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INNTERESTING

Deliverable 6.2:
Report on sustainability assessment results of screening INNTERESTING solutions

WP6, Task 6.2

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[1] PU = Public

PP = Restricted to other programme participants (including the Commission Services)

RE = Restricted to a group specified by the consortium (including the Commission Services)

CO = Confidential, only for members of the consortium (including the Commission Services)

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Document History

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Table of contents

Table of contents 3
Executive summary 6
1. Introduction 7
1.1. Purpose and content of this deliverable 8
1.1.1. Deviations from the plan 8
1.1.2. Structure of this deliverable 9
2. Goal and scope of the LCSA 10
2.1. Goal of the LCSA 10
2.2. Scope of the LCSA 11
2.2.1. Scope CS1 12
2.2.2. Scope CS2 13
2.2.3. Scope CS3 14
3. Qualitative life cycle impact assessment 15
3.1. General 15
3.2. CS1 15
3.3. CS2 16
3.4. CS3 18
3.5. Testing methods 18
4. Conclusions and next steps 24
4.1. General conclusions 24
4.2. Next steps in the LCSA 24
References 25

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

List of tables

Table 1: Specifications of the Reference Wind Turbine (RWT) and wind farm of CS1. 12
Table 2: Specifications of the RWT and wind farm of CS2...13
Table 3: Specifications of the RWT and wind farm of CS3...14

List of figures

Figure 1: The three pillars of the life cycle sustainability assessment. 7
Figure 2: The life cycle of a wind turbine 8
Figure 3: The three case studies of the INNTERESTING project.. 8
Figure 4: Illustration of the scope of the LCSA...11
Figure 5: Left – Schematic view of the 20 MW RWT (Ashuri et al., 2016). Right – Location of the NORCOWE virtual wind farm. 12
Figure 6: Left – Plot of the DTU 10 MW RWT (Bak et al., 2013). Right – Wind farm of CS2 is located in north Germany. 13
Figure 7: Left – Plot of 3.4 MW land-based wind turbine (Dykes, 2019). Right – Wind farm location of CS3: Burgos, Spain...14

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Abbreviations and acronyms

Acronym	Description
AEP	Annual Energy Production
BAU	Business-As-Usual
BOP	Balance Of Plant
CAPEX	Capital expenditures
CS	Case Study
FU	Functional Unit
LCA	(environmental) Life Cycle Assessment
LCC	(economic) Life Cycle Costing
LCOE	Levelized Cost Of Energy
LCSA	Life Cycle Sustainability Assessment
NORCOWE	Norwegian Centre for Offshore Wind Energy
OPEX	Operational expenditures
RCF	Rolling Contact Fatigue
RS	Reference Scenario
RSF	Ring Structural Failure
RWT	Reference Wind Turbine
S-LCA	Social Life Cycle Assessment

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Executive summary

This deliverable is the second of WP6 of the INNTERESTING project. WP6 revolves around the environmental, social and economic assessment of the three case studies defined within the project. In the three case studies disruptive technologies for new pitch bearings and gearboxes, and a novel lifetime extension concept of existing pitch bearings are being developed. In addition, hybrid testing methods are being developed to test pitch bearing and gearboxes so the need of large test benches can be eliminated. In order to maximise the innovation potential of INNTERESTING technology developments, without losing the potential of lowering environmental, social and economic impacts, a life cycle sustainability assessment (LCSA) is being performed iteratively in WP6.

This report describes the screening LCSA of the INNTERESTING concepts that are being developed. Due to data gaps, the content of D6.2 is limited to a more qualitative assessment. This D6.2 can thus be seen as a qualitative introduction to D6.3 which will quantify the possible environmental, economic, and socio-economic potential of the INNTERESTING solutions.

Findings from the qualitative assessment are that the INNTERESTING developments have an important potential in reducing the Levelized Cost Of Energy (LCOE) of wind turbines. These reductions are driven by: a decrease in energy production losses, decrease in operational costs due to less maintenance and repairs, decrease in initial material costs and replacement costs, and decrease in transport and logistic costs. A reduction in initial and operational material use would also result into a lower environmental and socio-economic impact. Section 3 includes findings per case study and on the hybrid testing methods.

