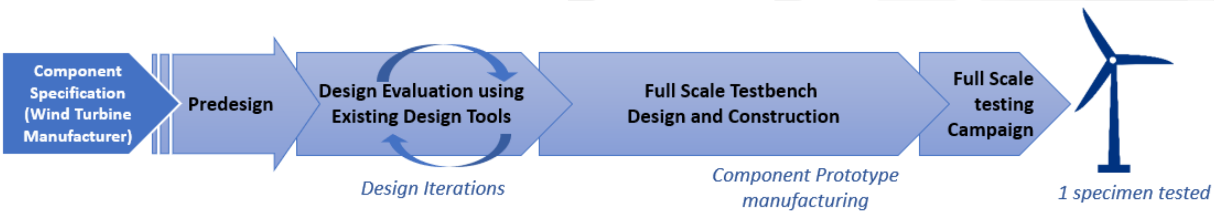

Figure 27: Current PDP for a wind turbine component

For the components involved in the INNTERESTING project, the PDP time can be close to 30 months for large scale components, mostly due to the development of the full-scale testbench (18-20 months) (Figure 27). The cost for the whole process, also considering the cost of the test bench and the tests, can be close to 7 M€ for the gearbox and 2,7 M€ for the pitch bearing (estimates based on indicative costs of current large test benches from manufacturer partners).

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2.6 Design lifetime requirement evolution and forecast

The expected design lifetime of onshore wind turbine affects its profitability, the timing of possible end-of-life decisions and its levelized costs. Consequently, the wind turbine market has been pushed to lengthen design lifetimes during the last years. A recent benchmark[58] shows how most wind project developers, sponsors and long-term owners from land-based wind power plants in the United States have increased project-life assumptions over time. From a typical term of ~20 years in the early 2000s to ~25 years by the mid-2010s and ~30 years recently. While current assumptions range from 25 to 40 years, with an average of 29.6 years (Figure 28). This can be slightly different in Europe, but as no available data has been found for Europe, and considering that global market trends are not so different, it can be a good approach to have as a reference.

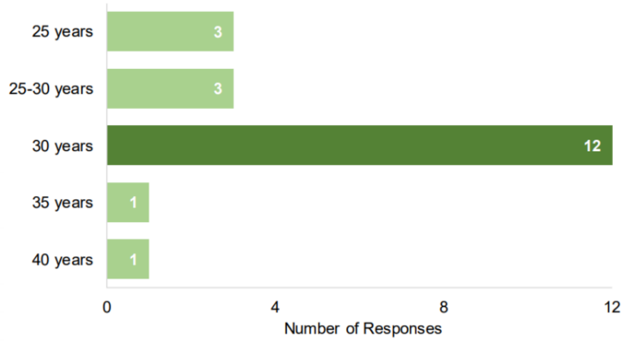

Figure 28: Current useful-life expectations for wind plants[57]

The study also shows the design lifetime evolution during the last 20 years (Figure 29Figure 21). By extrapolating this data, a design lifetime of 50 years can be expected in 2030 and near 100 years by 2050. However, it is worth mentioning that the design lifetime evolution within last two decades has increased in parallel with an extreme maturing process of wind turbine technologies. Thus, although an increasing tendency will remain, the mentioned numbers will be difficult to achieve.

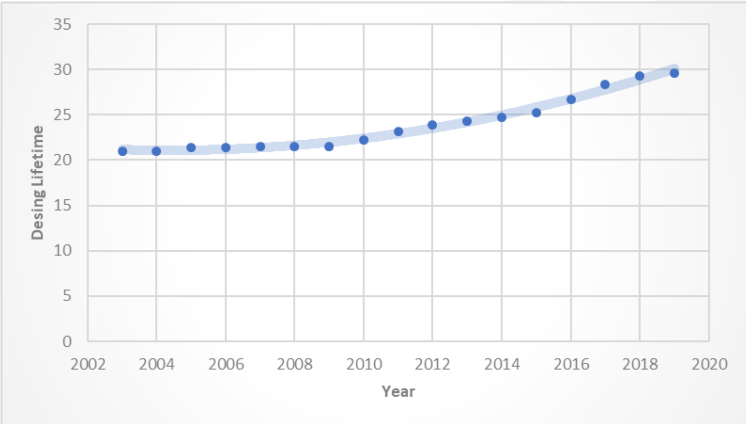

Figure 29: Design life during last years[59].

[58] Benchmarking anticipated wind project lifetimes: Results from a survey of U.S wind industry professionals. September 2019. https://eta-publications.lbl.gov/sites/default/files/wind_useful_life_report.pdf

[59] Benchmarking anticipated wind project lifetimes: Results from a survey of U.S wind industry professionals. September 2019. https://eta-publications.lbl.gov/sites/default/files/wind_useful_life_report.pdf

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2.7 Lifetime extension evolution and forecast

When the wind turbine achieves its design lifetime, asset managers and owner-operators face the end-of-life scenario with three main choices: decommission and return the site to previous use, repower the site with modern turbines or extend the life of the existing installed asset.

Lifetime extension is defined by Wind Europe as a process that "*differs from a normal operation and maintenance activities*, where *some of the components of an existing wind turbine are upgraded (e.g. generator) while the overall external layout of the farm remains unchanged (e.g. hub height, siting, size)".* This option is getting rapidly more attractive[60] since relevant energy production is achieved for a relatively low investment, which reduces the LCOE and increases the project revenue. Moreover, the lifetime extension option is pushed these days by several drivers as: (i) difficulties to find new park emplacements with good wind conditions[61]; (ii) the end of operation and maintenance contracts of parks with turbines in their end-of-life but in relatively good operation conditions; (iii) and the combined effect of an important public support reduction, challenging planning and regulatory approvals for repowering[62]. Finally, it has been estimated that the average cost of extending the life of an operational wind turbine is 100.000 €/MW compared to 1 million €/. MW for repowering[63]. Considering these benefits, the lifetime extension option will at least be examined for most of the wind parks when achieving their end-of-life in the near future as long as wind turbines achieve their design lifetime in relatively good conditions and local laws allow it.

Many onshore turbines operate 15 years and it is expected that 65 GW of the currentEuropean onshore fleet will reach their design lifetime by 2028[64], which is a 35% of the currently installed onshore capacity. Similar to this, FTI Consulting believes that more than 86 GW of wind capacity is expected to be decommissioned across Europe by 2030[65]. In this period, from 2020 to 2030, and knowing that the current European fleet has an average power of around 2.5 MW[66], it can be estimated that lifetime extension concepts will be potentially applicable to around 25-30 thousand turbines. For a second period, between 2030 and 2050, lifetime extension concepts developed for this first period need to be updated to consider two important changes: (i) an important size change in onshore wind turbines and (ii) environmental and implementation conditions to also apply them in offshore wind turbines that will start to reach their end-of-life. In 2050, and based on the current average design lifetime (29.6 years), the wind turbines installed in 2020 will require life extensions in 2050.

[60] An owners guide to wind turbine lifetime extensions. Windpower 2017. https://www.windpowerengineering.com/owners-guide-wind-turbine-lifetime-extensions/
[61] Repowering and lifetime extension: making the most of Europe's wind energy resource. Wind Europe. https://www.greentechmedia.com/articles/read/european-onshore-wind-turbines-need-upgrades-by-2022
[62] A decision support tool to assist with lifetime extension of wind turbines (T.Rubert, Renewable Energy 2018). https://reader.elsevier.com/reader/sd/pii/S0960148117312685?token=35C0C4B5825B8B7C8F740368158B41332E2F154BFE10CFACFE1D70C2005E077B37094A74D996D0D264DEE2BA4953712A
[63] Is lifetime extension of your ageing turbine the right solution? https://stateofgreen.com/en/partners/spica-technology/news/is-lifetime-extension-of-your-ageing-turbine-the-right-solution/
[64] 65GW of European Onshore wind turbines need upgrades or replacement by 2028. https://www.greentechmedia.com/articles/read/european-onshore-wind-turbines-need-upgrades-by-2022
[65] An owners guide to wind turbine lifetime extensions. Windpower 2017. https://www.windpowerengineering.com/owners-guide-wind-turbine-lifetime-extensions/
[66] Wind Energy in Europe in 2019: Trends and statistics https://www.windpowermonthly.com/article/1461367/average-turbine-size-reaches-24mw-updated

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Life extension supposes an LCOE reduction and a project revenue increase[67] regardless the type and depth of the lifetime extension actuation performed. Moreover, the investment itself is justified only by the operation and maintenance (O&M) costs reduction during this life extension period as shown in Figure 30. However, it can be also deduced that the simpler/lighter the life extension concepts applied (less investment), the lowest the LCOE (Figure 31). Thus, simple repairs and stiffening solutions applicable to different components could be economically more interesting than a complete retrofit of a wind turbine.

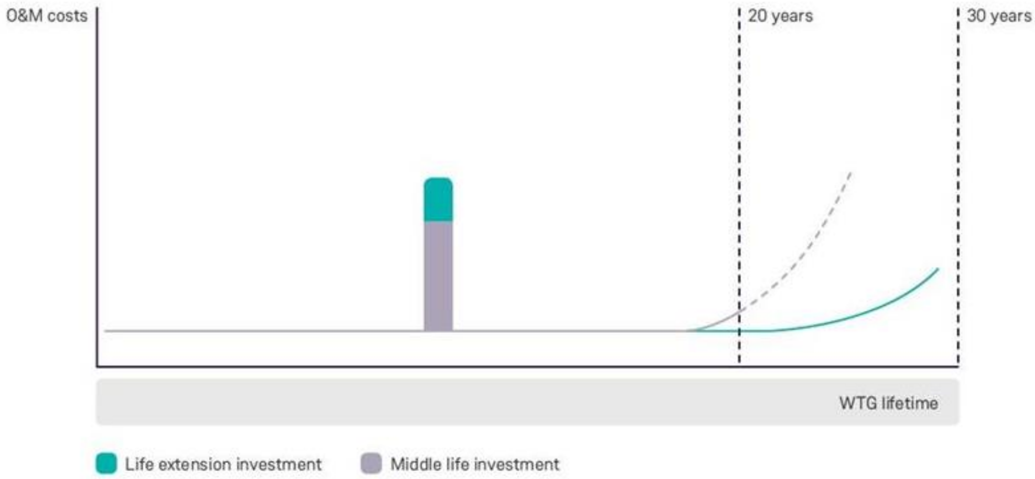

Figure 30: O&M costs and lifetime extension investment[68].

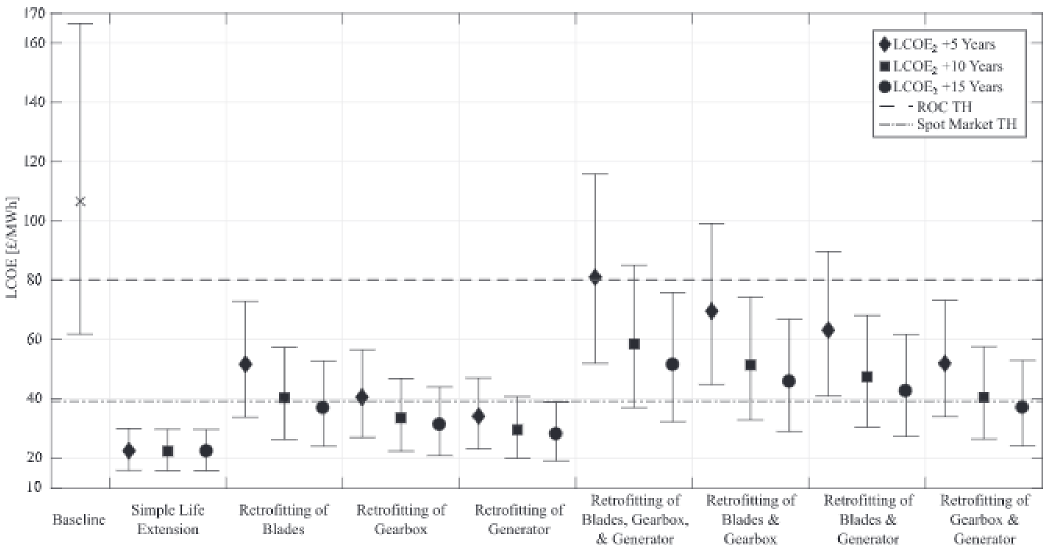

Figure 31: The effect of different lifetime extensions actuations on LCOE[69].

[67] An owners guide to wind turbine lifetime extensions. Windpower 2017. https://www.windpowerengineering.com/owners-guide-wind-turbine-lifetime-extensions/

[68] Life Extension, Lifetime upgrade. Siemens Gamesa. https://www.siemensgamesa.com/products-and-services/service-wind/life-extension

[69] A decision support tool to assist with lifetime extension of wind turbines (T.Rubert, Renewable Energy 2018). https://reader.elsevier.com/reader/sd/pii/S0960148117312685?token=35C0C4B5825B8B7C8F740368158B41332E2F154BFE10CFACFE1D70C2005E077B37094A74D996D0D264DEE2BA4953712A

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This scenario is encouraging wind turbine manufacturers to develop tools and methods to make decisions on the life extension or/and decommissioning of wind turbines close to the end of their design lifetime[70]. Siemens Gamesa, for instance, offers a life extension service to add 10 years to their installed 660 kW, 850 kW, and 2.0 MW wind turbines[71].The other two main manufacturers (GE[72] and Vestas[73]) also include a lifetime extension service within their service brochures. Thus, manufacturers want to develop these methods and offer them as a service.

The strategy for extending the useful lifetime of a wind turbine requires inspection of the components of the wind turbine and evaluating both, the operational data available and the problems encountered previously, to ascertain their integrity and the risk of failure during continued operation. Extending a turbine's life beyond its usual design life of 20 or 25 years requires the owner to demonstrate (through inspections, operational data, or both) that the annual probability of failure of structural components is still acceptable, considering the maintenance history and component-failure modes. For this reason, certification bodies, as DNV-GL, have already developed standards applicable to lifetime extension of wind turbines[74] and certification procedures to do so[75].

[70] Strategy for extending the useful lifetime of a wind turbine. https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Statistics-2019.pdf
[71] Life Extension. Lifetime upgrade by Siemens Gamesa. https://www.siemensgamesa.com/products-and-services/service-wind/life-extension
[72] Repowering and life extension for older onshore wind turbines. https://www.ge.com/renewableenergy/wind-energy/onshore-wind/services/upgrades-refurbishment
[73] Vestas lifetime extension. https://shop.vestas.com/en/services/consultancy-and-training/vestas-lifetime-extension/
[74] DNVGL-ST-0262 Life extension for wind turbines. https://rules.dnvgl.com/docs/pdf/DNVGL/ST/2016-03/DNVGL-ST-0262.pdf
[75] DNVGL-SE-0263 Cerftification of lifetime extension of wind turbines. https://rules.dnvgl.com/docs/pdf/DNVGL/SE/2016-03/DNVGL-SE-0263.pdf

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2.8 Summary of forecast values

Table 1: Current and forecast values

		ONSHORE WIND TURBINES						OFFSHORE WIND TURBINES					
		2020 - BAU		2030		2050		2020 - BAU		2030		2050	
	Unit	Avg *	Max**	Avg *	Max**	Avg *	Max**	Avg *	Max**	Avg *	Max**	Avg *	Max**
Worldwide: installed capacity	GW	620[a]		1787[b]		5044[b]		29.1[a]		228[b] 175-210[e]		1000[b]	
Europe: Installed capacity	GW	183[c]		215[b]-287[u]		483[b]		22[c]		78[b] 77-127[d]		215[b]	
Wind turbine unitary nominal power	MW	3,1[k]	5,3[m]	5	10[i]	10	>10	7,2[k]	12 [f]	10-12	15-20[n]	20[o]	>20
Capacity factor	%	24[k]		30-55[b]		32-55[b]		38[k]	63[f]	36-58[b]		43-60[b]	
Wind farm size	GW	***	Operating with 8, planned 20 for 2020 [l]	***	***	***	***	621[e]	1,21[j]	1-1.5	3	---	---
Number of turbines per wind farm	[]	***	1100, 7000[l]	***	***	***	***	87[e]	174[j]	83-125	125	---	---
Hub height	m	110[h]	101-161 [m]	90-127[p]	119[i]	Optimized values respect to the 10 MW in 2030		100	150[f]	Optimised values respect to the 12 MW in 2020	160.2[g]	Optimized values respect to the 20 MW in 2020	---
Rotor diameter	m	130[h]	158[m]	145[p]	178.3[i]		---	154	220[f]		276[g]		---
Blade length	m	62[h]	77,3[s]	71[p]	89[i]		---	75	107[f]		135[g]		---
Blade weight	Tn	16,4[h]	---		48[i]		---	---	---		259[g]		---
Blade root diameter	m	2,6[h]	3,4[r]	3,4[r]	5,6[i]		---	4[s]	6[s]		5.5-7[g]		8-10 [q]
Power train nominal torque (LSS)	kNm	2.925[h]	---	3946[t]	10.730		---	---	---		26.711[g]		---
Power train nominal speed	rpm	11,75[h]	---	12.1[t]	8.9[i]		---	---	---		7,15[g]		---

(*) Expected values for average size installed wind turbine.
(**) Maximum expected values for new installed wind turbine prototypes.
(***) For onshore wind farms, size and number of turbines range is high: each project defines different requirements: the landscape and space are important conditions.
--- Parameter information not found.
Values without any marks or references are predictions estimated by the authors of this deliverable

(a) GWEC. Global Wind Report 2019. March 2020.
(b) FUTURE OF WIND: Deployment, investment,technology, grid integration and socio-economic aspects. IRENA. October 2019
(c) Wind Energy in Europe in 2019. WindEurope. February 2020.
(d) World Energy Outlook 2019. IEA. November 2019

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(e) Offshore Wind Outlook 2019. IEA. November 2019
(f) Haliade-X 12 MW offshore wind turbine platform. www.ge.com/renewableenergy/wind-energy/offshore-wind/haliade-x-offshore-turbine
(g) T. Ashuri, etal, Aeroservoelastic design definition of a 20 MW common research wind turbine model, 19:2071-2087, Wind Energy, 2016.
(h) IEA Wind TCP Task 37: Systems Engineering in Wind Energy - WP2., Reference Wind TurbineS, Technical Report, IEA WIND, May 2019
(i) LIFES50+ H2020 project: D1.2 Wind turbine models for the design: Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50m, 2015
(j) Hornsea, the United Kingdom
(k) Wind Energy in Europe in 2019: Trends and statistics.
(l) Gansu Wind Farm in China
(m) GE 5.3 MW Cypress
(n) IEA: Offshore Wind Outlook 2019 report
(o) https://www.dnvgl.in/technology-innovation/broader-view/electrifying-the-future/third-generation-wind-power.html
(p) SG 5.0-145 Onshore wind turbine
(q) Value extrapolated from Figure 19: asymptote tendency for turbines >20 MW
(r) NREL offshore 5-MW baseline wind turbine
(s) Matching the diameter of the root blade to the hub average diameter (assuming a semi-spherical hub): Rotor diameter – (2* blade lengths) ~ average hub diameter
(t) Development of a 5 MW Reference Gearbox for Offshore Wind turbines, A. Rasekhi, Wind Energy, DOI: 10.1002/we
(u) Central scenario. Wind energy in Europe: Scenarios for 2030. Wind Europe. September 2017.

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2.9 New technological concepts and trends

Wind energy is a very active sector in terms of research and development, which includes new disruptive methods, concepts and technologies for wind turbines. Many engineering and research groups are actively working around the world to develop and bring these concepts to market, with a common objective of reducing the LCOE. The objective of this subsection is to identify new technological concepts and trends that could modify the forecasts given in the previous subsections of this document or impact the relevance of the technologies proposed in the INNTERESTING project.

A recent review of emerging technologies by the most important research institutes[76] summarizes some of the most relevant developments, considering their potential, challenges, application and technology readiness. That review study is used as a reference for this subsection.

The first disruptive concept that could impact the technologies developed withing the INNTERESTING project (for the specific CS) modifies the topology of current wind turbines completely, such as concepts related to *Airborne wind energy* (AWE, Figure 32). These concepts would eliminate the need of large bearings large gearboxes, and large test benches. Therefore, the testing methods to be developed in this project would also be unnecessary. These concepts convert wind energy into electricity with the common feature of autonomous kites or unmanned aircrafts, linked to the ground by one or more tethers. Their main benefit might be the removal of costly towers, blades and generators, and the advantage of being able to work at higher altitudes. The main challenges identified are related to the high complexity of the system, lack of proven reliability (durability of flexible materials) and limited knowledge. Some authors claim a scale-up possibility of these concepts above the 1MW range. However, most projects are in technology readiness levels (TRL) 3-5 and not expected to be commercially available in less than 10 years.

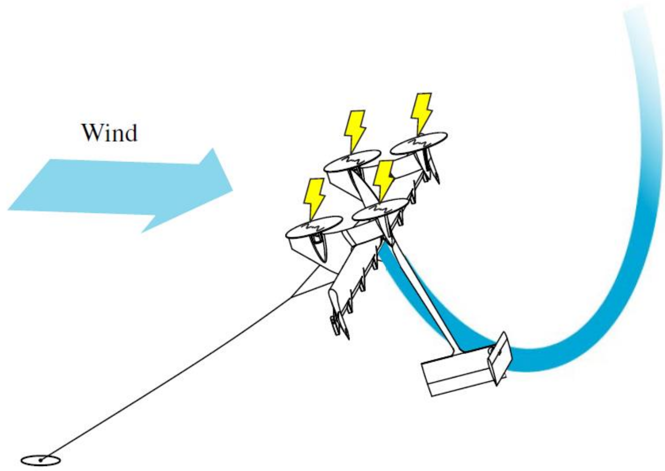

Figure 32: Tethered rigid wind AWT (airborne wind turbine) in crosswind flight with onboard mounted wind turbines [77]

[76] Future emerging technologies in the wind power sector: A European perspective, Renewable and Sustainable Energy Reviews, S. Watson, et al.,Volume 113,2019,109270,ISSN 1364-0321.
[77] Wijnja, Jelle & Schmehl, Roland & De Breuker, Roeland & Jensen, Kenneth & Vander Lind, Damon. (2018). Aeroelastic analysis of a large airborne wind turbine. 10.13140/RG.2.2.10916.99209.

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Floating offshore wind is considered an upcoming trend for the coming years and decades. Most of the concepts that are currently being developed are based on the well-stablished three bladed horizontal axis wind turbine configurations. However, there are some Vertical Axis Wind Turbine (VAWT) concepts specifically designed for floating platforms, which takes advantage of the low center of gravity of these concepts (since the generator is usually located at ground or sea level) [78] (Figure 33). The development and commercialization of VAWT concepts could eventually eliminate the need for gearboxes, since most concepts rely on direct drive permanent magnet generators. Despite this, large bearings might still be needed in these concepts as rotor support, to transfer bending loads to the tower. Although current TRL for some VAWT concepts is high (see Anew 1.5MW VAWT for example), as far as the authors know, large scale wind farms with VAWT are currently not being planned. Therefore, the probability of these VAWT concepts having an impact on the INNTERESTING project outcomes is expected to be low on the short-medium term, although this might change in the long term.

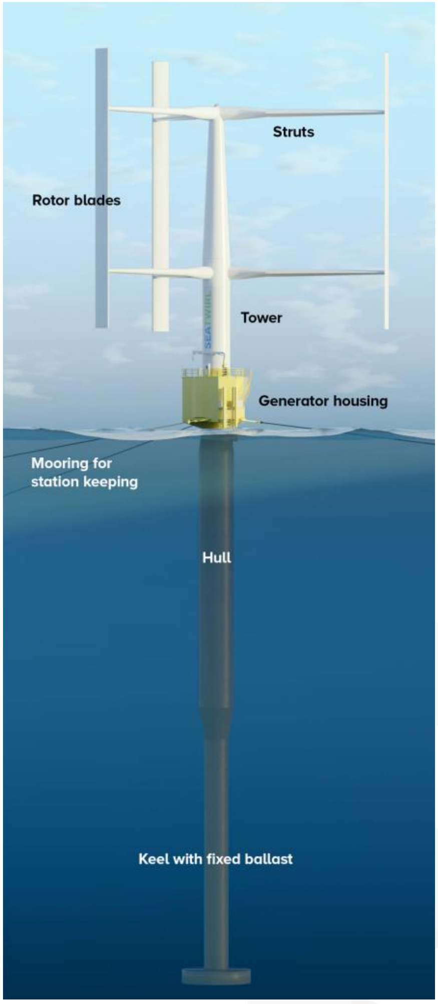

Figure 33: The SeaTwirl concept[79]

[78] Erik Möllerström, Paul Gipe, Jos Beurskens, Fredric Ottermo,A historical review of vertical axis wind turbines rated 100 kW and above, Renewable and Sustainable Energy Reviews, Volume 105, 2019, Pages 1-13, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2018.12.022.
[79] www.seatwirl.com

Technologies that fall inside the *smart rotor* categories (i.e. bend twist coupling, morphing, vortex generators, blades with movable parts, circulation control) try to obtain local optimal blade setting, which is hard to find in blades longer than 70m. Smart rotor technologies allow fatigue and extreme load reduction, maximising energy output, and are foreseen as key technologies for upscaling above the 20 MW range. However, all the analysed technologies still rely on blade pitching, and, therefore, the need of large pitch bearings is still foreseen even if smart rotor technologies above the 20MW range become standard.

The *multi rotor wind turbine*[80] concept increases the wind turbine nominal power without extending the blades. This configuration is based on using several small rotors equivalent to a large rotor to produce same amount of power. The greatest advantage lies in the standardization of the components and therefore their reduction in cost. It also reduces the loads on the system and improves the logistics for assembly and maintenance. This concept has already been validated in a 900 kW prototype installed by VESTAS in 2016, where (according to the Danish manufacturer) many technical benefits were observed, including a 1.5% power gain[81] (Figure 34).

Figure 34: Illustration of the multi-rotor concept demonstration turbine[82]

In this subsection new technological concepts and trends have been identified that can impact the INNTERESTING project objectives. In general, its impact has been identified as low, since although some concepts have already been validated, there is still a long way to go until their possible implementation.

[80] Sandip A Kale, *A review of multi-rotor wind turbine systems*, Journal of Sustainable manufacturing and renewable energy, vol. 2, 2013
[81] https://www.windpowermonthly.com/article/1521072/measurable-power-gains-found-multi-rotor-vestas-concept
[82] www.vestas.com

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3 ENVIRONMENTAL REQUIREMENTS FOR FUTURE WIND TURBINES

Wind energy constitutes huge benefits like renewable energy, employment generation (including manufacturing of wind turbines, installation of the system, operation and maintenance), energy security, etc. However, this section focusses on the potential negative environmental impacts associated with the deployment of wind turbines and the requirements in that framework for future wind turbines.

An appropriate design of the wind turbine can contribute to a decrease in adverse environmental factors[83]. Many of the problems described below have to be addressed in the permitting phase of a wind project and are subject to various regulations and laws.

Each aspect is first described for wind turbines in general, followed by specific findings related to the INNTERESTING project by focussing on the pitch bearing, gearbox components, and testing methods of large wind turbines.

3.1 Wind turbine noise

3.1.1 Types of noises

Noise levels can be measured, but the public's perception of the noise impact of wind turbines is a partly subjective determination. There are four types of noise that can be generated by wind turbine operation[83]:

1. Tonal (at discrete frequencies), caused by wind turbine components such as meshing gears, non-linear boundary layer instabilities interacting with a rotor blade surface, by vortex shedding from a blunt trailing edge, or unstable flows over holes or slits;
2. Broadband ('whooshing' sound), often caused by the interaction of wind turbine blades with atmospheric turbulence;
3. Low-frequency, mostly associated with downwind turbines, caused when the turbine blade encounters localized flow deficiencies;
4. Impulsive, may be caused by the interaction of wind turbine blades with disturbed air flow around the tower of a downwind machine, and/or the sudden deployment of tip breaks or actuators.

The cause of noises from wind turbines can be divided into two main categories: aerodynamic and mechanical. A turbine's sound power is the combined power of both. Aerodynamic noise is generated by the blades passing through the air. The power of aerodynamic noise is related to the ratio of the blade tip speed to wind speed. The mechanical noise is associated with the relevant motion between the various parts inside the nacelle (e.g. gearbox). The components move or rotate in order to convert kinetic energy to electricity with the expense of generating sound waves and vibration which is transmitted through the structural parts of the turbine[84].

[83] Manwell, J.F., McGowan, J.G., & Rogers, A.L. (2002). *Wind energy explained: theory, design and application*. Reprint, John Wiley & Sons, 2006.
[84] Pantazopoulou,P. (2010). Wind turbine noise measurements and abatement methods. In *Wind Power Generation and Wind Turbine Design*. WIT Transactions on State of the Art in Science and Engineering, Vol 44, 641-659.

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A tone is a narrow frequency of sound that is prominent against the neighbouring broadband noise. Tonal noise characteristics at wind farms can sometimes occur due to both aerodynamic noise sources from the turbine blades as well as mechanical noise sources within the nacelle (e.g. gearbox). Tonal noise characteristics can result in increased annoyance at receiver locations. Gearboxes have natural frequencies and mode-shapes dependent upon the stiffness of gear shafts and tooth pairs which can interact with tonal sources such as gear meshing frequencies to result in audible tones, and greatly increase the annoyance factor of wind farms and adversely impact on human health[85].

3.1.2 Wind turbine noise recommendations

The Guideline Development Group of the World Health Organization (WHO) conditionally recommends reducing noise levels produced by wind turbines to be below 45 dB[A] L_{den}, as wind turbine noise above this level is associated with adverse health effects[86].

In addition, the WHO recommends in their night noise guidelines an $L_{night,outside}$ of 40 dB as target to protect the public, including the most vulnerable groups such as children, the chronically ill and the elderly. For the countries where the night noise guideline cannot be achieved in the short term for various reasons, and where policy-makers choose to adopt a stepwise approach, an $L_{night,outside}$ value of 55 dB is recommended as an interim target. For setting these target the WHO considered the thresholds of night noise exposure indicated by $L_{night,outside}$ as defined in the Environmental Noise Directive (2002/49/EC)[87].

3.1.3 Wind turbine generator and noise relationship

Evidence shows that the more powerful the wind turbine generator (WTG)and the larger the WTG rotor diameter, the more noise it tends to emit;,. In addition, the more powerful the WTG, the greater the proportion of its noise is in the infrasound and low frequency sound ranges[88].