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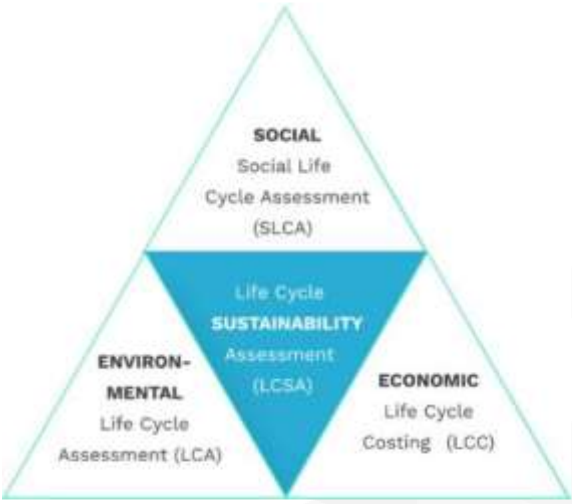
1. Introduction

The INNTERESTING project aims to accelerate wind energy technology development and increase lifetime extension of wind turbine components. The project revolves around three case studies in which disruptive technologies are being developed for new pitch bearings and gearboxes, and a novel lifetime extension concept of existing pitch bearings. On top of the case studies, hybrid testing methods are being developed for the two mentioned critical component to eliminate the need of large test benches. In order to maximise the innovation potential of INNTERESTING technology developments, without losing the potential of lowering environmental, social and economic impacts, a life cycle sustainability assessment (LCSA) is being performed iteratively throughout the project.

The LCSA consist of an environmental life cycle assessment (LCA), a social life cycle assessment (S-LCA) and life cycle costing (LCC). In the LCA, S-LCA, and LCC, the impact on the environmental, social/socio-economic, and economic aspects of wind turbines are assessed respectively (see Figure 1). By doing so we will gain insights in one of the challenges of wind energy we defined at the start of this project: i.e. the more demanding requirements for future wind turbines, specifically regarding the reduction of capital and operational expenditure (CAPEX/OPEX) and improvement of the environmental performance and social aspects of wind turbines. In addition, it relates to the fifth main objective of this project: to reduce environmental and economic impact and to improve social acceptance of the newly developed designs, concepts and testing methods.

Figure 1: The three pillars of the life cycle sustainability assessment.



Work Package 6 of the INNTERESTING project is fully dedicated to the execution of the LCSA and consists of three tasks corresponding with the three LCSA iterations that are being performed throughout the project:

- Task 6.1: assessment of the business-as-usual (BAU) reference scenarios (ended in August 2020).
- Task 6.2: screening of the concepts and hybrid testing methods developed within the project (hereinafter INNTERESTING solutions).
- Task 6.3: validation/final assessment of the INNTERESTING solutions.

This report (D6.2) describes the results of the Task 6.2 of the INNTERESTING project.

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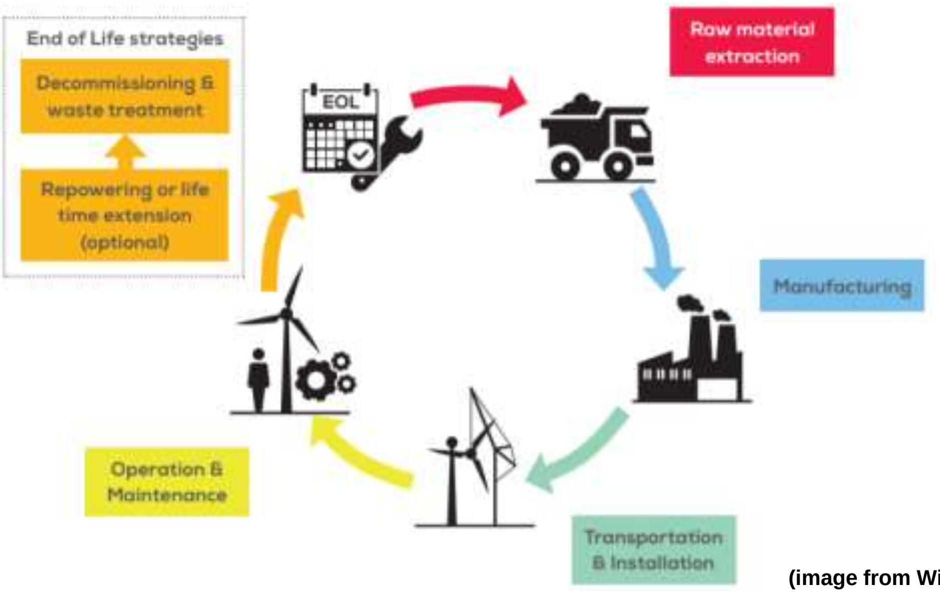
1.1. Purpose and content of this deliverable

As mentioned above, D6.2 presents the results of the second iteration of the LCSA, in which the INNTERESTING solutions are screened as preparation for the final LCSA in Task 6.3. The purpose of the assessment of the INNTERESTING solutions is to gain insights in the environmental, economic, and socio-economic performance during their life cycle (see Figure 2).

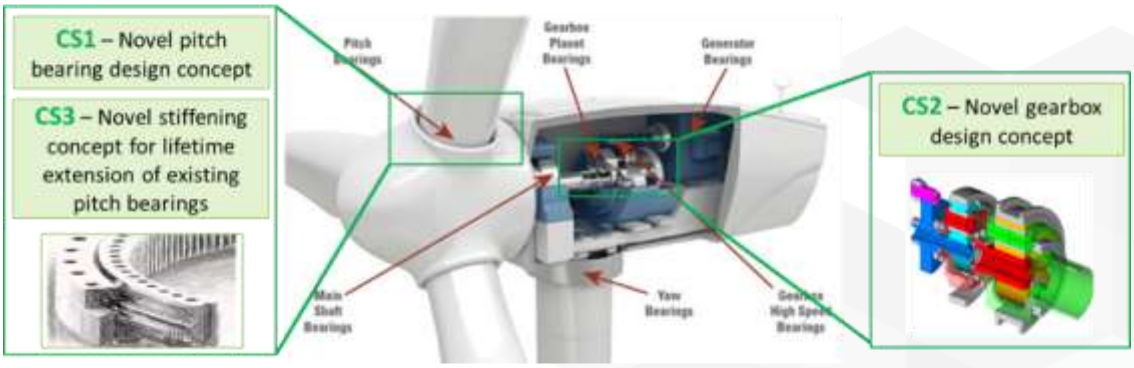
Figure 2: The life cycle of a wind turbine



(image from WindEurope)

The three case studies are presented in the next figure. For more technical information on the three case studies, please refer to section 6 of D1.1[2].

Figure 3: The three case studies of the INNTERESTING project.



1.1.1. Deviations from the plan

Due to a small number of gaps in essential inventory data, we have decided to limit the content of D6.2 to a more qualitative assessment and to also keep the reporting of the revision of the BAU scenarios for D6.3 [M36]. This D6.2 can thus be seen as a qualitative introduction to D6.3 describing the possible environmental, economic, and socio-economic potential of the

[2] D1.1 can be downloaded via: https://www.innterestingproject.eu/downloads/d1-1-technical-environmental-and-social-requirements-of-the-future-wind-turbines-and-lifetime-extension.pdf

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INNTERESTING solutions. The data already collected and modelling already done in T6.2 will be used and is necessary in T6.3.

The ongoing process of the technological developments in WP3-WP5 makes it difficult to collect all the necessary data. The data gaps make it not meaningful to already quantitatively report the interim results of the screening LCSA as was done in D6.1 for the BAU reference scenarios. As the results would not be representative enough and give an incorrect impression. Therefore, the qualitative findings based on the screening LCSA presented in this deliverable is the most fitting option to do to close Task 6.2. Actions have already be taken to close the data gaps (see also section 4.2).

1.1.2. Structure of this deliverable

After this first section, the content of this deliverable is structured as follows:

- Section 2 describes the goal and the scope of the LCSA: first in general for the LCSA throughout this project, followed by the scope per case study.
- Section 3 gives the findings based on a qualitative approached life cycle impact assessment, including subsections on general findings, findings per case study, and an comparative overview of the characteristics of the testing methods assessed.
- Section 4 concludes this deliverable with the conclusions and the next steps in the LCSA.

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2. Goal and scope of the LCSA

The methodological framework of the LCA was extensively described in D6.1. As main framework for the LCSA the ISO standards 14040:2006 and 14044:2006 are applied. ISO 14040/14044 specifies that the intended use and audience (goal) and the breadth and depth (scope) of a study must be clearly defined. The scope definition must be consistent with the goal of the study and provides a description of the (to be) assessed product system in terms of the system boundaries and a quantified functional unit. The following goal and scope definition are set up following the framework of ISO 14040:2006 and 14044:2006.

2.1. Goal of the LCSA

The reasons for carrying out LCSA iteratively throughout the INNTERESTING project are:

- To gain insights in one of the challenges of wind energy defined at the start of the project: i.e. the more demanding requirements for future wind turbines, specifically regarding the reduction of capital and operational expenditure (CAPEX/OPEX) and improvement of the environmental performance and social aspects of wind turbines.
- To meet the fifth objective of the project: i.e. to reduce environmental and economic impact and to improve social acceptance of the newly developed designs, concepts and testing methods.
- To maximise the innovation potential of INNTERESTING solutions without losing the potential of lowering environmental, social and economic impacts by identifying opportunities for improvement of the solutions. For instance, improvement activities on the most important impact-generating process stages during the life cycle of a wind turbine.
- To support sustainable (future) designs of wind turbines.
- To quantify and qualify the potential environmental, economic and social performance of wind turbines in order to support sustainable consumption.
- To communicate with various stakeholders (see also further down for the target audience of this study).

The target audience of this study consists of:

- The INNTERESTING project partners,
- The stakeholder advisory board of this project,
- The European Commission (through H2020 project),
- European policy makers,
- Other stakeholders, such as the industrial wind energy community, research community, and general public[3].

[3] Section 7.2 of D1.1 includes a mapping of identified stakeholders for this project.