In 2011, Møller and Pedersen[89] published a paper based on measurement of multiple turbines which showed both that the sound power level (L_{WA}) and low frequency sound power level (L_{WALF}) increase with increasing turbine size and that the apparent sound power increases more than proportionally to the nominal electric power. Therefore, to the extent that turbines follow the trend of the regression line (see Figure 35), a turbine of double size emits more than double the sound power.

Møller and Pedersen showed that with the following regression chart, which plots sound power level against nominal electric power, the two to generally increase together.

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[85] Dawson, B. & MacKenzie, N. (2014). Tonal characteristics of wind turbine drive trains. *Inter.noise 2014.* Proceedings
[86] World Health Organization, WHO Regional Office for Europe. (2018). *Environmental noise guidelines for the European Region*. Retrieved from http://www.euro.who.int/en/health-topics/environment-and-health/noise/environmental-noise-guidelines-for-the-european-region.
[87] World Health Organization, WHO Regional Office for Europe. (2009). *Night noise guidelines for Europe.* Retrieved from: http://www.euro.who.int/en/health-topics/environment-and-health/noise/publications/2009/night-noise-guidelines-for-europe.
[88] Crawford, M. (2014). *Overwhelming grounds for rejecting requested modification 2 for proposed Capital II wind farm*. Retrieved from https://waubrafoundation.org.au/wp-content/uploads/2015/01/Crawford-Dr-M.-Overwhelming-Grounds-for-Rejecting-Requested-Modification-2-for-Proposed-Capital-II-Wind-Farm-21-October-2014.pdf.
[89] Møller, H. & Pedersen, C.S. (2011). Low-frequency noise from large wind turbines. *The Journal of the Acoustical Society of America*, 129(6), 3727-3744.

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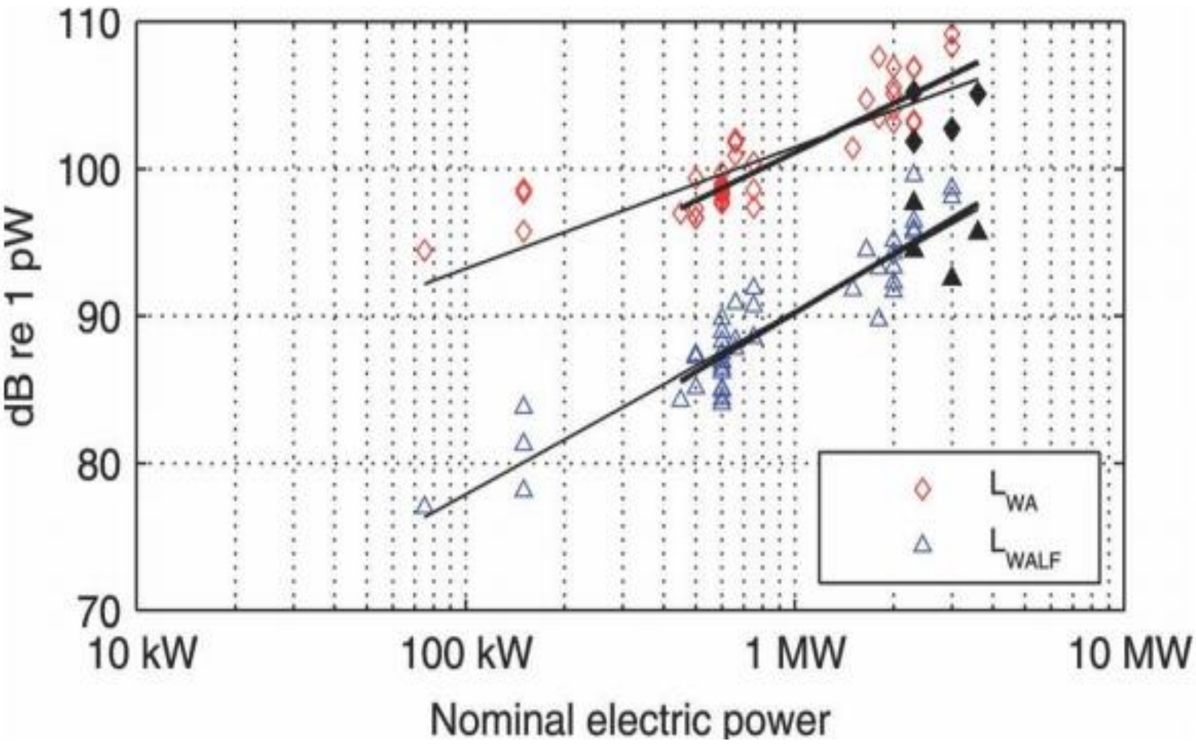

Figure 35: Red/blue marks are apparent sound power levels (L_{WA} and L_{WALF}) in the reference direction as a function of turbine size, assumed wind speed is 8 m/s. Regression lines: all turbines included (thin lines), four turbines below 450 kW excluded (bold lines). Black-filled marks are the four turbines below 460 kW[89].

3.1.4 Conclusion on wind turbine noise

To enable bigger wind turbines operating according regulations and without harm to environment, it is essential to have advanced simulation and prototype virtual validation methods. In previous research work on future wind turbines sound and noise issues have not been considered to a large extent. References on wind turbine noise of modern large scale turbines of 10 MW or even bigger than 3 MW are difficult to find. Thus it can be questioned whether they exist. However, it is known that noise emission will increase along the power, but the environmental regulations are expected to stay as they are. In addition, noise can be considered as one of the most significant factors affecting social acceptance of wind energy (see also section 4).

New component validations like plain bearing technology also fastens up the onshore wind turbine power increase. To support this trend both the mechanical reliability of the gearbox and the confidence against tonal free wind turbine behaviour needs to be considered.

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3.2 Impact on flora and fauna

3.2.1 General

Wind turbine sites have the potential to directly and indirectly affect biological resources (broad variety of plants and animals that live, use or pass through an area, soil, water, bacteria, fungi etc.). The effects on, or conflicts with, flora and fauna, if any, will depend on the plants and animals present, and on the design and layout of the wind energy facility[90].

3.2.2 Specific case: bird interaction with wind turbines

Regarding bird interactions there are both potential negative as well as positive effects to be mentioned in the framework of wind energy development.

- Potential negative effects on birds of wind energy development: bird electrocution and collision mortality; change to bird foraging habits; alteration of migration habits; reduction of available habitat; and disturbance of breeding, nesting and foraging.
- Potential positive effects on birds of wind energy development: protection of land from more dramatic habitat loss; provision of perch sites for roosting and hunting; provision and protection of nest sites on towers and ancillary facilities; protection or expansion of prey base; and protection of birds from indiscriminate harassment[91].

Mitigation measures consist of, among others, alternating tower designs, burying electrical lines, or leaving sufficiently large areas within a wind farm free of wind turbines to enable safer foraging and travel by birds. Fatalities could also be minimized or reduced by shutting down turbines during ≥1 season or in very strong winds[92]. An example of Dutch mitigation efforts compromises adding microphones, cameras and speakers to detect birds and bats. When detected, the wind turbines are actively halted to decrease mortality. Furthermore, the lowest point of the blade is 60 meters above ground, while most birds fly 20 to 35 meters above ground. To minimize downtime (monthly cost of 15 k€), research is done on methods to scare off the birds[93].

3.2.3 Conclusion on impact on flora and fauna

Bird interaction mitigation measures are not related to the development of pitch bearing and gearbox components, nor to the development of testing methods for prototype validation within INNTERESTING.

The turbine size, however, can have an impact on bird interaction. For a desired energy capacity, fewer larger turbines may be preferred over many smaller turbines to reduce the number of structures in the wind farm[91].

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[90] Manwell, J.F., McGowan, J.G., & Rogers, A.L. (2002). *Wind energy explained: theory, design and application*. Reprint, John Wiley & Sons, 2006.
[91] Manwell, J.F., McGowan, J.G., & Rogers, A.L. (2002). *Wind energy explained: theory, design and application*. Reprint, John Wiley & Sons, 2006.
[92] Smallwood, K. S., Rugge, L., & Morrison, M. L. (2009). Influence of behavior on bird mortality in wind energy developments. *The Journal of Wildlife Management*, 73(7), 1082-1098.
[93] NOS (2020). *Molens in Zeeland staan stil voor vogels en dat kost 15.000 euro per maand.* News article of February 6th 2020, retrieved from https://nos.nl/artikel/2321832-molens-in-zeeland-staan-stil-voor-vogels-en-dat-kost-15-000-euro-per-maand.html.

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3.3 Visual impact of wind turbines

The visual impact of wind farms is influenced by elements such as visual clarity, harmony, order, hierarchy, distance, contrast and movement[94]. The public's perception may change with the location of the wind turbines[91]. Offshore wind farms usually have more and bigger turbines than onshore wind farms. However, the visual impact is lower due to the distance from the coastline. Nevertheless, special attention to the visual impact of offshore wind parks could be needed in case of the highly valued uniqueness of the coastal landscape[95].

Visual impact mitigation measures (such as the use of uniform colour, structure types and surface finishes) are not directly related to the testing methods and component developments of the INNTERESTING project. The turbine size, however, is one of the important design characteristics when assessing the visual impact of a proposed wind farm development[96].

3.4 Electromagnetic interference effects

Key parameters that influence the extent of electromagnetic interference (EMI) caused by wind turbines include the type of wind turbine, wind turbine dimensions, turbine rotational speed, blade construction material, blade angel and geometry and tower geometry[97].

There is a trend of more complex electronic monitoring equipment for large wind turbines, because of the increasing availability requirements[98]. The overall dimensions, and particularly the diameter of the rotor, are important design variables for the cause of interference[97]. Careful and adequate wind farm design can prevent any possible inference problems on communication systems[99].

EMI effects are not directly related to the testing methods and component developments of the INNTERESTING project.

3.5 Land-use environmental impacts

Land-use issues include government regulations and permitting on the one hand and issues with an impact on public acceptance (such as turbine density, access roads and rural preservation) on the other hand. Many of the actions to ensure that wind energy projects are consistent and compatible with land use requirements involve the layout and design of the wind farm[97]. For the distribution of territorial sea area, negotiations are needed amongst energy companies (offshore wind farms), nature conservation and environmental organisations, fishery, etc.[100].

Land-use issues are not directly related to the testing methods and component developments of the INNTERESTING project.

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[94] Bishop, I. D., & Miller, D. R. (2007). Visual assessment of off-shore wind turbines: The influence of distance, contrast, movement and social variables. *Renewable Energy*, 32(5), 814-831.
[95] European Wind Energy Association (2009) *Wind Energy - The Facts: A Guide to the Technology, Economics and Future of Wind Power*. Retrieved from: https://www.wind-energy-the-facts.org/.
[96] Stanton, C. (1995). The visual impact and design of wind farms in the landscape. In *Wind energy conversion 1994*. Proceedings.
[97] Manwell, J.F., McGowan, J.G., & Rogers, A.L. (2002). *Wind energy explained: theory, design and application*. Reprint, John Wiley & Sons, 2006.
[98] Krug et al. (2004) and Matsuzaki & Todoroki (2005) cited in: Krug, F., & Lewke, B. (2009). Electromagnetic interference on large wind turbines. *Energies*, 2(4), 1118-1129.
[99] European Wind Energy Association (2009) *Wind Energy - The Facts: A Guide to the Technology, Economics and Future of Wind Power*. Retrieved from: https://www.wind-energy-the-facts.org/.
[100] NOS (2020). *Akkoord over gebruik Nederlandse deel Noordzee: 'Het wordt passen en meten'*. News article of February 10th 2020, retrieved from https://nos.nl/artikel/2322441-akkoord-over-gebruik-nederlandse-deel-noordzee-het-wordt-passen-en-meten.html.

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3.6 Shadow flicker and flashing

Shadow flicker occurs when the moving blades of the wind turbine rotor cast moving shadows that cause a flickering effect, or when sunlight is reflected from turbine blades which causes a flashing effect. This could annoy people living close to the turbine[97].

Mitigation measures of shadow flickering, such as downtime at specific time periods, careful siting, bigger distance between turbine and closest neighbour, or careful use of materials for the blades, are not directly related to the testing methods and component developments of the INNTERESTING project.

3.7 Environmental impacts based on life cycle assessment

The environmental burdens due to material use and embodied energy, and benefits due to energy generation over the life cycle of wind turbines can be quantified via an environmental life cycle assessment (LCA). A cradle-to-grave LCA assesses the complete life cycle from the extraction of raw materials to manufacturing, transport, installation, use, and end-of-life. Results of an LCA are expressed as environmental indicators such as *global warming potential* (in kg CO_2 equivalents) and *abiotic depletion potential for non-fossil and metals* (in kg Sb equivalents). General frameworks, like the ISO 14040:2006 and EN 15804:2012+A2:2019, provide unified guidelines on how to perform an LCA.

In 2004, the World Energy Council compared different energy systems based on LCA[101] and concluded that:

> “The life cycle emissions of wind power depend on the amount of material and work needed to construct the wind turbines. The amount of electricity produced by a wind turbine during its life also depends on the load factor of the turbine. This factor is determined by the local wind statistics and the dimensions and other properties of the wind turbine. […] the number of turbines in a wind farm is not expected to affect the life cycle emissions significantly.”

The above conclusion that the environmental impact of wind turbines depends on the amount of material, i.e. that the manufacturing is the most impacting life cycle stage, is still valid when looking at more recent LCA studies of wind turbines[102].

In a review paper, Munir et al[103] conclude that large turbines have a better energy efficiency and lower environmental impacts per kWh produced than medium or small wind turbines. However, they also noticed that increasing the size after a certain range may have a counterproductive effect on the environmental impact.

[101] World Energy Council. (2004). *Comparison of energy systems using Life Cycle Assessment*. Retrieved from: https://www.worldenergy.org/publications/entry/comparison-of-energy-systems-using-life-cycle-assessment.

[102] For example:

- Life Cycle Assessment of a Nordex Windfarm with Delta4000 turbines, by Sphera for the Nordex Group, dating from 20/03/2020. Retrieved from https://www.nordex-online.com/wp-content/uploads/sites/3/2020/03/LCA-of-Nordex-Windfarm-with-Delta4000-turbines-without-Annex-B.pdf.
- Vestas have published roughly twenty LCA reports on their website, dating between 2011 and 2019: https://www.vestas.com/en/about/sustainability#!available-reports.
- European Wind Energy Association (2009) *Wind Energy - The Facts: A Guide to the Technology, Economics and Future of Wind Power*. Retrieved from: https://www.wind-energy-the-facts.org/.

[103] Munir, N.B., Huque, Z. & Kommalapati, R.R. (2016). Impact of Different Parameters on Life Cycle Analysis, Embodied Energy and Environmental Emissions for Wind Turbine System. *Journal of Environmental Protection*, 7, 1005-1015.

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In WP6 of the INNTERESTING project environmental LCAs will also be performed, specifically the LCA results of three BAU reference scenarios will be reported in D6.1 [M8], the results of the screening LCA of the three INNTERESTING case studies in D6.2 [M30], and the results of the final LCA of the INNTERESTING case studies in D6.3 [M36]. By comparing the LCA results of the INNTERESTING case studies with the results of the BAU reference scenarios, the environmental benefits of the concepts and solutions designed within the INNTERSTING project will be shown quantitively.