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2.2. Scope of the LCSA

The product system under study is a wind turbine (excluding balance of plant (BOP) for the LCA and S-LCA and including the BOP for the LCC) developed, produced, installed, used and decommissioned on the European market.

In the first iteration of the LCSA (see D6.1) three BAU reference wind turbines were assessed, i.e. one reference scenario (RS) per case study (CS). In this second iteration, the three case studies and the hybrid testing method are screened as preparation for the final iteration. In the final iteration, which will be reported in D6.3, everything will come together: a revision of the BAU reference scenario's including an assessment of the BAU testing method and the final assessment to validate the INNTERESTING solutions.

The specific functional unit and characteristics of each CS are given in subsections 2.2.1 – 2.2.3. The general functional unit, system boundaries and other scope related aspects applied throughout all iterations of the LCSA are fully described in D6.1. Only the general functional unit (FU) is given below, as it is a key aspect of an LCSA, LCA, LCC, and S-LCA. It is a reference unit which enables comparison of different product systems under study if the same principles are applied in the comparative assessment.

- **General functional unit**

The FU is defined as: **1 kWh of the total electricity output delivered to the grid over the service life by a wind turbine**. Thus, not delivered to the consumer. Therefore, grid distribution losses are not considered. This FU is made specific per CS in subsections 2.2.1 – 2.2.3 (and per RS in D6.1). Per CS (and corresponding RS) a reference wind farm is also included as an assumption.

Figure 4: Illustration of the scope of the LCSA.

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2.2.1. Scope CS1

- **Functional unit CS1**

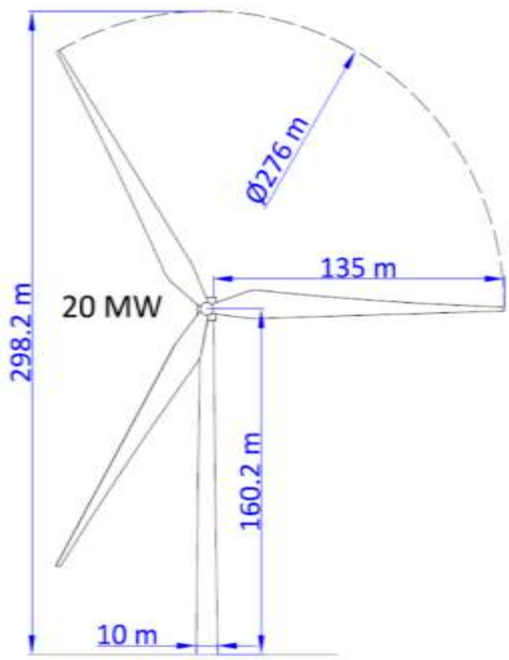
Based on the general FU, the specific FU of CS1 is as follows: **1 kWh of the total electricity output delivered to the grid over the service life of 40 years by a 20 MW offshore wind turbine with innovative pitch bearings**.

- **Specifications CS1**

Table 1: Specifications of the Reference Wind Turbine (RWT) and wind farm of CS1.

Dimensions	276 m rotor diameter 160 m hub height 3 blades
Assumptions wind farm	Located in NORCOWE virtual wind farm Total capacity of 100x20 MW
Specific component	Innovative pitch bearing with a new rolling element design Specific data from Laulagun Bearings SA
RWT / generic data source other components	20 MW common research wind turbine model by T. Ashuri et al. (2016)

Figure 5: Left – Schematic view of the 20 MW RWT (Ashuri et al., 2016).
Right – Location of the NORCOWE virtual wind farm.



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2.2.2. Scope CS2

- **Functional unit CS2**

The specific FU of CS2 is as follows: **1 kWh of the total electricity output delivered to the grid over the service life of 25 years by a 10 MW onshore wind turbine with a so-called classical Danish design with an innovative gearbox**.

- **Specifications CS2**

Table 2: Specifications of the RWT and wind farm of CS2.

Dimensions	202 m rotor diameter 119 m hub height 3 blades
Assumptions wind farm	Located in north Germany with an average wind speed of 9 m/s Total capacity of 10x10 MW
Specific component	Innovative gearbox with new journal bearing design Specific data provided by Moventas Gears OY
RWT / generic data source other components	DTU 10-MW Reference Wind Turbine by Bak et al. (2013) 10MW RWT Costs Models v1.02 by Chaviaropoulos (2016)

Figure 6: Left – Plot of the DTU 10 MW RWT (Bak et al., 2013).
Right – Wind farm of CS2 is located in north Germany.

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2.2.3. Scope CS3

- **Functional unit CS3**

The specific FU of CS3 is as follows: **1 kWh of the total electricity output delivered to the grid over the service life of 20 years by a <u>3.4 MW onshore</u> wind turbine <u>with (a) prematurely failed pitch bearing(s)</u> in year 4 to which an <u>innovative reparation and stiffening solution</u> will be applied.**

- **Specifications CS3**

Table 3: Specifications of the RWT and wind farm of CS3.