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4 SOCIAL REQUIREMENTS FOR FUTURE WIND TURBINES

In addition to the environmental LCA (see section 3.7), the social and socio-economic aspects that may affect stakeholders over the life cycle of the wind turbines will be evaluated in a social LCA (S-LCA). The S-LCA will identify potential social hotspots for workers, local community, society, value chain actors and consumers, which will be discussed in WP6.

This section gives an overview of the key messages from the literature review on social acceptance towards wind energy. In addition, section 5 provides a non-exhaustive overview of identified relevant projects and research on social acceptance of wind power as examples of good practices.

4.1 Definition of social acceptance

In 2016, the Joint Research Centre (JRC) of the European Commission[104] published a report on the status of social acceptance of wind energy so far and the main lessons learnt from 20 years of research. Regarding the definition of social acceptance, they state "Notwithstanding the criticisms of the term 'social acceptance' and the risk that it oversimplifies a complex social phenomenon, it continues to have a widespread recognition and has heuristic value for which there is presently no adequate alternative."

"There are a number of definitions of social acceptance made in the literature, including those based on lack of effective opposition to a project or a Pareto optimal trade off where welfare decreasing impacts are balanced by welfare increasing aspects (Cohen et al., 2014). A more general **definition of social acceptance**, adopted for the purpose of this report, is:

'**a favourable or positive response (including attitude, intention, behaviour and — where appropriate — use) relating to proposed or in situ technology or social technical system by members of a given social unit (country or region, community or town and household, organisation)'** (Upham, 2015, p. 107)"[104].

The International Energy Agency Wind Technology Collaboration Programme (IEA Wind TCP)[105] is an international co-operation that shares information and research activities to advance wind energy research, development and deployment in member countries[106]. The IEA Wind TCP has a specific Task dedicated to **social acceptance**[107]**, Task 28, as it continues to be a key constraint on the development of wind energy projects within participating countries.**

The Task 28 work plan and objectives states that "Wind energy forms an important part of policy goals in IEA Wind TCP member countries working to meet their renewable energy obligations. […] Projects that encounter concerned host communities – and, in some cases, opposition – can have increased costs and timelines, which decrease the overall rate of wind energy deployment. […] To achieve renewable energy policy objectives, social acceptance

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[104] Ellis, G. & Ferraro, G. (2016). *The social acceptance of wind energy. Where we stand and the path ahead.* JRC Science for policy report. EUR 28182 EN, doi 10.2789/696070

[105] https://community.ieawind.org/about/about-iea-wind

[106] There are currently 26 contracting parties from 21 member countries, the Chinese Wind Energy Association (CWEA), the European Commission, and WindEurope (formerly the European Wind Energy Association) participating in the IEA Wind TCP. These member countries and organizations form a global network of researchers and policy experts focused on sharing the latest technology research and best practices to overcome specific barriers for wind energy deployment.

[107] https://community.ieawind.org/task28/home

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needs to focus on the needs of all stakeholders such as policy makers, regulators, developers, local communities and special interest groups"[107].

IEA Wind TCP Task 28 applies the same definition as the JRC for 'social acceptance', i.e. "a favourable or positive response relating to proposed or developed technology by members of a given social unit (country or region, community or town and household, organization).".

4.2 Aspects of social acceptance

Social acceptance of wind power has often been characterized by a NIMBY (not in my backyard) syndrome. **The NIMBY-explanation is ,however, a too simplistic way of explaining all variables involved when determining the general and local public acceptance of a specific wind power development**. This means that the question of social acceptance really has many components: e.g. the general attitude towards wind power in the population as a whole, the acceptance in the population who will experience the local impacts, the conflict management strategies and economic involvement[108].

The elements of social acceptance of wind energy as defined by IEA Wind Task include:

Figure 36: The elements of social acceptance of wind energy as defined by IEA Wind Task 28[109].

[108] Rand, J. & Hoen, B. (2017). Thirty years of North American wind energy acceptance research: What have we learned? Article in *Energy Research & Social Science*, 29, 135–148;
Ellis, G. & Ferraro, G. (2016). *The social acceptance of wind energy. Where we stand and the path ahead.* JRC Science for policy report. EUR 28182 EN, doi 10.2789/696070;
Wolsink (2007) cited in: Peeters, K. et al. (2009). *Scientific report of the research project: Landscape capacity and social attitudes towards wind energy projects in Belgium*. 2006-2009. Belgian Science Policy – Science for a sustainable development. Available at https://ees.kuleuven.be/geography/projects/lacsawep/lacsawep-final-report.pdf;
Offshore Wind Energy website (no date). *4 Social Acceptance.* https://www.offshorewindenergy.org/CA-OWEE/Envi_4.html.
[109] Source: http://www.socialacceptance.ch/

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The results of the IEA Wind Task 28 work in the period 2012-2015 are available at http://www.socialacceptance.ch/. The work over the years has resulted in a database[110] with over 200 publications of projects and include the following topics:

1. Definition of social acceptance;
2. National wind energy concepts;
3. Stakeholders/target groups;
4. Distributional justice;
5. Procedural design;
6. Well-being;
7. Implementation strategies.

More information on results and publications of IEA Wind Task 28 are given in section 5.2.1.

4.3 Influences on social acceptance

Table 2 summarizes the influences on social acceptances of wind energy projects identified by Ellis and Ferraro[111] during their literature review.

Table 2: Summary of influences on social acceptance of wind energy projects[111]

Issue	Key influences
Individual attitudes	Age, gender etc. Strength of place attachment Political beliefs and voting preferences Emotional response Prior experience of wind turbines Attitudes to environmental issues Psychological factors including perception of social norms Individual roles (consumer, landowner etc.) Familiarity with wind energy
Relationships	Type and level of social capital Trust in government other public agencies and developers Proximity to, and visibility of, turbines Technology-society relationships Time, reflecting the dynamic nature of social acceptance National-local policy Regulator-developer links Discourses within and between communities
Contextual issues	Policy regimes Project design — turbine height, colour number and massing Place attachment Range and mix of actors Ownership of proposed project Specific siting issues Cumulative impacts
Perceived impacts	Noise Landscape Shadow flicker Property values Level of economic benefit

110 Available at http://www.socialacceptance.ch/WPrList.aspx?TR=E
111 Ellis, G. & Ferraro, G. (2016). *The social acceptance of wind energy. Where we stand and the path ahead.* JRC Science for policy report. EUR 28182 EN, doi 10.2789/696070

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	Bio-diversity: bats, birds Infrasound Navigation lights Health concerns Levels of economic benefits Disruption of 'place' Efficiency of turbines and wind energy Distributive justice
Process-related issues	Trust in institutions involved Transparency and openness Procedural justice Expectations and aspirations of public participation Availability and quality of information Power in the participation process Value places on lay and expert knowledge Timing Discourses of community, developer, regulatory bodies Fait accompli

4.4 Discussion on social acceptance

One of the main conclusions made by Ellis and Ferraro[112] is that there is **a need to increase the overall acceptance at society level, rather than at the level of individual projects**. However, also in individual projects actions can be taken to increase acceptance of the host community. This can be done, for example, by organizing effective public participation in the wind energy project and by increasing the economic benefit the host community has from the project[112;113]. Social acceptance depends on the characteristics of the location, policy regime and actors involved, therefore social acceptance challenges are different for each project[112].

The **main message from the literature review** by Ellis and Ferraro[112] on social acceptance of wind energy is that there is a vast range of literature available but it is **difficult to derive an overview** due to the complex range of case studies with different variables and measurements. In addition they state that "Case studies have been undertaken all over the world, providing a substantial body of evidence for which there is, as yet, **a lack of comprehensive and systematic review to identify common findings** and outstanding research questions.".

The recent publication of Rand and Hoen[114] comes to **the same conclusion: important insights are produced, yet knowledge gaps remain**. The review by Rand and Hoen synthesizes literature, revealing the following lessons learned:

- North American support for wind power has been consistently high.
- The NIMBY explanation for resistance to wind power development is invalid.
- Socio-economic impacts of wind power development are strongly tied to acceptance.
- Sound and visual impacts of wind power projects are strongly tied to annoyance and opposition, and ignoring these concerns can exacerbate conflict.

[112] Ellis, G. & Ferraro, G. (2016). *The social acceptance of wind energy. Where we stand and the path ahead.* JRC Science for policy report. EUR 28182 EN, doi 10.2789/696070
[113] Liebe, U., Bartczak, A. & Meyerhoff, J. (2017). A Turbine is not only a Turbine: The Role of Social Context and Fairness Characteristics for the Local Acceptance of Wind Power. *Energy Policy,* 107, 300-308. https://doi.org/10.1016/j.enpol.2017.04.043.
[114] Rand, J. & Hoen, B. (2017). Thirty years of North American wind energy acceptance research: What have we learned? Article in *Energy Research & Social Science*, 29, 135-148.

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- Environmental concerns matter, though less than other factors, and these concerns can both help and hinder wind power development.
- Issues of fairness, participation, and trust during the development process influence acceptance.
- Distance from turbines affects other explanatory variables, but alone its influence is unclear.
- Viewing opposition as something to be overcome prevents meaningful understanding and implementation of best practices.
- Implementation of research findings into practice has been limited.

Rand and Hoen[115] conclude that with continued research efforts and a commitment toward implementing research findings into developer and policymaker practice, conflict and perceived injustices around proposed and existing wind power projects might be significantly lessened.

4.5 Conclusion on social acceptance

Based on our literature research, no major difference is to be expected for social acceptance of the host community of a wind energy project with or without the solutions developed within INNTERESTING. There may be small improvements on some points. Enevoldsen and Sovacool[116] report that less maintenance and thus less idle time may lead to stronger acceptance. Research on the influence of wind farm life time on social acceptance is lacking. One of the conclusions of the literature review performed in the WISE Power project[117] is that public participation so far concentrates on the phases of planning, permitting and construction and little experience has been shared about the late phases of a wind farm lifecycle (operation and maintenance, decommissioning and repowering). However, they may become more important in the future.

While we could not find any information in the reviewed literature on the influence of the life span of wind turbines on social acceptance, there were some findings reported on social acceptance of repowering. Repowering is the replacement of old less productive wind turbines with new turbines. It is a relevant strategy because newer wind turbines often generate more energy with fewer wind turbines. The WinWind project[118] reports on the social acceptance of the repowering of the Abruzzo wind farm in Italy and mentions that it has been highly effective in achieving social acceptance in Abruzzo. It came along with a number of other initiatives and a consolidation of existing benefits.

Further research is thus necessary to learn more about the difference in social acceptance of wind farms with an extended life time versus repowering. It might as well be that extending the lifetime of existing wind turbines may be easier to accept for a community than replacing the wind turbines completely.

[115] Rand, J. & Hoen, B. (2017). Thirty years of North American wind energy acceptance research: What have we learned? *Energy Research & Social Science*, 29, 135-148.
[116] Enevoldsen & Sovacool (2016). Examining the social acceptance of wind energy: Practical guidelines for onshore wind project development in France. *Renewable and Sustainable Energy Reviews,* 53, 178-184.
[117] Dütschke E. & Wesche J.P. (2015). *Status quo of social acceptance strategies and practices in the wind industry.* Deliverable D2.2 of WISEPower Project. Available at http://wisepower-project.eu/.
[118] https://winwind-project.eu/fileadmin/user_upload/Resources/Posters/WinWind-case-study-poster_Abruzzo.pdf

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5 IDENTIFICATION AND ASSESSMENT OF GOOD PRACTICES

This section provides a non-exhaustive overview of identified relevant projects and research on social acceptance of wind power as examples of good practices.

5.1 Identification of relevant projects

The following two relevant projects related to the social acceptance of wind energy development have been identified: WISE Power and WinWind. They will be discussed briefly in this section including an overview of their relevant results.

5.1.1 WISE Power

The European project WISE Power[119] was executed between May 2014 and October 2016. The project on social acceptance of wind energy aimed at significantly **improve of local engagement and support for wind turbines while enhancing local community participation in the planning and implementation of wind energy projects**. By promoting social acceptance pathways that demonstrate how processes for active community engagement and ownership work and how they can be applied. The project had a strong focus on alternative financing[120] - such as community and cooperative funding of wind farms - as a method to enhance social engagement.

Several reports were published from this project, such as:

- The WISE Power result-oriented report[121]
- The report on the 'status quo of social acceptance strategies and practices in the wind industry'[122]
- The 'Report on innovative financing models for wind projects, expected to be supportive of social acceptance'[123]

Within the framework of the WISE Power project **a toolkit "WE Engage**"[124] was developed. The WE Engage Toolkit is designed to help all stakeholders build, implement and deliver effective and meaningful social engagement strategies in relation to onshore wind farms. The toolkit has been split into user groups so that - developers, transmission network operators, communities, local authorities and other stakeholders can use the tool in the way best **suited to specific needs**.

The toolkit is an interactive tool that relies on input from users by building a bank of case studies from across Europe, showing good practice and learning points from real life experience.

[119] http://wisepower-project.eu/
120 Report on innovative financing models for wind farms:
http://wisepower-project.eu/wp-content/uploads/20150209WISEPower_Deliverable_3-1_v3_Final.pdf
[121] http://wisepower-project.eu/wp-content/uploads/FINAL_WISE-Power-Result_oriented-report_Deliverable-D1.1-1.pdf
[122] http://wisepower-project.eu/wp-content/uploads/20150319_WISE_Power_Deliverable_2-2_final.pdf
[123] http://wisepower-project.eu/wp-content/uploads/20150401_WISEPower_Deliverable_3-3_Final1.pdf
[124] http://www.we-engage.eu/about-the-project/

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5.1.2 WinWind

In the H2020 WinWind project[125], that ran between October 2017 until March 2020, the overall objective was to enhance the socially inclusive and environmentally sound market uptake of wind energy by increasing its social acceptance in wind energy scarce regions. The specific objectives were: screening, analysing, discussing, replicating, testing, and disseminating feasible solutions for increasing social acceptance and thereby the uptake of wind energy. The project considered from a multidisciplinary perspective cases of 'wind energy scarce regions' (WESR) in Germany, Spain, Italy, Latvia, Norway and Poland.

Deliverable 4.3[126] provided a synthesis and comparative analysis on the lessons learnt concerning the successful removal of barriers of social acceptance, as well as the extent to which such measures are potentially transferable to other regions or countries. By establishing active stakeholder desks in the six countries, the project has reviewed critical barriers that hold back social acceptance, completed a comprehensive analysis of the barriers and drivers to achieve socially-inclusive wind energy projects from economic, social and environmental perspectives and indicated promising best practices.

Another outcome that resulted from the WinWind project is the recently published handbook: **A WinWin(d) for all. The handbook for socially inclusive wind energy**[127]. The goal of the handbook is to provide guidance on how public engagement for socially-inclusive wind energy projects can be approached and should be considered as a snapshot of results produced by a diverse consortium spanning the six countries. In the handbook they state that the most important ingredients for working out a successful strategy to overcome barriers to wind energy acceptance are: **active engagement of stakeholders and fair participation procedures**.

A complementary instrument to this handbook is the **online interactive tool "Pocket WinWind**"[128]. It provides further insights responding directly to the specific informational needs of developers, public decision makers and citizens. The tool provides support regarding how to approach challenges and make use of opportunities to achieve socially inclusive wind energy projects.

5.2 Identification of relevant research

5.2.1 Research outcomes by IEA Wind Task 28

This subsection highlights some additional relevant research results from IEA Wind Task 28 than the ones already given in section 4.

IEA Wind Task 28 published in 2010 a **state-of-the-art report on social acceptance of wind energy**, including ten country-specific state-of-the-art reports (for Canada, Denmark, Finland, Ireland, Japan, Norway, Switzerland, Italy, Germany, and USA)[129]. The reports discuss issues that are common across political, cultural, and national boundaries and highlights what is known along with mechanisms, strategies, and development models that have successfully resolved social acceptance challenges in the past.

[125] https://winwind-project.eu/
[126] Ecorys Spain, 2019. WinWind. Deliverable 4.3. Synthesis & comparative analysis of best practice case studies for promoting the social acceptance of wind energy https://winwind-project.eu/fileadmin/user_upload/Resources/Deliverables/Del_4.3.pdf
[127] https://winwind-project.eu/fileadmin/user_upload/Resources/WinWind_Handbook-2020-www-2.pdf
[128] https://www.pocketwinwind.eu/
[129] Available at http://www.socialacceptance.ch/ under results

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IEA Wind Task 28 also drafted an **expert group summary** on **recommended practices on social acceptance of wind energy projects**[130]. It includes strategies from around the world that have been successfully used to improve wind power projects, for the benefit of all, and strategies on how to implement projects that are acceptable to a majority. The recommendations are structured around the five elements of social acceptance of wind energy as defined by IEA Wind Task 28: (1) well-being, (2) policy and strategies, (3) procedural design, (4) distributional justice, and (5) implementation strategies (see Figure 36).

A more recent IEA Wind project (2017-2019)[131] had the objective to produce **an internationally recognised source of best practice guidelines** on offshore wind farm projects community acceptance and stakeholder engagement. Results of this project are not available online (yet).

On 26 September 2019 IEA Wind Task 28 hosted the **webinar**[132] "**International perspectives on social acceptance of offshore wind energy: an online roundtable**" in which they shared **lessons learned** from four international researchers. The accompanying introduction text mentions that despite increasing technological, market, and political acceptance of offshore wind, **the acceptance by local communities and stakeholders is a key determinant of deployment**. Additionally, although a rich literature exists on social acceptance and attitudes toward land-based wind, there is **less understanding and consensus regarding social responses to offshore wind**.

5.2.2 Other relevant research papers and articles

This sub-section presents a non-exhaustive list of identified relevant recent research articles related to social acceptance by civil society of wind energy developments (or renewable energy developments in general). The reference to the article are given first, followed by an abstract with the highlights of the article.

Bauwens, T., Devine-Wright, P. (2018). Positive energies? An empirical study of community energy participation and attitudes to renewable energy. *Energy Policy,* 118, 612-625. https://doi.org/10.1016/j.enpol.2018.03.062

> This paper gives an analysis of the relations between community energy membership and attitudes towards renewable and wind energy. The authors concluded that cooperative community members are more positive than non-members and that important differences among cooperative members can be identified. Their findings provide evidence for the positive benefits of public participation in renewable energy. Even recent members that have a more financially driven motivation than environmentally driven motivation have more positive attitudes to renewable and wind energy in comparison to non-members. This is an important finding because of recent shifts in the policy strategy of several European countries, with potentially negative consequences for the future of the participatory dimension of renewable energy deployment. The paper concludes that participation in community energy is complex, with varying degrees of commitment and future research needs to make this more apparent, distinguishing between communities of place and interest and gauging the impact of membership over time.

[130] http://www.socialacceptance.ch/images/RP_14_Social_Acceptance_FINAL.pdf
[131] https://community.ieawind.org/HigherLogic/System/DownloadDocumentFile.ashx?DocumentFileKey=f6c89045-f582-8765-cf87-30980b0a9935&forceDialog=0
[132] The webinar was recorded and is available on https://windexchange.energy.gov/webinars#6998.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 851245.

Liebe, U., Bartczak, A., Meyerhoff, J. (2017). A turbine is not only a turbine: The role of social context and fairness characteristics for the local acceptance of wind power. *Energy Policy*, 107, 300-308. https://doi.org/10.1016/j.enpol.2017.04.043

The article presents the results of factorial survey experiment on local acceptance of wind turbines in Germany and Poland, two countries differing in installed wind power capacity. Respondents were surveyed with hypothetical situations describing the construction of wind farms varying in the opportunity to participate in the planning process (participatory justice), the distribution of turbines across regions (distributive justice), and ownership, among other characteristics. The authors found that:

- Respondents are willing to accept new turbines in their vicinity if they can participate in decision making, the turbines are owned by a group of citizens, and if the generated electricity is consumed in the region instead of being exported.
- Overall, participatory justice is more important than distributive justice.
- Respondents who already have turbines in their vicinity show higher acceptance levels than those who are not yet affected.
- Thus, the negative externalities are likely to be overestimated in the planning and implementation process.

Devine-Wright, P., & Wiersma, B. (2019). Understanding community acceptance of a potential offshore wind energy project in different locations: An island-based analysis of 'place-technology fit'. *Energy Policy*, 111086. https://doi.org/10.1016/j.enpol.2019.111086

The paper addresses the gap of investion of the 'place-technology fit' of a potential renewable energy project before it is proposed, while it can inform technology deployment by taking local knowledge and preferences into account. Analysis results show that acceptance of the same project design differed significantly across alternative development locations. The authors identified that the most important predictor of acceptance was support for using wind energy for the local electricity supply. They concluded that place matters for community acceptance and that security and autonomy are co-benefits of local renewable energy projects that deserve further research.

Roddis, P., Carver, S., Dallimer, M, Norman, P., Ziv, G. (2018). The role of community acceptance in planning outcomes for onshore wind and solar farms: An energy justice analysis. Applied Energy, 226, 353-364. https://doi.org/10.1016/j.apenergy.2018.05.087

The article gives an analysis of the effect that community acceptance has had on planning applications for onshore wind and solar farms in Great Britain between 1990 and 2017. As a result it identified a set of twelve variables for community acceptance with statistically significant effects: four for onshore wind, four for solar farms, and four spanning both. For both technologies, the visibility of a project, its installed capacity, the social deprivation of the area, and the year of the application are significant indicators. The additional significant indicators identified for onshore wind are: impact on scenic recreation, remoteness, turbine capacity, and population density of the district. The authors concluded that aesthetics and visual impacts are strongly associated with planning outcomes, which is in line with much of the existing literature on public acceptance of both technologies. No political variables were found to be significant for either of the technologies. In terms of aesthetic variables, the less that the project represented a 'new' visual addition to the landscape, the more likely it was to be

approved. Environmental variables were not found significant for onshore wind. An important finding for onshore wind is that the capacity of individual wind turbines had a positive effect: for each 1 MW increase in turbine capacity, the likelihood of a positive planning outcome increased by 1.5 times. This suggests that small onshore wind projects with fewer larger turbines are preferable.

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6 INNTERESTING CASE STUDIES:SPECIFICATIONS

In recent years, various reference wind turbines (RWT, Table 3) have been defined, which have served as the basis for many research. One of the great advantages of using these RWTs is that their description and many of their analyses are available to the public, provided by the institutions and projects that have developed them. They share the specifications of a representative utility-scale multimegawatt turbine. In this project, these turbines will be the basis for the development of the case studies as starting data, turbine descriptions, etc. are public and usable by any person concerned.

Table 3 summarises the most significant reference turbines that appear in the literature. Some of them have been defined within European projects or by entities working within the wind sector. The turbines presented here are based on the type with three-bladed upwind. Other types of RWTs that demonstrate the feasibility of different wind turbine concepts are excluded in Table 3). For example, 30 MW Tri-rotorRWT developed by DTU for multi-rotor design analysis [133] or other concepts as DeepWind 5 MW, a vertical axis wind turbine developed in the DeepWind project[134].

Table 3: overview of three-bladed RWTs: Open-access designs of wind turbine systems, with supporting models for simulation and design.

Reference wind turbine (MW)	Location	Wind turbine name	Dimensions		Documentation and repositories for model's data
			Hub height [m]	Rotor diameter [m]	
0,75	Onshore	WindPACT 750 kW Wind Turbine (NREL)	60	50	135, 136
1,5	Onshore	WindPACT 1.5 MW Wind Turbine (NREL)	84	70	
3	Onshore	WindPACT 3 MW Wind Turbine (NREL)	119	99	
3,4	Onshore	IEA-3.4-130-RWT (IEA Wind TCP)	110	130	137, 138
5	Offshore	NREL offshore 5-MW baseline wind turbine[139]	90	126	140

[133] Christos Galinos, HAWC2 Model of a Fictitious 30MW Tri-Rotor WT based on DTU 10MW RWT, March 2018.
[134] Verelst, D. R., Aagaard Madsen, H., Kragh, K. A., & Belloni, F. (2014), Detailed Load Analysis of the baseline 5MW DeepWind Concept,
[135] https://github.com/WISDEM/Ref_Turbines/tree/master/WindPACT
[136] https://www.nrel.gov/docs/fy18osti/67667.pdf
[137] https://www.nrel.gov/docs/fy19osti/73492.pdf
[138] https://github.com/IEAWindTask37/IEA-3.4-130-RWT
[139] Jonkman J, et al. *Definition of a 5-MW Reference Wind Turbine for Offshore SystemsDevelopment*. NREL: Colorado, 2005.
[140] J. Jonkman, S. Butterfield, W. Musial, G Scott, Definition of a 5-MW Reference Wind turbine for offshore system development, Technical report 2009.

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8	Offshore	LEANWIND 8 MW	110	164	141
10	Offshore	DTU 10-MW RWT (medium Speed, Multiple-Stage Gearbox)	119	178	142, 143
10	Offshore	IEA-10.0-198-RWT (IEA Wind TCP) (based on DTO 10 MW: Direct-drive)	119	198	144,145
15	Offshore	IEA-15-240-RWT (IEA Wind TCP)	150	240	146, 147
20	Offshore	20MW RWT	160.2	276	148

Based on the data summarised in Table 1 and the RWT models available, the size of the wind turbines defined for each INNTERESTING CS are the following:

- **CS1:** for the **new pitch bearing concept** to be used in future larger wind turbines by 2030-2050, the selected nominal power is 20 MW (which is the expected maximum size by 2030 and the average size for 2050 for offshore).
- **CS2:** for the **next generation wind turbine main gearbox GBX concept,** including novel gearing and bearing systems to increase torque density and reliability in the future, the selected nominal power is 10 MW (it is the expected maximum size by 2030 and the average size for 2050 for onshore).
- **CS3**: for the **reparation and stiffening concept**, the selected nominal power is 3,4 MW (which corresponds with current average size). The wind turbine will be installed in 2020, and the pitch bearing will fail at an early stage of the lifetime (<10 years): a reparation and stiffening solution will be required.

Table 4: Expected average WT nominal power (data from Table 1).

		ONSHORE WIND TURBINES						OFFSHORE WIND TURBINES					
		2020 - BAU		2030		2050		2020 - BAU		2030		2050	
	Unit	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max
Wind turbine unitary nominal power	MW	3,1	5,3	5	10	10	>10	7,2	12	10-12	15-20	20	>20
		CS3			CS2	CS2					CS1	CS1	

The next subsections described the INNTERESTING case studies in more detail.

[141] https://pdf.directindustry.com/pdf/vestas/offshore-v164-80-mw-v112-33-mw/20680-310439.html
[142] Bac C, et al. *Description of the DTU 10 MW Reference Wind Turbine*. DTU Wind Energy:Frederiksborgvej, 2013.
[143] http://www.hawc2.dk/Download/HAWC2-Model/DTU-10-MW-Reference-Wind-Turbine
[144] https://www.nrel.gov/docs/fy19osti/73492.pdf
[145] https://github.com/IEAWindTask37/IEA-10.0-198-RWT
[146] https://www.nrel.gov/docs/fy20osti/75698.pdf
[147] https://github.com/IEAWindTask37/IEA-15-240-RWT
[148] https://github.com/tashuri/20MW-wind-turbine-model

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6.1 Specifications for future pitch bearings (CS1)

CS1 is based on a pitch bearing that will be installed in a 20 MW wind turbine from the year 2030 onwards. The wind turbine will be based on the 20 MW RWT, with a hub height of 160, rotor diameter of 276 m and the pitch bearing diameter of 7 m. The CS1 WT will be installed in the NORCOWE reference wind farm with a size of 2.04 GW and 102 turbines (wind farm size estimated from Table 1, between the average size and maximum size expected for 2030).

The original NORCOWE virtual wind farm location is considered for obtaining free field meteorological data: the wind farm is located about 45 nautical miles (80 kilometres) west of the Northern Germany Sylt island on the edge of the potential aptitude for wind turbines off the Schleswig-Holstein North Sea coast. The coordinates are: 55º 11,7 'N, 007º 9,5' E (Figure 37). The evaluation and definition of the loads will be defined in the deliverable of task T2.1 (WP2: Probabilistic loading data set and statistical results).

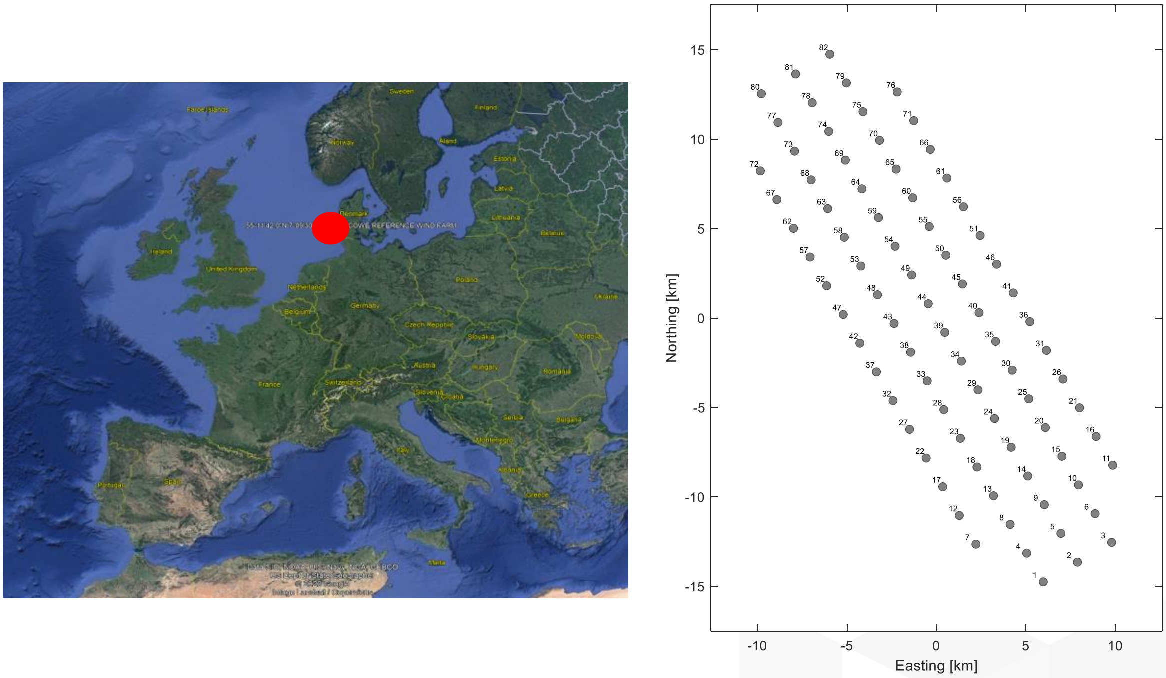

Figure 37. Virtual wind farm location for CS1 and Wind farm layout for CS1

Description of Fatigue and extreme Loads

This 20MW wind turbine model has been derived from upscaling the DTU 10MW reference wind turbine in the INNWIND project. An OpenFAST model of the turbine has been used for simulations (defined in Table 4). Due to the great length of the tower, in this case, all the DOFs for blades, drive, yaw and tower have been activated. In that way, the effects of negative damping, resulting from a high wind thrust and the tower flexibility, in the blade root loads are taken into consideration. Although the turbine is supposed to be an offshore wind turbine, it has a fixed bottom platform and the analysis focuses on blade bearings, ignoring the loads on platform and the tower. Thus, a rigid platform has been considered and the onshore wind turbine standard has been applied for the design of the load case simulations.