Dimensions	130 m rotor diameter 110 m hub height 3 blades
Assumptions wind farm	Located in Burgos, Spain Total capacity of 20x3.4 MW
Specific component	Pitch bearing with a diameter of 2.6 m that will fail prematurely and to which an innovative reparation or stiffening solution is applied Specific data provided by IKERLAN
RWT / generic data source other components	IEA Wind Task 37 3.4-MW Land-Based Wind Turbine by Bortolotti et al. (2019)

Figure 7: Left – Plot of 3.4 MW land-based wind turbine (Dykes, 2019).
Right – Wind farm location of CS3: Burgos, Spain.

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3. Qualitative life cycle impact assessment

This section first gives an impression of the possible life cycle impact on the sustainability aspects of the RWTs in general, followed by a section per CS, and lastly a qualitative comparison is given regarding the BAU and INNTERESTING testing methods. As explained in section 1.1.1, a qualitative approach is applied to finish Task 6.2 due to data gaps and the quantitative results will only be presented in D6.3 [M36].

3.1. General

Future larger wind turbines create opportunities to reduce the Levelized Cost of Energy (LCOE). The opportunities for LCOE reduction from the BAU RSs are driven by the decrease in production losses and by the decrease in OPEX, while changes in material costs could both have a positive or a negative impact on the LCOE. Also transportation and logistics challenges need to be taken into account.

For the BAU RSs, the capital expenditures have the biggest share (57% to 72%) within the total expenditures over the lifetime. CAPEX include costs of turbine materials, balance of plant, transport, assembly and installation, and financial costs. The costs of the turbine are the highest, followed by the balance of plant (BOP) costs. The second major contributor to costs is represented by the operational expenditures, defined as costs in the operational period of the wind turbine. The OPEX represent between 26% and 38% of the complete life cycle costs of the BAU cases, with the highest share for the offshore case RS1. Unfortunately, operations and maintenance market data are not widely available. Moreover, OPEX can vary greatly between projects. Differences can be appointed amongst others to the distinction between onshore and offshore, the distance from the project to the maintenance facilities, and the meteorological climate at the site (Stehly & Beiter, 2020).

For each BAU case, assumptions on the Annual Energy Production (AEP) were made in Task 6.1 (see D6.1). For RS1, an AEP of 86 000 MWh/y was assumed. For RS2, LCOE calculations were based on an AEP of 46 211 MWh/y, with production losses ranging from 6 to 10%. For RS3, an AEP of 7 148 MWh/y was assumed. The CSs intend to extend the service life of the RWT in comparison with BAU and therefore increase the total amount of energy produced during the service life. This makes it plausible that potential environmental, economic, and socio-economic impacts of the CSs will be lower per FU (i.e. 1 kWh of the total electricity output) in comparison to the BAU RSs.

3.2. CS1

For the new CS1 pitch bearing concept to be used in future larger wind turbines, the selected nominal power is 20 MW, which is the expected maximum size by 2030 and the average size for 2050 for offshore. For these future wind turbines, there is a requirement of a longer lifetime. A service life of 40 years is considered, which is a 60% increase in lifetime with respect to the BAU.

The innovative solution for the pitch bearing that LAULAGUN is developing, is based on a new rolling element design. In the new design for the 20 MW wind turbine, the stiffness and capacity of the bearing are higher, and some failure modes that are related to curved raceways are avoided. In Deliverable D1.2[4] an overview was made of failure modes to be overcome in the

[4] Deliverable ‘D1.2 - New pitch bearing final design’ - confidential report.

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bearing designed for the 20 MW turbine of the future. Rolling Contact Fatigue (RCF) and Ring Structural Failure (RSF) are two failure modes with a high probability to occur in CS1.

For the offshore BAU case (RS1), the operational expenditures represent 38% of the complete life cycle cost. In general, OPEX are relatively higher compared to an onshore plant. The offshore maintenance costs consist largely of maintenance personnel cost, access vessel cost, special maintenance vessel cost (jack-up, crane, etc.) and spare parts cost (assembled or individual spare parts). Periods of maintenance also involve production losses due to downtime (Karyotakis, 2011; Nachimuthu et al, 2019).

Compared to the BAU, the new pitch bearing concept has an important potential in reducing the LCOE. The new concept will be validated for 40 years of lifetime. Current bearings are not designed and tested for a service life of more than 25 years. Therefore, for a lifetime of 40 years, the probability of failure is high for the BAU. The lower occurrence of failures and replacements for the innovative concept as a consequence of a longer lifetime results in lower maintenance costs. For the logistic challenges, there are no differences foreseen between BAU and the new concept. For both cases, there will be difficulties in transporting 6m to 7m diameter bearings. The weight of the BAU and CS1 bearing are almost the same.