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For this study, the simulations for most DLCs from IEC 61400 – 1 cases have been included, instead of only the ones from DLC 1. This is due to the large size of the turbine, which supposes higher forces from wind, and so, higher deflections in the blades and the tower even while idling or parked. The simulated cases correspond with the ultimate loading cases, due to the importance of them in such a large turbine. Additionally, fatigue loading case DLC 1.2 was performed because normal operation supposes around 90% of fatigue loading in a wind turbine. For the fatigue case simulations, wind speeds from cut-in to cut-out every 2 m/s, with a normal turbulence model and 6 seeds for each speed, have been simulated. The rest of the design load case simulations have been carried out following the rule: normal operation in DLCs 1.1, 1.3, 1.4 and 1.5; normal operation with various fault cases, such as pitch system failure and grid loss, in DLCs 2.1, 2.2 and 2.3; start up combined with extreme wind events in DLCs 3.2 and 3.3; normal shutdown combined with extreme wind events in DLC 4.2; emergency shutdown in DLC 5.1; parked situation combined with extreme winds in DLCs 6.1, 6.2 and 6.3; and parked situation with fault conditions in DLC 7.1.

The required lifetime, based on the information in the subsection on chapter 2.6 Design lifetime requirement evolution and forecast, should be more than 50 years for wind turbines installed from 2030 on. For this CS, a more conservative lifetime value will be defined: 40 years (a 33-60% increase in lifetime respect to the current values).

Environmental condition, regulation, and other requirements

Some other environmental condition requirements are included in the next list:

- Surrounding temperatures in the range of -30°C (243K) to +50°C (323K) and humidity up to 100% for operational conditions.
- Surrounding temperatures in a range of -45°C (228K) to +55°C (328K) and humidity up to 100% for survival conditions.
- Ozone and ultraviolet radiation protection.
- Salinity: 35 mug/m3
- Solar radiation: 1000W/m2
- Salt, sand, and general dirt particles in the air.
- Lightning strike possibility

The new pitch bearing design must comply with the regulations in force at the time of manufacture (between 2030 and 2050). The current regulations are listed in ANNEX 1. In 10-30 years these regulations are expected to adapt to the new requirements defined in the future.

The new pitch bearing concept for this CS will be described in the INNTERESTING project, Work Package no.1 – Task 1.2. In Task 6.1 a BAU reference scenario for CS1 will be assessed from an environmental, economic and social point of view via an LCA, Life Cycle Costing (LCC) and S-LCA respectively. Based on the results of those assessments, a hotspot analysis will be performed to show which life cycle stages and processes within the life cycle of BAU reference scenario 1 generate the main important impacts. This will then be used to define possible environmental, economic or social requirements for CS1.

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6.2 Specifications for future gearbox (CS2)

CS2 is based on a new gearbox concept that will be installed in a 10 MW onshore wind turbine from the year 2030 onwards. The wind turbine will be based on the 10 MW RWT, with a hub height of 119, rotor diameter of 202 m and a torque density up to level of 200Nm/kg. The wind turbine will be installed in Germany, in a farm size of 100MW (10 turbines). For this CS, lifetime value will be defined: at 30 years (~20% increase in lifetime respect to the current values).

Figure 38: CS2 will be located in Germany (100 GW wind farm)

Description of fatigue and extreme loads

The load cases IEC wind class 2 location are simulated by VTT. As a requirement for load case calculations, a simulation model of a 10 MW wind turbine with >200 m rotor diameter and a maximum tip speed of 87 m/s was selected for the basis of calculations. To full fill this requirement the available IEA 10MW reference wind turbine aeroelastic simulation model was modified.

The load cases for ultimate loads include IEC load cases: DLC 1.3, DLC 1.4, DLC 2.1, DLC 2.2, DLC 5.1. and DLC 6.2., and the fatigue loads include IEC load cases: DLC 1.2, DLC 2.4., DLC 3.1. DLC 4.1, DLC 6.4. Loads are presented in the non-rotating GL coordinate system.

Environmental condition, regulation, and other requirements

Some other environmental condition requirements are included in the next list:

- Surrounding temperatures in the range of -20°C (243K) to +60°C (323K)
- Relative humidity lower than 95%
- Directive 85/337/EEC Environmental Impact Assessment
- Safety requirement according to DNV-GL classification requirements.
- Directive 2002/49/EC Environmetal noise directive
- IEC 61400 – 1 Wind turbines – Part 1: Design requirements
- IEC 61400 - 4 Wind turbines — Part 4: Design requirements for wind turbine gearboxes

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- IEC 61400 - 11 Wind turbines - Part 11: Acoustic noise measurement techniques
- Gearbox vibration (<1.5mm/s2), noise (45dB[A]) and tonality requirement (0dB)
- Gearbox mechanical efficiency >96%
- ISO 6336 1-6 (2019) Calculation of load capacity of spur and helical gears
- ISO 281 Rolling bearings - Dynamic load ratings and rating life
- 262 500 operating hours
- Calculated component failure probability <1%

Concerning the social and environmental requirements the wind turbine noise is a critical issue. Particularly the noise of the gearbox should be kept within the acceptable level for the social acceptance. As already mentioned in section 3.1.2, the Guideline Development Group (GDG) of the WHO conditionally recommends reducing noise levels produced by wind turbines to be below 45 dB[A] L^{den}, to avoid associated adverse health effects caused by noises above this level.

The dynamical behaviour of the gearbox can generate vibrations during the operation of the wind turbine that will affect the performance and lifetime, as well as the noise of the turbine. The transfer of vibrations to the structural parts of the wind turbine can be prevented or reduced by using damping components for the gearbox. Proper management of gear dynamics by effecting damping will provide more stable operational conditions, lower noise and longer lifetime.

The new gearbox concept for this CS will be described in the INNTERESTING project, Work Package no.1 – Task 1.3. Similar to the first CS, Task 6.1 will assess a BAU reference scenario for CS2 via an LCA, LCC, and S-LCA. The results from Task 6.1 will be used to define possible additional environmental or social requirements, as well as possible economic requirements for CS2.

6.3 Specifications for lifetime extension of pitch bearings (CS3)

CS3 is based on a pitch bearing that will be installed in a 3,4 MW wind turbine in 2020. As a reference, the wind turbine power selected for this case study is close to the average size installed in 2019 (3,1MW, summarised in Table 1). Besides, it coincides with the turbines that are currently being installed in medium to high wind speed farms in the north of Spain[149, 150].

Among the many wind farm locations in Spain, the province of Burgos gathers suitable conditions for this case study. Nonetheless, Burgos is one of the biggest wind energy producers in Spain and leader within the region of Castile and León[151]. Therefore, a representative wind farm named ***InnFarm*** (fictitious name) has been chosen to serve as a case study. This site contains 20 wind turbines with a unitary power of 3,4MW and a total wind farm size of 68 MW (Figure 39).

149 https://renewablesnow.com/news/ibedrola-to-acquire-118-mw-of-spanish-wind-from-siemens-gamesa-673574/
150 https://www.iberdrola.com/about-us/lines-business/flagship-projects/cavar-onshore-wind-farm-complex
151 https://www.ceeiburgos.es/sites/default/files/ficheros-publicados/energia-burgos.pdf

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It should be highlighted that the chosen site only serves as a source of information for a representative wind speed estimation and wind turbine size. Theoretical geometries for the INNTERESTING project have been built based on public resources[152] and Ikerlan's knowledge in this field.

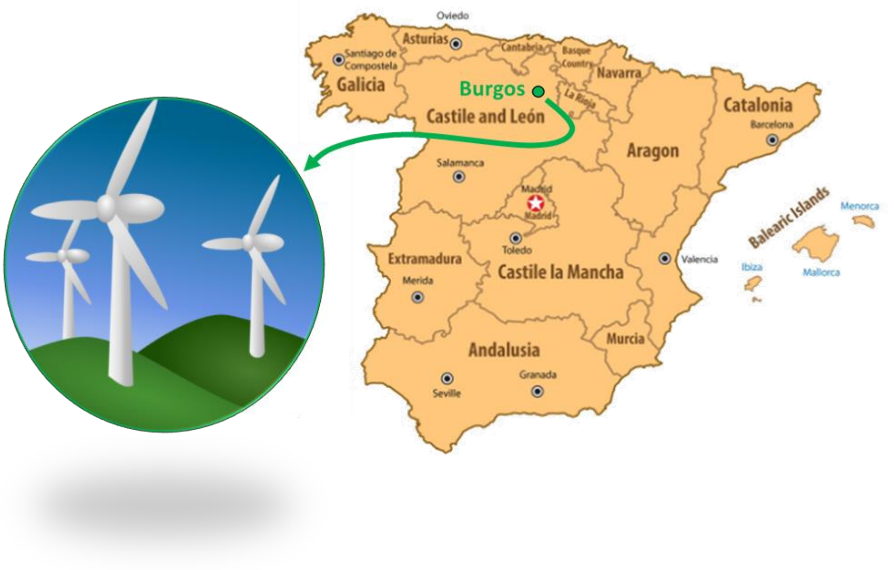

Figure 39 CS3 reference wind farm location: Burgos (Spain) [153, 154]

Description of the wind turbine

The current case study is based on a 3,4 MW wind turbine with a rotor diameter of Ø130 m and a hub height of 110 m. This turbine is assembled with three blades 62m long, with a weight of 16,4 tons per blade and root diameter of 2.6 m at the bolted joint with the pitch bearing. In addition, the blade presents a coning of 3 degrees[155].

This kind of turbines is suitable for medium to high wind speed onshore sites. Moreover, they are characterized by high energy production with low noise emission levels[156] and an estimated lifetime of 20 years.

Description of the rotor hub assembly

The current case study (CS3) focuses on the pitch bearings, which connect the blades to the hub and transmit loads between them. The whole assembly has been designed within the INNTERESTING project. The purpose of this development is to serve as a research case study. Consequently, the generated geometries have no commercial references.

As shown in Figure 40, only the main structural components have been included in the assembly. Some parts, such as the hydraulic actuators for pitch rotation, have been suppressed due to their low or negligible structural contribution. Besides, only the blade root section, which is the closest to the bearing, has been represented.

[152] https://www.nrel.gov/docs/fy09osti/38060.pdf. Definition of a 5-MW Reference Wind Turbine for Offshore System Development.
[153] https://es.m.wikipedia.org/wiki/Archivo:Wind-turbine-icon.svg
[154] https://www.tripsavvy.com/spain-regions-map-4136320
[155] IEA Wind TCP Task 37: Systems Engineering in Wind Energy - WP2., Reference Wind TurbineS, Technical Report, IEA WIND, May 2019
[156] https://www.siemensgamesa.com/en-int/products-and-services/onshore/wind-turbine-sg-3-4-132

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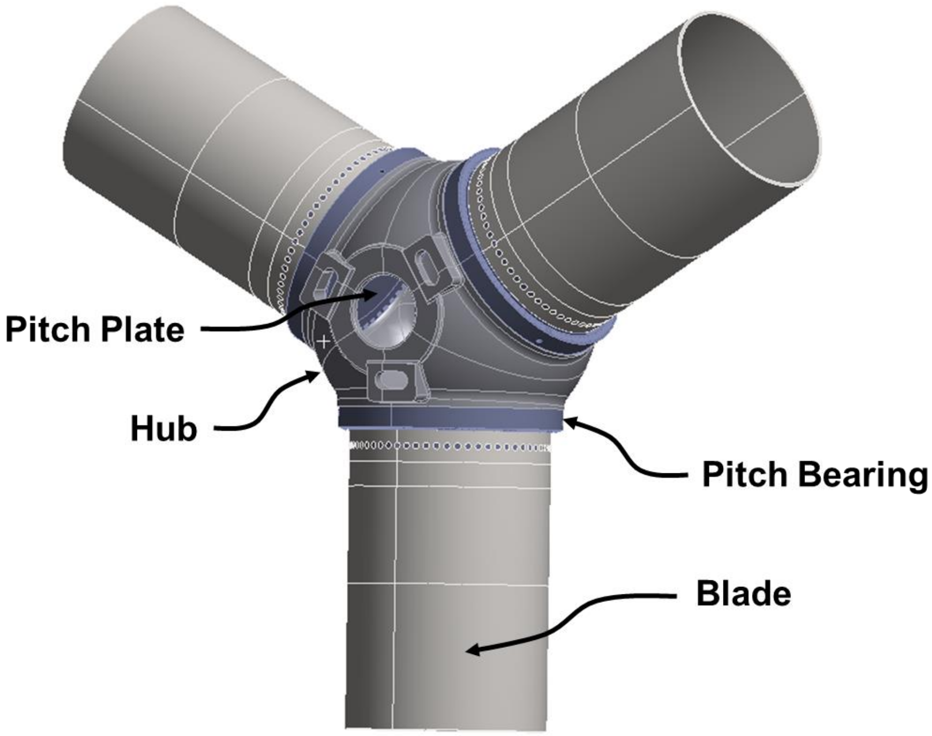

Figure 40: CS3 assembly

The main properties of the designed assembly are gathered in Table 5.

Table 5: Main properties of CS3 assembly

Component	Material	Mass	Dimensions
Hub	Cast Iron	15 t	Ø3,4m x 3,1m
Bearing	42CrMo4	3,2 t	Øext 2,7 m
Blade (Root section)	Glass Fiber Reinforced Epoxy	3,8 t	Ø2,5 m x 3,7 m
Pitch Plate	Structural Steel	1,9 t	Ø2,5 m

The main parts included in the assembly are connected by means of bolted joints. Two types of bolt connections are distinguished (Figure 41):

- **Hub to bearing outer ring bolted joint:** M36 double-end threaded studs are used. One end is inserted into the hub threaded holes, whereas the second one is fixed to the outer ring by means of a washer and nut.
- **Blade to bearing inner ring and pitch plate bolted joint:** M36 double-end threaded studs are used. One end is threaded into the T-bolt connection, which consists in a metallic insert located on the glass-fiber blade. The stud goes through the bearing inner ring and the pitch plate. The second end is locked by means of a washer and nut.