Moreover, with the new testing methods developed with the INNTERESTING project (see section 3.5) the time needed to verify the new (and future) bearing design(s) is reduced much. Due to the shorter time needed to test, more tests can be performed to optimise the bearing design and LAULAGUN has more confidence in the performance of the new design.

For the pitch bearing in RS1, there were no specific data available on operational expenditures. Maintenance costs calculations for all wind turbine components were based on literature research. The impact on maintenance costs and on initial costs due to a longer lifetime, due to a lower probability of failure and due to the reduction of materials will be estimated quantitatively in D6.3 for CS1.

3.3. CS2

The new CS2 journal bearing design for future wind turbines, with the development of next generation plain bearing technology and the development of new gear materials, is expected to enable an increase of torque density in future gearboxes with increased reliability. For the new concept to be used in future larger wind turbines, the selected nominal power is 10 MW, which is the expected maximum size by 2030 and the average size for 2050 for offshore. A service life of 25 years is considered, which is a 25% increase in lifetime with respect to the BAU.

The impact on costs for this case study are related to size and weight limitations, to lifetime and to reliability. There are also important differences in the costs of testing between RS2 and CS2. This topic is discussed below in subsection 3.5. For the BAU case (RS2), the operational expenditures represent 36% of the complete life cycle cost. The gearbox operational costs account for 6% of the total OPEX of the wind turbine.

For the BAU, a torque density of ~125 Nm per used kg, and a gearbox weight of about 104 000 kg was assumed. With the innovative concept, the torque density could increase up to ~200 Nm per used kg and lower the gearbox weight to 64 000 kg. A higher torque density of the gearbox is a necessity if standard size turbine nacelles are to be used in the future, as

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transportation and dimension limits are pushed to the limits already. A higher torque density also enables a lighter weight of the gearbox, decreasing costs of transportation and logistics, material costs and the environmental and social impact of the product[5]. New high-strength materials and surface treatment methods could, on the other hand, have a reverse impact on costs.

Secondly, the innovative concept has a positive impact on the reliability. Wind turbine reliability depends on the reliability of some of its key components. Gearbox failures are for example seen as one of the most common and most critical failures. A gearbox failure causes downtime for repairs or replacement and important electricity production losses. Maintenance of wind turbines are typically conducted twice a year. A maintenance would normally involve thorough inspection of the entire system, replacement of fluids, lubrication and servicing of mechanical parts. Repairs and replacements would be conducted if necessary. These time-based inspections and maintenance activities are often expensive and require undesired downtime (Chan & Mo; 2017). An increased reliability as a result of the new CS2 journal bearing design decreases the risks of shutdowns due to malfunctioning of the turbine drivetrain and increases the lifetime of the product[5]. This increases the energy production on an annual basis and over the total lifetime, and lowers OPEX during the lifetime of the turbine.

Further, the transportation of a gearbox is a difficult and very costly part of the installation of the wind turbine. Hoisting the nacelle onto the tower requires the largest crane capacity of all wind turbine components to install because of the lift height and mass (Cotrell et al., 2014). For CS2, the tower height is 119 m and the mass of the drivetrain and nacelle with the gearbox installed is about 436 t. Progressively larger wind turbine nacelles need to be lifted onto progressively taller towers by larger cranes. The logistics of the larger crane classes is increasingly challenging. One way to reduce the nacelle mass that must be lifted onto the tower is for example to hoist and install the gearbox in the nacelle after the nacelle is installed. However, this increases the cost and difficulty of the installation and can only reduce mass to a certain extent. Another challenge is the difficulty of transporting and manoeuvring large cranes within the wind plant, between wind plants, and in complex terrain (Cotrell et al., 2014). This must be taken into account for future land-based wind turbines. There is, however, a development of innovative technologies for wind turbine assembly cranes and maintenance cranes, in order to eliminate the height restrictions for turbines and render both the assembly and replacement process faster and more cost-effective. New technologies apply fixed mounting of the cranes in the turbine and use the turbine's tower for support. This addresses the risk of falling cranes and makes the cranes independent of ground conditions (ScottishPower Renewables, 2022; Mammoet, 2022).

For the gearbox in RS2, specific data on costs of materials and labour hours for maintenance of the gearbox were available. Maintenance costs calculations for all other wind turbine components were based on literature research. The impact on costs due to a longer lifetime, due to a lower probability of failure, and due to changes in size and weight of the component will be estimated quantitatively in D6.3 for CS2.

Regarding the S-LCA, company specific risk levels have been collected on gearbox production both for the BAU RS2 and for the INNTERESTING solution. These data have been integrated in the S-LCA model and will be used in the final reporting in D6.3.

[5] Deliverable 'D1.3 - Novel journal bearing final design' - confidential report.

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3.4. CS3

For the CS3 reparation and stiffening concept, the selected nominal power is 3.4 MW, which corresponds to the current average size. To assess this case study, we assume that the wind turbine was installed in 2020 and that the pitch bearing is expected to fail at an early stage of the lifetime (i.e. four years after the installation of the turbine in 2024). A reparation and stiffening solution will subsequently be required, with the aim to continue the service life of 20 years.

For the BAU case (RS3), the operational expenditures represent 26% of the complete life cycle cost. In the event of a failure of the pitch bearing, the replacement and redesign of the three bearings is assumed to cause a downtime of six months. The failure could for instance originate from higher actual loads than the design loads. Decommissioning would take place after 20 years.

For the new concept (CS3), the reparation and stiffening solution would lower the downtime to one and a half months. A significant improvement is expected due to lower production losses and avoided costs of redesign and replacement (including costs of logistics, reinvestment and end of life of the three old bearings). Thanks to the stiffening solution, risks of failure for the component are strongly reduced, even for higher loads, and therefore maintenance costs are also reduced. The costs of the stiffening solution (person hours for repair actions, material costs, costs of logistics, etc.) are additional costs that need to be considered for CS3, however these costs are relatively small compared to the other large economic advantages of the new concept.

For the pitch bearing in RS3, there were no specific data available on operational expenditures. Maintenance cost calculations for all wind turbine components were based on literature research. The impact on costs due to a longer lifetime, due to a lower probability of failure and due to the avoidance of replacement and redesign will be estimated quantitatively in D6.3 for CS3.

3.5. Testing methods

The next tables present an overview of the characteristics of the BAU testing method and INNTERESTING experimental testing methods. The first table regards the testing method of pitch bearings and the second table the testing method of gearboxes. The quantitative LCSA results of the testing methods will be included in D6.3, including an allocation of the testing methods to the respective RSs and CSs.

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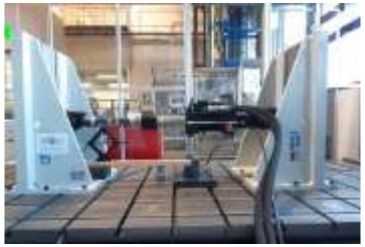
- **Pitch bearing testing methods**

	BAU testing method	**INNTERESTING experimental testing method**		
	Blade bearing test	**Rolling contact fatigue (RCF) test**	**Ring structural fatigue (RSF) test**	**Rolling element test**
	Windbox blade bearing test bench 	RCF simplified test bench 	Hydraulic test bench 	Hydraulic press rolling element test bench 
Purpose of test bench	Aimed at conducting tests on the hub, the blade bearings and the bearing-hub and the blade-bearing joints	Aimed to test the RCF failure mode, possible crack on the raceways of bearings 	Aimed to test to test RSF failure mode, possible crack in outer ring of bearings 	Aimed to test contact pressure failure mode to validate roller elements 
Test object	A complete (prototype of) bearing	Samples of a complete (prototype of) bearing	Samples of a complete (prototype of) bearing, close-to-square cross section, not flat specimens	Alternative designs of rolling elements
Number of objects tested in one test campaign	1 prototype of bearing	10 samples/bearing (design)	20 samples/bearing (design)	4 rollers

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	BAU testing method	INNTERESTING experimental testing method		
	Blade bearing test	**Rolling contact fatigue (RCF) test**	**Ring structural fatigue (RSF) test**	**Rolling element test**
Type of test campaign, when successful/the test result	Endurance, test is successful if no failure occurred after test run	To characterise the materials and to look for failures; followed by upscaling the results with virtual model; result is knowledge on how well the new component will perform	Lab-scale reproduction of RSF failure mode that can act as intermediate scale between characterisation and prediction scales, followed by upscaling the results with a virtual model, to avoid failure in the future	Validation test of rolling elements, test is successful if no failure occurred after test run
Runtime physical test per (prototype) test campaign	5-9 months/bearing	10 hours/sample => ~0,5 month/bearing	6 months/bearing	2 months/bearing
Runtime virtual test per test campaign	Not applicable	80 person hours/bearing design +20 hours computer time	80 person hours/bearing design +20 hours computer time	not applicable
Expected technical lifespan test bench	20	15	15	20
Estimated number of tested objects during lifespan	60	300	600	80
Estimated number of wind turbine models tested during lifespan	20	30	15	40
Strengths of testing method	Tests complete prototype	Small changes in the material or manufacturing process of a bearing can be reproduced easily without the need to manufacture a complete prototype	Fast and low-cost experimental campaigns	Can test many different roller sizes, fast test campaigns
Weakness of testing method	Costly, small number of objects that can be tested	Test samples, not complete prototypes	Test method is newly developed, still in an testing phase	Can only test axial load in one direction, not a moment