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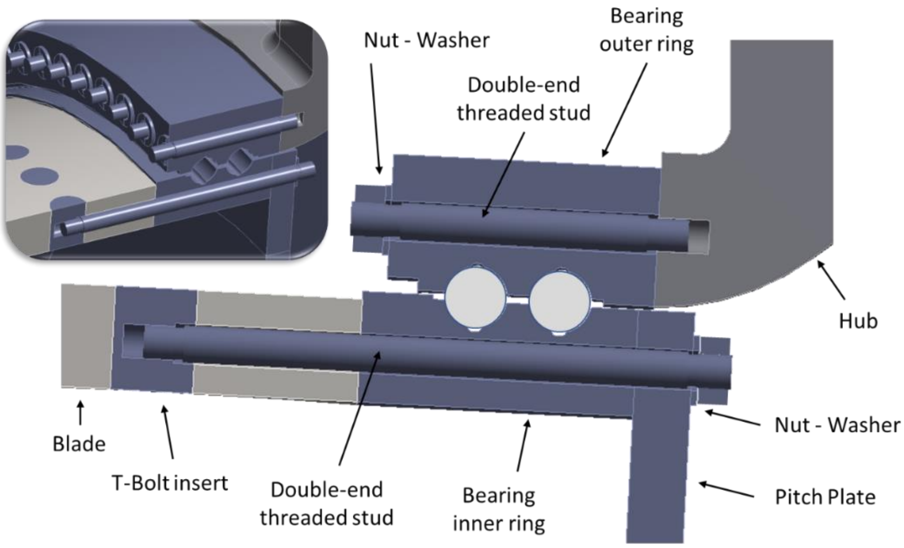

Figure 41: Bolted joint section view

Description of the pitch bearing

The pitch bearing assessed in this case study is a double row slewing bearing. The function of the pitch bearings is to connect the blade to the hub, allowing the relative rotation between them to adjust the angle of attack. Slewing bearings are characterized by supporting heavy loads at slow turning velocities, which make them suitable for pitch angle control purpose.

Each of the two rows contains 112 balls with a diameter of 60 mm. Each ball rolls along 4 toroidal raceways that are machined on the bearing ring perimeter. The race minor diameter is slightly bigger than the one of the balls. This is key to assure a punctual contact between the ball and each raceway. Therefore, the loads will be transmitted from one ring to the other through a diagonal path across the balls. The angle of these diagonals is designed to be 45 degrees when unloaded. This angle will rise as the loads increase (Figure 42).

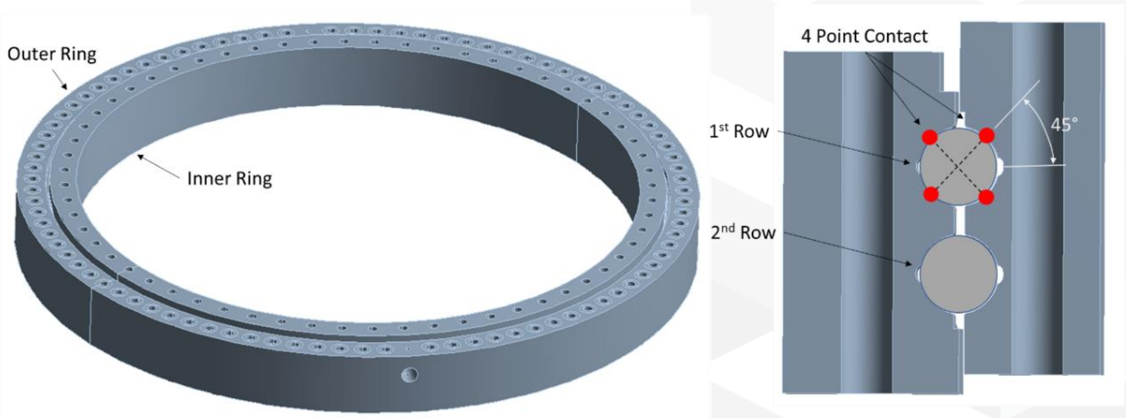

Figure 42: Bearing general view and detail of four-point contact

The bearing outer diameter is 2.8 m, whereas the inner diameter is approximately 2.3 m. The diameter axial height, that defines the distance between the hub flange and the blade root, is 0,28 m (Figure 43). The ball rolling diameter, also known as race diameter, is 2,5 m. This is in

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line with the blade root dimensions of the reference wind turbine[157] (2,6 m) as described previously.

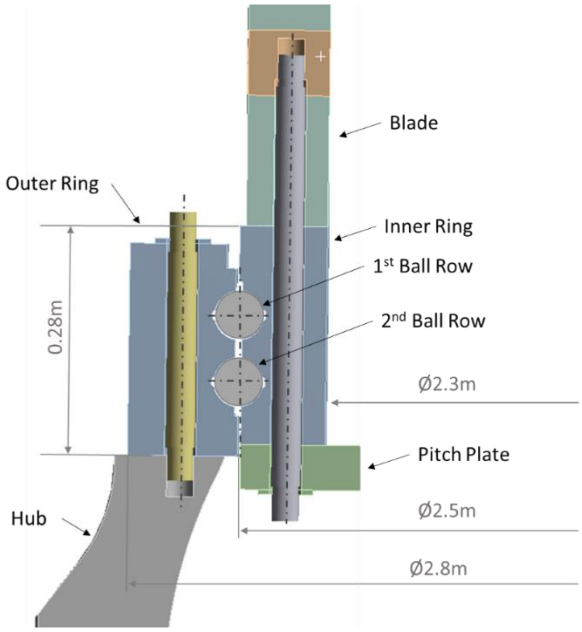

Figure 43: Bearing bolted connection main dimensions.

The geometry of this bearing has been conceived with the aim to serve as a research case study. Therefore, only the main structural features have been represented. Other details such as greasing holes, ball cages, seals or small chamfers have been suppressed. This simplifies the subsequent Finite Element Model generation while providing an accurate stiffness approach.

Description of fatigue loads

The 3D model described in previous paragraphs has been assessed under fatigue structural loads for a lifetime of 20 years. For dimensioning loads of the 3.4MW wind turbine, an OpenFAST model of the IEA 3.4MW onshore wind turbine has been chosen[158]. This is a land-based design, a class IIIA geared configuration with a rated electrical power of 3.4-MW. For the study of loads in blade bearings, blade root loads have been obtained via simulation. The simulations included all cases from design load case 1 from de IEC 61400 – 1 standard. Normal operation cases, DLC 1, encompasses around 90% of loads suffered by a turbine, so it has been determined enough for the dimensioning of loads of the turbine. For the simulations with OpenFAST, the model has been configured to allow only DOFs for blades and drive, considering the tower as rigid. Simulations for DLC 1 have been done following the rule, with wind speeds from cut-in to cut-out every 2 m/s for normal, DLC 1.1, and extreme, DLC 1.3, turbulence cases, each speed with at least 6 different random wind seeds, and critical events such as extreme wind direction change in DLC 1.4 and extreme vertical and horizontal wind shear in DLC 1.5. Moreover, simulations for DLC 1.2 have been carried out for fatigue analysis.

The fatigue load timeseries have been used to obtain an equivalent load in the form of turning moment and angle of application for a defined number of cycles. Rainflow counting method is

[157] IEA Wind TCP Task 37: Systems Engineering in Wind Energy - WP2., Reference Wind TurbineS, Technical Report, IEA WIND, May 2019
[158] https://renewablesnow.com/news/ibedrola-to-acquire-118-mw-of-spanish-wind-from-siemens-gamesa-673574/

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used to analyze time-series data in order to reduce a range of different moments to a series of simple moments and angles. The underlying postprocessing algorithm takes into account the magnitude, duration and occurrence of each event. The obtained Rainflow diagram in Figure 44 shows the number of occurrences (hotter colors mean more occurrences, while colder colors mean fewer) for cycles classified by mean and range values.

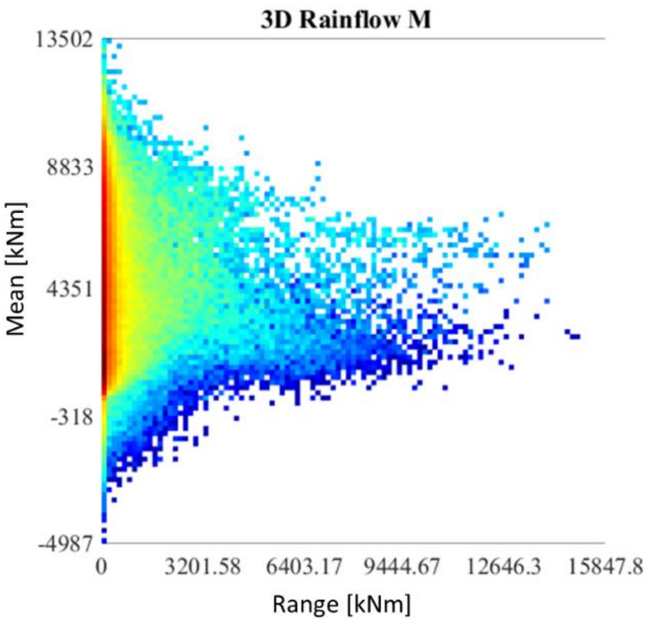

Figure 44: Moment and angle rainflow diagrams

In addition to the latter, a target lifetime value is defined as a certain amount of cycles (1.00e7). As a result, an equivalent moment and its angle are calculated for a certain number of cycles. According to this methodology, the application of the obtained moment onto the structure repeatedly along with the number of cycles previously defined, would generate a fatigue damage equivalent to the whole time series set. Besides, the retrieved data give structural information about the highest stressed zones, without the need of performing complicated fatigue analyses. This is very useful in the early stages of the design, where agile iterations are required in order to define the main dimensions of the bearing. The obtained moment for a target lifetime of 1.00e7 cycles is 10864kNm, applied at 71 degrees.

Bearing Ring Structural Failure assessment

Wind turbine pitch bearings present a variety of failure modes. Each one is associated with different phenomena related to loads, environmental conditions, age or bearing topology, among others. This case study is focused on the Ring Structural Failure (RSF), which can eventually produce a crack initiation on the bearing ring and even the fracture of the bearing section if it is not detected in advance (Figure 45). The ultimate consequences of this failure mode involve the impossibility to orient the blade towards the wind conveniently and even the collapse of the turbine due to a blade loss.

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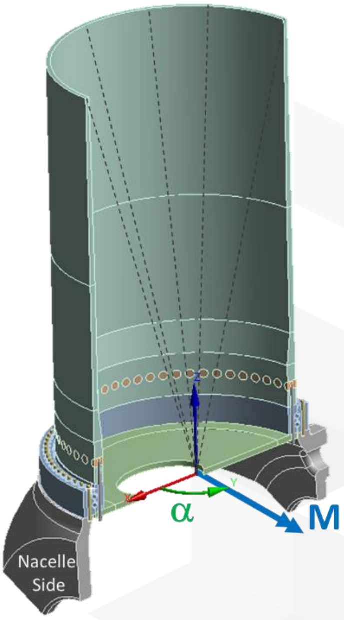
Figure 45: Cracks on bearing outer rings[159, 160]

Considering the structural responsibility of these components, finite element methods and advanced fatigue calculations are used to evaluate the damage of each feature under the fatigue timeseries described in previous paragraphs.

In Figure 47 a simplified fatigue assessment example is defined, where the stress range obtained from the structural Finite Element Model is evaluated with respect to the corresponding S/N curve (Synthetic curves for non-welded forged and rolled parts[161]). In this hypothetical case, the geometrical model has been evaluated with respect to an equivalent moment under 1e7 cycles (Figure 46). The stress results predict an early failure at 2.00e6 cycles, nonetheless. Hence the predicted damage is 5, which is greater than the unity. This means that, according to the analysis, a crack initiation would occur after one-fifth of the projected lifetime is consumed. ***Considering a target life of 20 years, a crack initiation would arise on the bolt hole surface during the 4th year, thus making the bearing fail prematurely.***



[159] Image source: Romax Technology
[160] https://www.windpowerengineering.com/making-short-lived-pitch-bearing-work-longer/
[161] Germanischer Lloyd: Guideline for the Certification of Wind Turbines

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Figure 46: Equivalent moment (M) and angle (α) representation

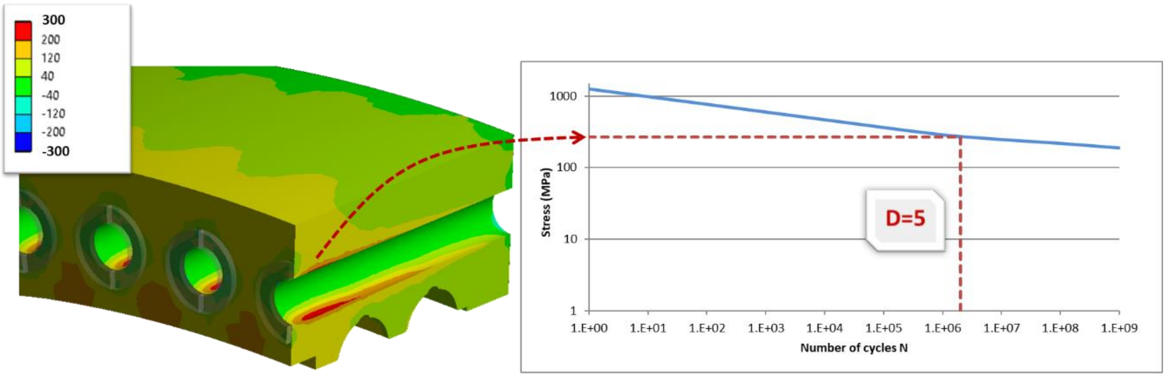

Figure 47: Stress results under equivalent moment [MPa] and damage calculation in S/N curve

Considering the fatal consequences that an unexpected failure can trigger, corrective actions are needed to extend its serviceable life, while guaranteeing full structural reliability.

Moreover, wind farms owners and managers are interested in extending pitch bearing performance beyond the target lifetime. Indeed, they perform active maintenance activities based on best practices learnt through many years of experience and manufacturers recommendations[162]. However, these procedures cannot ensure the bearing operability beyond the target lifetime.

The INNTERESTING project presents the current case study (CS3), which aims to extend the pitch bearings serviceable life up to, or even beyond the projected lifetime. This objective is applicable to two different scenarios:

- **Reparation of failed bearings** in order to slow crack propagation down.
- **Stiffening of serviceable bearings** in order to delay crack initiation.

The developed reparation techniques will fulfil the most demanding requirements related to pitch bearing integrity, such as:

- Environmental conditions (temperature, humidity)
  - Survival condition temperature range: –30ºC to 65ºC regarding surrounding temperature.
  - Operating condition temperature range: –20ºC to 60ºC regarding surrounding temperature.
  - Relative humidity lower than 95%
  - Sun radiation intensity: 1000 W/m2. The blade bearing is subjected to this solar radiation just during the assembly process of the field. Once finished the blade bearing is protected by a cover during its whole lifetime.
  - Possibility of lightning strikes.
- Structural reliability
- Cost
- In-field repairability and subsequent inspectionability

The repaired or stiffened bearing must meet the defined standards for onshore wind turbine components (ANNEX 1).

[162] https://www.windpowerengineering.com/extending-wind-turbine-life-with-pitch-bearing-upgrades/

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This task also comprehends the analysis of the lifetime extension tendency of existing wind farms (mainly onshore, see section 2.7).