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- **Gearbox testing**

	BAU testing method	INNTERESTING experimental testing method		
	Full-scale gearbox test	**Component-scale performance test**	**Journal bearing laboratory-scale test**	**Gear contact RCF laboratory-scale test**
	10MW test run facility (building hall 25*60*17m with 2 cranes, 2 electrical motors, supporting devices, air conditioning etc.)	Reuses existing, down-scaled test run facility	Journal bearing test rig 	Twin disc test 
Purpose of test bench	Aimed at conducting tests on PPLH gearbox types on full-scale	Aimed to perform miniaturised pilot tests, to test reliability and lifetime estimations; followed by upscaling the results with a virtual model to larger gearbox scale	Aimed to carry out component-scale sliding bearing tests with sensor set-ups for virtual sensing; followed by upscaling the results with Lab-to-Field upscaling tool to larger scale journal bearing test	Aimed to test the applicability based on rolling contact fatigue of high strength steel for gear contacts
Test object	A complete (prototype of) gearbox in 5 degree tilt angle	A smaller megawatt class gearbox system 1MW product scale	2 journal bearings with shaft	Samples of different gear materials
Number of objects tested in one test campaign	1 gearbox	1 smaller gearbox	2 bearings	20 experiments

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	BAU testing method	INNTERESTING experimental testing method		
	Full-scale gearbox test	**Component-scale performance test**	**Journal bearing laboratory-scale test**	**Gear contact RCF laboratory-scale test**
Type of test campaign, when successful/the test result	Life time test, test is successful if no failure occurred after test run	Prototype testing	Evaluation of the different material solutions for optimising the design concepts and to provide data for reliability estimations to reduce risks in the development process	Evaluation of the rolling contact fatigue of different gear materials to estimate the performance of the materials in gear contacts
Runtime physical test per test campaign – prototype testing	500 hours/prototype	20 hours/prototype	7 hours/component + 7 hours for sample assembly	100 days
Runtime physical test per test campaign – serial testing	5 hours/gearbox	not applicable/not needed anymore	not applicable	not applicable
Runtime virtual test per test campaign	not applicable	320 hours	24 hours	140 hours
Expected technical lifespan test bench	7	15	50	40
Estimated number of tested objects during lifespan	6604	30	500	800
Estimated number of wind turbine models tested during lifespan	4	15	100	5

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	BAU testing method	INNTERESTING experimental testing method		
	Full-scale gearbox test	**Component-scale performance test**	**Journal bearing laboratory-scale test**	**Gear contact RCF laboratory-scale test**
Strengths of testing method	Simulates real situation	Reuses existing test run facility, no need for serial testing anymore when virtual testing is reliable	Using existing, standard test rig; fast; possible to get more data from the results	Using existing test rig; easy to use for different test parameters (load, speed, roll-to-slide ratio; temperature; sample materials; lubricants; etc.); accelerated testing; simple test samples
Weakness of testing method	Takes time and costly facilities	Test method is newly developed, TRL4	Applicability of the upscaling is critical	In some cases, simulating of the application contact conditions with the test samples can make the manufacturing of the samples challenging (like in the case of simulating ht gear contact with axial direction grounding of the test discs for CS2 in INNTERESTING)

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4. Conclusions and next steps

4.1. General conclusions

The opportunities for LCOE reduction, when comparing the BAU to the innovative solutions, are described in this report. An LCOE reduction will be driven by the increase in energy production through increasing reliability and longer lifetime. A second driver in decreasing the LCOE is through reductions in CAPEX, especially reinvestments and initial material costs. Other LCOE reductions are derived from decreasing OPEX through enhanced operation and maintenance activities and lowering the cost of capital as a consequence of increased certainty of future plant performance and reduced risk.

In general, when less material is used, the environmental impact of the material use will also decrease. This applies unless the decrease in material weight is caused by the use of alternative lightweight materials that may have a more environmental impacting production process.

In general, also the social impacts, investigated following the methodology described in D6.1, of the innovative solutions will decrease compared to BAU. If the CAPEX decreases due to lower material costs, the social impact will also decrease, at least if the material type remains the same. Similarly, social impacts will reduce due to a lower replacement rate of components during operation of the turbines.

4.2. Next steps in the LCSA

Working group meetings per case study were held at the M30 consortium meeting on 27 and 28 June 2022. These offline face-to-face meetings were very useful to discus the data gaps. We were able to close a number of the data gaps and to define action points to close the ones still open. The next months will be used to collect the final inventory data and to finalise the LCSA models and BAU revision. The aim is to already present (a part) of the LCSA results at the final project event scheduled on 28 September 2022 at Wind Energy Hamburg.

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