The solution for this CS will be described in the INNTERESTING project, Work Package no.1 – Task 1.4. The specifications will be technical (lifetime extension[163], structural integrity, environmental conditions[164], etc.), environmental (based on the LCA of Task 6.1), and economic requirements (CAPEX, OPEX, investment returns, etc. based on the LCC of Task 6.1). Regarding social issues as discussed in section 4.5, further research is needed to learn more about the social acceptance of lifetime extensions of wind farms. The social and socio-economic aspects that may affect stakeholders over the life cycle of the lifetime extension concept will be evaluated with the S-LCA in Task 6.2 and compared with S-LCA results of Task 6.1 of the BAU reference scenario for CS3.

163 https://rules.dnvgl.com/docs/pdf/dnv/codes/docs/2010-10/rp-c205.pdf
164 https://rules.dnvgl.com/docs/pdf/DNVGL/ST/2016-09/DNVGL-ST-0361.pdf

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7 COMMUNICATION AND RELATIONSHIP BUILDING

One of the main objectives of the INNTERESTING project is **to reduce environmental and economic impact and to improve social acceptance of the newly developed designs, concepts and testing methods**.

The first part of this objective "reducing environmental and economic impact" will be quantified via environmental LCA (see section 3.7) and economic LCC respectively. The results of those assessments will be used to strategically support the developments within the case studies.

To fulfil the second part of the objective "improving the social acceptance" of the solutions developed within this project, specific actions will be taken to foster social acceptance of the technology. These specific actions are:

- Identification and assessment of good practices regarding community acceptance developed in the energy sector – see section 5;
- A communication and relationship building plan – see section 7.1;
- Identification and mapping of the stakeholders – see section 7.2.

7.1 Communication and relationship building plan

In section 4.5 we already concluded that no major difference is to be expected for social acceptance of the host community of a wind energy project with or without the technology developed within INNTERESTING. However, we still want to contribute in enabling the social acceptance and trust in (future) large wind turbines and lifetime extension. To do so, we will establish a dialogue at EU level, involving relevant stakeholders and transnational organisations. This dialogue will be held via several channels[165]:

- Steering committee meetings;
- The annual stakeholder consultation meetings during the course of the project;
- The project website: a page specifically dedicated to social acceptance of wind energy will be set up to engage local community and interest groups by giving the opportunity for them to provide their feedback on this matter.

The results of this dialogue and relationship building will be reported in deliverable D7.4 on an annual basis (M12, M24 and M36).

7.2 Identification and mapping of the stakeholders

To know with which parties a dialogue needs to be established and which key stakeholders of the wind energy value chain needs to be contacted for feedback on our research work during this project, it is important to define a Stakeholder Group. In order to do so, a high-level identification and mapping of stakeholders has been carried out, as shown in the Table 6. The process was developed considering the following points:

- **Relevant target groups** in the wind energy value chain were identified considering the need to gather input both from a technical point of view (mostly industrial companies, with a role in the validation process, related to the case studies -pitch bearings and

[165] See also D7.1 – communication plan for the foreseen communications activities in the iNNTERESTING project.

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gearboxes- or to the life extension service) and from a sustainability point of view (entities connected to social, environmental or economical sustainability of wind energy).

- **Rationale** for each target group to be involved in INNTERESTING was analysed, which helps to understand why they would be interested in being part of the Stakeholder Group and how they could contribute to better understand future technical, environmental and social requirements. i.e. to consolidate our research outcomes.
- **Key organizations** in each target group were identified, with a specific focus on those with relevant activity in Europe.

After this identification, an Excel file with contact details of adequate profiles from each of these organizations was completed. This information was used to invite a limited number of candidates to be part of the technical subgroup of the Stakeholder Group. The sustainability subgroup is open for participation by interested representatives from wind energy associations, policy makers and regulators, civil society organisations, environmental and social NGOs, or citizens in general.

Table 6: Main targets for the stakeholder group

	Target group	T	S	Rationale	Examples
Industrial community	**Wind turbine manufacturing companies**	X		· Potential users and prescribers of new design tools and hybrid validation methods · Customers for new gearbox and bearings technologies · Usually, also suppliers of O&M services (interested in life extension)	· Siemens Gamesa, Vestas, GE, Enercon, Nordex Acciona, MHI Vestas
	Component manufacturers	X		· Potential users of new design tools and hybrid validation methods	· Pitch manufacturers: Liebherr, NSK, NTN, Rollix, Schaefler, Scheerer, SKF, Timken · Gearbox manufacturers: Hansen Industrial Gearboxes, Winergy, ZOLLERN, Siemens Gamesa (Echesa)
	Test-bench owners	X		· Potential providers of new services connected to hybrid validation methods · Relevant knowledge of the validation process	· Cener, Fraunhofer IWES, LORC, ORE Catapult, WINDBOX
	Engineering companies	X		· Relevant knowledge of the validation process (as test-bench designers) · Providers of life extension services	· IDOM, Nabla Wind, Aeroblade, Ynfiniti, DEWI, e-Bo, UL
	Wind and energy platforms and associations	X		· Knowledge of relevant market and technology trends in the wind sector · Prescribers of new vailidation methods, case studies and design tools	· WindEurope, EERA, ETIPWind, ELBE Alliance, MRE S3P
	Standardisation and certification bodies	X		· Responsible for validation and dissemination of new approaches	· DNV GL, COWI A/S, ICF, Hatch Ltd, Intertek, UL, TUV SUD, Wood Group
	Wind farm developers	X		· Potential users and prescribers of life extension services · Potential users and prescribers of new design tools and hybrid validation methods	· Iberdrola, Acciona Energía, E.ON, EDF, EDP, ENEL, Invenergy, Orsted, Vattenfall
Research	**Research community:** universities, R&D divisions companies, researchers and students	X		· Research on new hybrid validation methods · Research on new bearings and gearboxes technologies · Research on life extension	· Fraunhofer, DTU, SINTEF, RISE · International Energy Agency Wind Technology Collaboration Programme (IEA Wind TCP) · CENER - National Renewable Energy Centre of Spain
	Other **H2020 projects** in related fields	X	X	· Research on wind energy technology development or LCC	· COREWIND, I4OFFSHORE, ROMEO, SETWind, WATEREYE
Public auth	**Policymakers and regulators**		X	· Decision makers of policy priorities	· Local autorities, national regulatory bodies · DG ENER, DG ENV, DG GROW, DG JRC
	Standardisation and certification bodies	X	X	· Knowledge of standardisation and regulation of wind energy technology development	· CLC/TC 88, IEC/TC 88
General public	**Workers**		X	· Practical experiences on the working conditions and job quality in producing, instaling and maintaning wind turbines	· EU-OSHA
	Citizens in generals; Civil society organisation; Environmental NGOs; Social NGOs		X	· Public participation process · Knowledge of relevant local initiatives and experiences	· ECOS, EEB, ANEC/BUEC

T: Candidates to provide technical input in the Stakeholder Group
S: Candidates to provide sustainability input in the Stakeholder Group

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8 ANNEX 1

Design guidelines and standards for onshore and/or offshore:

- AGMA 923: B05 Metallurgical Specifications for Steel Gearing
- ASTM A1089M Standard Specification for Highly Loaded Anti-Friction Bearing Steel
- ASTM A295 Standard Specification for High-Carbon Anti-Friction Bearing Steel
- ASTM D471 - 06e1 - Standard Test Method for Rubber Property—Effect of Liquids
- ASTM E45 - 11 Standard Test Methods for Determining the Inclusion Content of Steel
- DIN 50602. Metallographic examination; microscopic examination of special steels using standard diagrams to assess the content of non-metallic inclusions.
- DNVGL-ST-0361 Machinery for wind turbines
- EN 10083: Steels for quenching and tempering - Part 3: Technical delivery conditions for alloy steels.
- EN 10084: Case hardening steels - Technical delivery conditions.
- EN 10149: Hot-rolled flat products made of high yield strength steels for cold forming.
- EN 10204. Metallic Products – Types of Inspection Documents
- EN 10228-1,3: Non destructive testing of steel forgings
- EN 10250: Open die steel forgings for general engineering purposes.
- EN 1993-1 EUROCODE 3: Design of steel structures.
- EN ISO 15549: Non-destructive testing - Eddy current testing - General principles
- EN ISO 2808, Paints and varnishes - Determination of film thickness;
- EN ISO 6508-1 Metallic Materials - Rockwell Hardness Test. Part 1: Test Method
- EN/ISO 15548-1, 2 and 3 - Non-destructive testing - Equipment for eddy current examination
- EN/ISO 9712 - Non-destructive testing - Qualification and certification of NDT Personnel
- Germanischer Lloyd. Rules and Guidelines. IV Industrial Services. 2. Guideline for the Certification of Offshore Wind Turbines. Edition 2012.
- Germanischer Lloyd: Guideline for the Certification of Wind Turbines. Edition 2010
- GL Note on Engineering Details: Required documentation for the assessment of large diameter rolling bearing rings and raceways (GL RC-M-StSca-extern-002, Revision 1)
- GMS16080: Protections for handling, packing, storage and transportation
- GPR11120: Validation and homologation of metallizing and duplex systems process.
- IEC 60529:2004: Degrees of Protection Provided by Enclosures (IP Code).
- IEC 61400-1. Wind turbines, Design requirements
- IEC 61400-22: Wind Turbines – part 22: Conformity testing and certification
- IEC 62305-3: Protection against lightning - Part 3: Physical damages to structures and life hazard.
- IEC TR 61400-24: Wind turbine generator systems. Part 24: Lightning protection
- IEC-WT-01: IEC System for Conformity Testing and Certification of Wind Turbines
- ISO 11666. Non-destructive testing of welds – Ultrasonic testing – Acceptance levels.
- ISO 12944-1, Paints and varnishes -- Corrosion protection of steel structures by protective paint systems -- Part 1: General introduction;

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- ISO 12944-2 Paints and varnishes – Corrosion protection of steel structures by protective paint systems -- Part 2: Classification of environments
- ISO 12944-3 Paints and varnishes – Corrosion protection of steel structures by protective paint systems -- Part 2: Design considerations
- ISO 12944-5, Paints and varnishes -- Corrosion protection of steel structures by protective paint systems -- Part 5: Protective paint systems.
- ISO 12944-6 Paints and varnishes – Corrosion protection of steel structures by protective paint systems -- Part 6: Laboratory performance test methods
- ISO 15609-1. Specification and qualification of welding procedures for metallic materials – Welding procedure specification – Part 1: Arc welding.
- ISO 15614-1. Specification and qualification of welding procedures for metallic materials – Welding procedure test – Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys.
- ISO 17637. Non-destructive testing of welds – Visual testing of fusion-welded joints.
- ISO 17638. Non-destructive testing of welds – Magnetic particle testing.
- ISO 17640. Non-destructive testing of welds – Ultrasonic testing – Techniques, testing levels and assessment.
- ISO 2063. Thermal spraying -- Metallic and other inorganic coatings -- Zinc, aluminium and their alloys
- ISO 23277. Non-destructive testing of welds – Penetrant testing of welds – Acceptance levels.
- ISO 23278. Non-destructive testing of welds – Magnetic particle testing of welds – Acceptance levels.
- ISO 2768-1, 2: General tolerances
- ISO 281:2007 Rolling bearings - Dynamic load ratings and rating life
- ISO 3290-1 – Rolling bearing – Balls – Part 1-Steel balls
- ISO 3452-1. Non-destructive testing – Penetrant testing – Part 1: General principles.
- ISO 3754:1977: Steel - Determination of effective depth of hardening after flame or induction hardening
- ISO 4014:1999. Hexagonal head bolts - Product grades A and B.
- ISO 4032:1999 Hexagonal nuts. Style 1 - Product grades A and B.
- ISO 4624, Paints and varnishes - Pull-off test for adhesion;
- ISO 4967: Determination of content of nonmetallic inclusions – Micrographic method using standard diagrams.
- ISO 5817. Welding – Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) – Quality levels for imperfections.
- ISO 5949. Tool steels and bearing steels – Micrographic method for assessing the distribution of carbides using reference photomicrographs
- ISO 6507-1. Metallic materials – Vickers hardness. Part 1: Test Method
- ISO 683-17. Heat treatable steels, alloy steels and free cutting steels
- ISO 7089:2000. Plain washers. Normal series - Product grade A.
- ISO 76 Rolling bearings - Static load ratings.
- ISO 8501-1, Preparation of steel substrates before application of paints and related products -- Visual assessment of surface cleanliness -- Part 1: Rust grades and preparation grades of uncoated steel substrates and of steel substrates after overall removal of previous coatings;

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- ISO 8501-3. Preparation of steel substrates before application of paints and related products -- Visual assessment of surface cleanliness -- Part 3: Preparation grades of welds, edges and other areas with surface imperfections
- ISO 8502-6, Preparation of steel substrates before application of paints and related products - Tests for the assessment of surface cleanliness - Part 6: Extraction of soluble contaminants for analysis - The Bresle method;
- ISO 8502-9, Preparation of steel substrates before application of paints and related products - Tests for the assessment of surface cleanliness - Part 9: Field method for the conductometric determination of water-soluble salts.
- ISO 8503-1, Preparation of steel substrates before application of paints and related products - Surface roughness characteristics of blast-cleaned steel substrates - Part 1: Specifications and definitions for ISO surface profile comparators for the assessment of abrasive blast-cleaned surfaces;
- ISO 8503-2, Preparation of steel substrates before application of paints and related products -- Surface roughness characteristics of blast-cleaned steel substrates -- Part 2: Method for the grading of surface profile of abrasive blast-cleaned steel -- Comparator procedure;
- ISO 898-1:2009 Mechanical properties of fasteners made of carbon steel and alloy steel. Part 1. Bolts, screws and studs with specified property classes – Coarse thread and time pitch thread.
- ISO 9001 - Quality management systems – Requirements.
- ISO 9223 Corrosion of Metals and Alloys – Corrosivity of Atmosphere-Classification
- ISO 9606-1. Qualification testing of welders – Fusion welding – Part 1: Steels.
- ISO 9712: Non-destructive testing - Qualification and certification of NDT personnel.
- ISO TS 16281_2008 Rolling bearings - Methods for calculating the modified reference rating life for universally loaded bearings.
- ISO/TR 1281-1:2008 Rolling bearings - Explanatory notes on ISO 281. Part1: Basic dynamic load rating and basic rating life.
- ISO/TR 1281-2:2008 Rolling bearings - Explanatory notes on ISO 281. Part 2: Modified rating life calculation based on a systems approach to fatigue stresses.
- NACE SP0188:2006, Discontinuity (Holiday) Testing of New Protective Coatings on Conductive Substrates
- NREL/TP-500-42362 Wind Turbine Design Guideline DG03: Yaw and Pitch Rolling Bearing Life
- NREL/TP-500-42362 Wind Turbine Design Guideline DG03: Yaw and Pitch Rolling Bearing Life.
- STN-TC-1A: Personnel qualification and certification in non-destructive testing.
- UNE EN 60721 – Classification of environmental conditions. Classification of groups of environmental parameters and their severities. Storage
- VDI 2230 Part 1 Systematic calculation of high duty bolted joints. Joints with one cylindrical bolt. February 2003
- ZPS 1009603 - NDT-personnel qualification - Specific technical requirements

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